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Landscape and Ecosystem Diversity, Dynamics and Management in the Yellow River Source Zone

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To our families and colleagues who provided immense support that helped us make this project happen

Preface—A Personal Comment

> Just as landscape defines character, culture springs from a spirit of place.
>
> Wade Davis (2009, p. 33).

Landscapes evoke multiple memories and emotions through layers upon layers of interactions and interpretations, convergent and divergent, steadfast and emergent, contemporary and historical. They evoke notions of place. Identity. Home. Belonging. Nostalgia (Solastalgia). Perhaps inevitably, contestation is common. Hopefully, a 'duty of care' emerges from the midst of these connections.

Just as 'beauty lies in the eye of the beholder', scientific framings that are used to tackle any issue bring particular perspectives to bear, shaping what is seen (entities, patterns, linkages, etc.) and how it is assessed. Inevitably, approaches to landscape analysis reflect our training and experience. Everything is contextual. Instinct and intuition come to the fore. What is new/familiar? How does it relate to what has been seen/experienced previously? This has enormous implications for how these understandings are derived and how they are used to inform management applications.

The Upper Yellow River is an intriguing and awe-inspiring place. Although it presently attracts relatively few overseas visitors, rapid infrastructure developments will make the area much more accessible in coming years. To date, most environmental research in this region has been derived from remotely sensed and modelled applications. This book supplements these analyses through various field investigations. Work conducted by researchers at Qinghai University is supplemented by insights and perspectives from various researchers at the University of Auckland in New Zealand, who worked alongside researchers at Tsinghua University and the Chinese Academy of Sciences in Beijing as part of the environmental arm of the Three Brothers (Plus) Project since 2007.

Writing and compiling this book has been a very demanding process, pulling together threads of enquiry from divergent sources and perspectives. Given many contestations relating to various issues in environmental science and management in the region, we have not tried to force a consistent perspective throughout the book. Such is the nature of research. Having said this, we hope that the book does justice to our own voices among many others that are not directly considered here.

Although it is not always possible to avoid technical terminology, we have tried to minimize the use of jargon in efforts to make the book accessible to a non-specialist audience.

The landscapes and ecosystems of the Upper Yellow River have their own particular magic. Hopefully, our efforts in this book enable others to share some of that magic, and encourage others to experience it directly. At the same time, we have to look after the special values of such places …

The dark night gave me black eyes,

I use them nonetheless seeking for the light.

A Generation: Gu Cheng

Reference

Davis, W. (2009). *The wayfinders: Why ancient wisdom matters in the modern world*. House of Anansi.

Oneroa, Waiheke Island
November 2015

Gary John Brierley

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Although this book is first and foremost New Zealand–China collaboration, a recurrent thread of Australian thinking pervades those parts of the book with which the lead editor was involved. Reflections upon vast landscapes provide an ongoing sense of intrigue and inspiration, providing a distinctly calming influence among tempestuous circumstances (anyone undertaking such ventures should carefully consider the practicalities of workload, professional and personal commitments within which such work is completed, remembering that opportunistic moments of inspiration may be somewhat delusional). With patience and hard work, we got there in the end! This would not have happened without support structures around us. We extend particular thanks to family and friends who helped us get there, in the sincere hope that our efforts to work through challenges that were faced, and successfully negotiated, prove to be both productive and worthwhile. Truly, sincere thanks!

We particularly acknowledge the efforts of many colleagues who supported field ventures in the Upper Yellow River Basin. This includes those who helped make this happen through logistical and administrative support from afar. Conversations and sharing of perspective were truly invaluable. Thanks to all participants for openness in promoting a healthy and lively spirit of enquiry. Also, the parties were truly memorable, underpinning the remarkable social and cultural spirit of the New Zealand–Qinghai connections. And if these spirits weren't quite sufficient, the baijou did the rest!

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- Figure 1 on page 2 in Yao, T., Masson-Delmotte, V., Gao, J. et al. (2013). A review of climatic controls on δ^{18O} in precipitation over the Tibetan Plateau: Observations and simulations. *Reviews of Geophysics*. 51: 525–548.
- Figure 1 on p. 2941 in Chen, H., Zhu, Q., Peng, C. et al. (2013). The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau. *Global Change Biology*. 19: 2940–2955, doi: 10.1111/gcb.12277
- Figure 3 on p. 77 in Li X.L, Gao J., Brierley G., et al., (2013a). Rangeland degradation on the Qinghai-Tibet Plateau: Implications for rehabilitation. *Land Degradation and Development*, 24: 72–80.

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Contents

Chapter 1
Introduction: Landscape and Ecosystem Diversity in the Yellow River Source Zone

Gary John Brierley, Xilai Li, Carola Cullum and Jay Gao

Abstract The Upper Yellow River lies at the margins of and atop the Qinghai–Tibet Plateau. This chapter provides an overview of contemporary understandings of the geography, geology, climate, geomorphology and palaeoenvironments, vegetation, and fauna of the area. Tectonic uplift and river incision have induced a wide range of charismatic landscapes, many of which retain a significant imprint from Quaternary environmental changes, especially the glaciated mountains, vast lake, river, permafrost, desert and loess landscapes, and countless wetland areas. The plateau is an important alpine biodiversity hot spot. The high elevation, along with prevailing semi-arid/arid climatic conditions and associated vegetation cover, has created distinctive but vulnerable ecosystems. Large grassland areas support sparse populations of nomadic herdsmen. Mounting evidence suggests that human activities over thousands of years have induced a regime shift from forest cover to grazing-adapted grassland across much of the plateau. In recent decades, population growth has accompanied demands for economic expansion as part of the 'Great Development of the West' in China. Climate change and human activities threaten the landscapes and ecosystems of the Upper Yellow River. Telltale signs of accelerated environmental adjustments include retreating glaciers, melting permafrost, decreasing river flows, shrinking lakes and wetlands, hillslope instability, degrading vegetation, declining grassland productivity, salinity problems, and

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accelerated desertification. In outlining the structure of this book, this chapter draws attention to three key threads of enquiry: the primacy of landscape diversity and notions of place as an integrative platform for applied research, the importance of field-based understandings alongside remotely sensed applications, and how viewing humans as part of ecosystems helps to shape prospects for more effective approaches to environmental management.

Keywords Landscape · Ecosystem · Geodiversity · Climate change · Human impact · Degradation · Ecosystem services · Environmental management

1.1 Opening Statement: What the Book Is About and Why It Has Been Written

Concerns for environmental and societal security are especially pronounced in those parts of the world where strong pressures for development exist alongside severe threats to biodiversity and the natural environment. These tensions lie at the heart of the sustainability agenda. They are played out on an ongoing basis in the source zone of the Yellow River, where societal pressures for rapid economic development compete against desires to preserve the natural resources upon which that development depends.

The source zone of the Yellow River is perhaps most renowned for its topographic setting atop the Qinghai–Tibet Plateau—the highest plateau in the world (Fig. 1.1). The plateau has an average elevation of 4000 m above sea level and an area of about 2.6 million km^2, stretching approximately 1000 km north to south and 2500 km east to west. Framed alongside adjacent mountain ranges, this area is sometimes referred to as the 'Third Pole' or the 'Roof of the World' (Qiu 2008). The area is peculiarly cold for its latitude—colder than anywhere else outside the polar regions. After the Antarctic and the Arctic, the Qinghai–Tibet Plateau and surrounding mountains make up the Earth's largest store of ice, with more than 100,000 km^2 of glaciers (Qiu 2008; Yao et al. 2012). In addition to being the source region for many of the world's great rivers, including the Tsangpo–Brahmaputra, Mekong, Yangtze, and Yellow Rivers, much of the surface of the high central plateau drains internally to large basins, such as the Qaidam and Qinghai Lake basins. The Sanjiangyuan (Three River Source Zone) comprises the headwaters of the Yellow, Yangtze, and Lancang (Mekong) Rivers. This region is known as the 'kidney of the earth', the 'cradle of living forms', and 'the water tower of China', acting as a vital reservoir for water resources in East Asia (Qiu 2008; Yao et al. 2012). Approaches to environmental management atop the plateau have enormous implications for much of China and, beyond, exerting a significant influence upon the social and economic development of China, India, Nepal, Tajikistan, Pakistan, Afghanistan, and Bhutan—collectively home for one-fifth of the world's population (Yao et al. 2012).

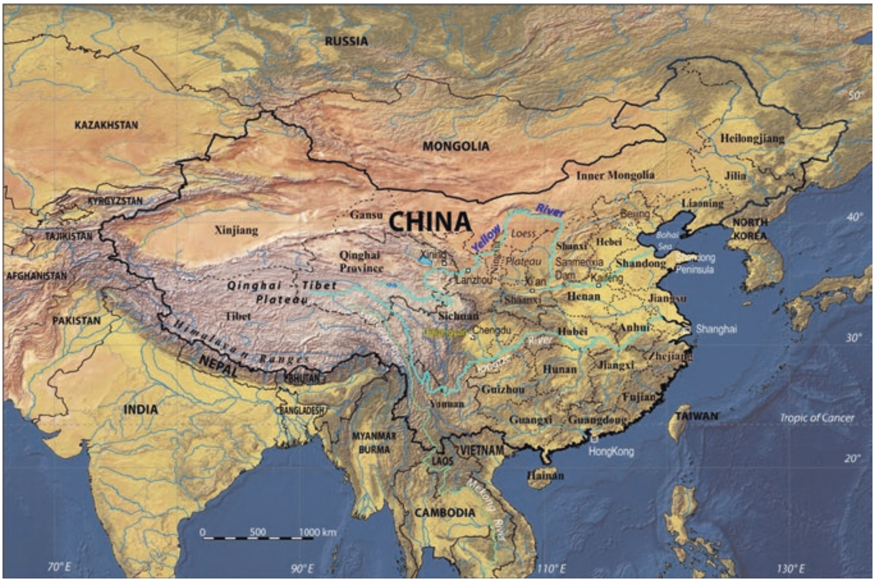

Fig. 1.1 The Yellow River Source Zone lies within the Qinghai–Tibet Plateau. This is the highest and largest plateau in the world, extending over an area of 2.58 million km^2. Elevations range from 3000 to 5000 m. Qinghai Province is shown in relation to adjacent mountain and desert area in China and neighbouring states. Collectively, the headwaters of the Yellow, Yangtze, and Lancang (Mekong) rivers make up the Sanjiangyuan (Three River Source Zone) in southern Qinghai Province

This book provides an overview of the remarkable landscapes and ecosystems of the Upper Yellow River in the north-eastern part of the Qinghai–Tibet Plateau. Tectonic uplift and river incision have induced a wide range of charismatic landscapes in this region, many of which retain a significant imprint from Quaternary environmental changes (Fig. 1.2). Large sedimentary basins were infilled by vast volumes of lacustrine, riverine, and aeolian (wind-blown) sediments over millions of years. These basins and intervening mountain ranges were then incised and reworked by the Upper Yellow River and its tributaries, creating dramatic gorges and extensive terrace sequences that are up to 1 km deep and tens of kilometres wide (Craddock et al. 2010). Uplift and river capture have realigned rivers and created new inland-draining basins, such as the Qinghai Lake. The imprint of past climates is seen in the glaciated mountains, vast lake, river, permafrost and desert landscapes, and countless wetland areas. Aeolian processes mould and reshape landscapes, with localized areas of active sand dunes representing a mere 'drop in the ocean' relative to the vast volumes of finer-grained loess deposits that drape the north-eastern part of the region and the adjacent Loess Plateau.

The climate of the region is harsh and inhospitable. Although the average annual temperature is below 0 °C, the area is subjected to very long hours of sunshine. Annual precipitation across the region decreases from the south-east to north-west, ranging from 250 to 750 mm.

Subdued landscapes of the 'headwaters' region of the Upper Yellow River above Zhaling Lake

Eling Lake, close to the headwaters of the Yellow River - the 'Mother River of China'

Dunes and wetlands at Star Lakes near Maduo

Antelope crossing a tributary of the Upper Yellow River near Maduo. Note the largely decoupled hillslope-valley floor interactions in this area

Tributary of the Upper Yellow River between Huashixia and Dari, with the Anyemachen Mountains in the background

Incisional landscapes of Chengen He, a tributary of the Upper Yellow River that has incised through the vast deposits of a previously inland-draining' (trapped) basin

Fig. 1.2 Characteristic physical landscapes of the Qinghai–Tibet Plateau

The high elevation, along with prevailing semi-arid/arid climatic conditions and associated vegetation cover, has created distinctive but vulnerable ecosystems, with many iconic and endemic species, some of which are threatened or endangered (Fig. 1.3). Spatial distributions of many living forms have been marginalized in this area. The plateau is an important alpine biodiversity hot spot, with estimates of the number of plant species ranging from 9000 to 12,000 (Liu et al. 2014).

Eroding sandstone landscapes of the middle reaches of the Upper Yellow River

Majestic sandstone landscapes of the middle reaches of the Upper Yellow River

Dramatic terraces of the Upper Yellow River at Kesheng, Henan County

A majestic telescopic fan of the Upper Yellow River downstream of Tongde

Dissected sandstone (Danxia) landscapes at Guide, adjacent to an anabranching reach of the Upper Yellow River

Dissected sandstone (Danxia) badland landscapes of the Upper Yellow River at Guide

Fig. 1.2 (continued)

Over 20 % of these species are endemic. Biodiversity tends to decrease with altitude, as well as towards the colder and drier north-west. Ecosystem types in the region range from subtropical rain forest in the south-east to alpine desert in the north-west. Much of the region now has a sparse cover of shrubs and occasional trees, with alpine grasslands comprising more than 50 % of the whole plateau area (Chen et al. 2014; Qiao and Duan 2016, Chap. 6). Large areas of grassland, characterized by a flourishing herbaceous layer when healthy, support sparse populations of nomadic herdsmen.

Fig. 1.3 Distinctive fauna of the Upper Yellow River

A distinct anthropogenic signature sits atop the natural variability of the region (Fig. 1.4). Despite its inhospitable environment, the Qinghai–Tibet Plateau is now occupied by over seven million people, mostly indigenous Tibetans. Tibetan families account for the vast majority of the herding families, with a small number of other nationalities such as Chinese Han, Hui, Sala, and Mongolian. The population is very small relative to the vast area.

The plateau was once considered one of the world's most recently populated areas by humans. However, archaeological, linguistic, and genetic findings have transformed this perspective in recent decades. Emerging understandings indicate that the population of this region has multiple origins, extending back at least 20–30,000 years (Aldenderfer and Yinong 2004; Brantingham and Xing 2006; Qin et al. 2010). Genetic studies indicate that the uniquely evolved physiological capacities seen among modern Tibetan populations required long-term exposure to high-elevation selective pressures. Seasonal foraging in high-elevation settings of the plateau likely began between 30,000 and 15,000 years ago. More permanent

Tibetan cultural values are a characteristic feature of the region

Agriculture at the margins (near Qinghai Lake), where water is a prized asset, and desertification an inevitable risk

A typical grassland scene. Tending yak is the mainstay of the agricultural economy of Qinghai Province

Yak grazing landscapes of the Qinghai-Tibet Plateau

A typical grassland scene: low relief landscapes and wetlands with yak between Huashixia and Maduo

Alpine meadow vegetation … 'golf course' rangelands of the Upper Yellow River

Typical grassland scene, Qinghai Province

Bee keeping among the rapeseed (canola) near Qinghai Lake

Regional towns such as Tongde are largely agriculturally based, with limited industrial development

Xining, the capital of Qinghai Province, is by far the largest city in the Upper Yellow River Basin

Fig. 1.4 Characteristic sociocultural landscapes of the eastern part of the Qinghai–Tibet Plateau occupation of the plateau probably did not begin until about 8200 years ago, when herders from low-elevation environments were driven further afield by emerging settled agricultural groups. By 6000 years ago, herders in mid-elevation areas were joined by agriculturalists, so herders migrated to still higher altitudes (Qin et al. 2010).

There is mounting evidence to suggest that human activities over thousands of years have induced a regime shift in vegetation dynamics across much of the plateau from forest cover to grazing-adapted grassland ecosystems (Miehe et al. 2009). While grassland vegetation would have been present within the open basins and valleys of the plateau, woody vegetation and trees would have been found on sunny mid-slopes and sheltered gorges (Tane 2011). However, these forested areas have disappeared over the last 6000 years, due likely to human activities (Herzschuh et al. 2010; Miehe et al. 2009). The history of nomadic people herding yaks possibly stretches back over 8800 years (Miehe et al. 2008a, b, 2009). The emergence of modern grazing systems around 2200 years ago instigated the establishment of grazing-adapted *Kobresia* pastures (see Miehe et al. 2009, 2011, 2014; Schlütz and Lehmkuhl 2009).

Livestock grazing is the main component of the regional economy (Fig. 1.4). Although agriculture is practised up to an elevation of 3300 m, the area of tillage atop the plateau is very limited, restricted primarily to fertile valley floors at the margins of the plateau. It accounts for only 0.3 % of the land area of the Yellow River Source Zone.

Low population numbers, the low intensity of farming practices, and the lack of industrial development have restricted the impacts of human activities upon landscapes of the region. In general terms, animal husbandry practices associated with the predominantly Tibetan peoples of this area have been ‘sustainable’ for several thousand years. However, population growth and development pressures are increasing—both in their extensiveness and their intensity. Demands for economic expansion as part of the ‘Great Development of the West’ have been supported by extensive infrastructure programmes that make the region increasingly accessible, helping to establish primary industries, mining developments, and tourism. Inevitably, the rapid development of the region is impacting upon traditional lifestyles and land use practices. Some researchers contend that population increases and policy-induced land use changes since the 1980s have led to overgrazing and consequent grassland degradation, wetland loss, and desertification (Fan et al. 2010; Gao 2016, Chap. 10; Li et al. 2012; Li et al. 2016a, Chap. 7; Qiao and Duan 2016, Chap. 6; Li and Wang 2016, Chap. 8; Tane et al. 2016, Chap. 13; Zhang et al. 2015). Others attribute these changes to shifts in climate (see discussion in Li et al. 2016a, Chap. 7). To date, a coherent picture of the underlying mechanisms causing these changes is yet to emerge (see Chen et al. 2013; Harris 2010; Li et al. 2013). Lack of clarity on these issues adds to uncertainty as to the most appropriate management responses (see Brierley et al. 2016b, Chap. 15; Harris et al. 2015; Wen et al. 2013; Wu et al. 2013; Zhang et al. 2013).

The United Nations Convention to Combat Desertification (UNCCD) defines land degradation such as that seen in the landscapes of the Upper Yellow River as ‘a persistent reduction in biological and economic productivity’ (UNCCD 1994).

It is especially prevalent in dryland regions, where degradation exerts adverse impacts on biomass productivity and landscapes and ecosystems are characterized by extremely low primary productivity, nutrient poor soils, and sparse and patchy vegetation, impacting upon prospects for food security, biodiversity, and environmental sustainability (Mueller et al. 2014). Physical processes of land degradation include soil erosion by wind and water and changes to soil structure such as crusting and compaction. Significant chemical processes include acidification, leaching, salinization, and nutrient depletion. Biological processes include alterations to plant cover and ecosystem functionality (e.g. invasive species) resulting in a loss of biodiversity. Collectively, these processes reduce soil fertility and the economic productivity of the land. As a consequence, these systems become increasingly vulnerable to social and environmental perturbations, impacting on the ecosystem services provided by these landscapes.

Both climate change and human activities threaten the landscapes and ecosystems of the Upper Yellow River. In recent decades, telltale signs of accelerated environmental adjustments have become evident: retreating glaciers, melting permafrost, decreasing river flows, shrinking lakes and wetlands, hillslope instability, degrading vegetation, declining grassland productivity, salinity problems, and accelerated desertification (Fig. 1.5). Mean temperature across the plateau as a whole has increased by up to 0.3 °C a decade over the last 60 years—approximately three times the global rate (Piao et al. 2011; Qiu 2008). Climate and cryospheric changes have been especially pronounced over the last three decades (Kang et al. 2010). Increasing precipitation trends in central areas of the plateau in recent decades contrast with decreasing trends at the plateau margins. Evaporation is increasing across the area. As a result, river discharge shows a declining trend in the semi-humid and humid zones in the eastern and southern plateau. Permafrost areas are especially at risk, as rising temperatures cause the active ground layer—which freezes and thaws every year—to thicken. This not only presents challenges for construction and infrastructure maintenance, but also endangers the plateau's alpine ecosystems (Qiu 2008). The lower limit of permafrost has risen by 40–80 m over the last 50 years, with the total area declining by about 7 % (Jin et al. 2007).

Significant controversy surrounds approaches to the protection of environmental values in the region, with differing perspectives upon the role of local peoples as agents of landscape change, impacts upon ecosystems (especially grassland and wetland degradation), and prospective environmental futures (see Brierley et al. 2016b, Chap. 15). Balancing the benefits of economic development and societal well-being against environmental risks and desires for conservation and rehabilitation is a critical challenge. Immense environmental, political, developmental, and cultural issues are at play.

Despite the global significance of the area, in biophysical and sociocultural terms, the formal literature on the landscapes and ecosystems of the Upper Yellow River is remarkably thin and lacking in coherence. Sound, integrated guidance for informed decision-making is lacking. The marked variability in the diversity of landscape forms and processes is seldom appreciated, with few attempts to appropriately contextualize understandings in spatial and temporal terms.

Retreating glacier atop the Qinghai-Tibet Plateau, viewed from the Xining-Lhasa railway

Changes to permafrost impact upon hillslope processes such as these solifluction lobes at Huashixia

Hillslope wetlands, valley margin features and floodplain ponds are sensitive to climate and land use change

Desertification threatens local areas of the Upper Yellow River basin as a result of changing vegetation patterns

Dust/sand storm at the margins of Qinghai Lake

Plateau pika: Friend or foe? Ecosystem engineer or pest?

Fig. 1.5 Environmental and sociocultural values of the Upper Yellow River and adjacent regions that are under threat

Biological diversity is inextricably linked to the variety of landscapes in any ecoregion. Geodiversity is fundamental to habitat diversity, presenting a major control on the distribution of life, as ecological potential is highly dependent on the quality and quantity of available habitat. Understanding controls on the quantity, quality, and distribution of natural habitat provides fundamental insights into the health and resilience of associated ecosystems and their potential for recovery if degraded. More importantly, analyses of landscapes also provide an integrative basis to assess economic opportunities and sociocultural connections, from which a sense of identity and belonging emerges.

Biophysical attributes also exert a critical influence upon ecosystem services, such as water quality and quantity, habitat availability and viability, nutrient cycling, soil fertility/health (including microfauna), and key measures of ecosystem functionality. These issues are fundamental to societal well-being. Despite their importance, scientific understandings of environmental issues in the source zone of the Yellow River remain fragmented, with relatively little integration among fields such as geomorphology, terrestrial and aquatic ecology, hydrology (water resources), climatology, and human ecology (see Qi 2016, Chap. 11). More importantly, discipline-bound framings seldom extend across to meaningful incorporation of socio-economic and cultural associations, and local knowledge. Such fragmentation engenders incomplete and possibly incorrect understandings of socio-ecological systems, limiting our capacity to generate appropriate approaches to the management of complex environmental issues. Appropriate management programmes strive to establish healthy, productive, and resilient ecosystems that are able to recover from, rather than resist, disturbance. A sound information base that conveys coherent process-based understanding of spatial and temporal diversity, variability, and evolutionary traits is a fundamental requirement for effective management practice.

Among many factors, the inaccessibility of the region has inhibited efforts to generate coherent, systematic understandings of key biophysical attributes of the landscapes and ecosystems in this region. In recent decades, this shortcoming has been rectified, in part, by much greater availability of remotely sensed information. While such data sources provide an invaluable basis to establish a sense of context and variability, they are only a partial alternative (and not entirely appropriate) substitute for field-based analyses.

This book seeks to start to address this shortcoming, using a geomorphic (landscape) approach to relate locally derived, field-based understandings of landscapes and ecosystems to broader, remotely sensed applications undertaken across the Upper Yellow River. In this book, the distinctive landscapes of the Upper Yellow River provided a fundamental backdrop for collaborations among researchers from differing cultural and disciplinary backgrounds, including environmental scientists (geomorphologists, hydrologists, soil scientists, ecologists (terrestrial and aquatic)), agricultural scientists, and engineers. A concerted effort has been made to link threads together in an effective manner, reflecting upon spatial and temporal variability across the region.

Scientific and managerial controversies abound in the source zone of the Yellow River. Examples of major issues include the following:

- The specific timing of the development and infilling of sedimentary basins atop the Qinghai–Tibet Plateau, their relationships to phases of tectonic uplift, and subsequent responses to river incision (and associated timings of river capture that fashioned the evolution of drainage networks) are yet to be resolved.
- Although it is now broadly recognized that the Last Glacial Maximum (around 15,000 years ago) was much smaller than previous phases of glacial expansion, the magnitude and extent of past phases of glacial activity remains contentious.

- Accurate and comprehensive understanding of lake, desert, and sand dune histories is underdeveloped.
- Relationships between landscape forms and processes and vegetation interactions, soil development, biodiversity patterns and traits, etc., are poorly established.
- Controversy surrounds the history of human settlement atop the plateau and associated impacts upon environmental conditions. Additional insights are required to assess how and why humans adapted to (and in turn impacted upon) environmental conditions upon the plateau.
- There is significant disagreement about the extent, timing, gravity, and underlying causes of environmental degradation in differing parts of the region, and the designation and implementation of management responses. Key examples include issues such as ecological migration programmes through an imposed reserve (Ran et al. 2016, Chap. 14), and approaches to the management of grassland, wetland, and desertification issues (such as the use of enclosures, revegetation programmes, whether plateau pika is a fundamental ecosystem engineer or a pest).

One thing is for sure—there are countless opportunities for future research in this region!

The key premise of this book is a simple one—we must have appropriate understandings of resources before we can manage them effectively. Despite assertions that 'wilderness is dead' (Wohl 2013), and recognizing explicitly that we live in an increasingly human-dominated world (the Anthropocene), there are still some truly remarkable and remote areas where we remain in awe of nature's beauty and overwhelming majesty. Somehow, the vast yet diverse landscapes and ecosystems of the Upper Yellow River make humans feel quite insignificant! However, the pronounced and pervasive sociocultural imprint on the landscapes and ecosystems of the region presents ongoing concerns for human relations to nature, and our quest for notional 'harmony' in efforts to ensure that a 'duty of care' protects distinctive attributes of the region into the future. It is hoped that the scientific foundations outlined in this book can be used alongside local understandings to develop shared, authentic, and genuinely grounded approaches to environmental management of this remarkable place. Our intent is to support the development of socially situated science that effectively bridges and combines fieldwork and remotely sensed applications. However, prospects for the emergence and uptake of truly shared understandings are one thing—it is their uptake and ongoing adaptation that fashions environmental outcomes.

The remainder of this chapter presents contextual information on the geology, climate, geomorphology/soils, palaeoenvironmental conditions, vegetation, fauna, and human activities of the Upper Yellow River. The chapter concludes with a summary of the structure of the book. Prior to considering these issues, a geographic overview of the Yellow River Basin sets the scene for more detailed investigations of the landscapes and ecosystems of the region.

1.2 An Overview of the Yellow River Basin

The Yellow River (Huang He in Chinese Pinyin) has a special place in the hearts and minds of many Chinese people. As a source of great prosperity, it is often referred to as China's pride, the Mother River and the 'cradle of Chinese civilization'. The river has long-standing cultural associations. In traditional Chinese folklore, it was considered to flow from heaven as a continuation of the Milky Way (Elvin and Liu 1998). Conversely, the river is sometimes referred to as 'China's sorrow' or the 'Scourge of the Sons of Han'. Floods along the lower course of the river in 1332–1333 and in 1887 and 1931 are among the most devastating natural disasters anywhere in the world, as subsequent famines and disease killed more than a million people in each instance.

The Yangtze and Yellow rivers provide major links between the world's largest continent (Asia) and its largest ocean (the Pacific). From its origins in Qinghai Province, the Yellow River flows across eight other provinces and autonomous regions before emptying into the Yellow Sea north of the Shandong Peninsula (Fig. 1.6). The river provides water for around 150 million people, approximately 9 % of China's population. It is 5464 km long and drains an area of 753,000 km^2 (IRTCES 2005). Its basin extends approximately 1900 km from west to east and 1100 km from north to south. It is the third longest river in Asia and the sixth longest river in the world.

The average annual discharge of the Yellow River is greater than 2100 m^3 s^{-1}. Around 60 % of the annual flow occurs during the rainy season from July to

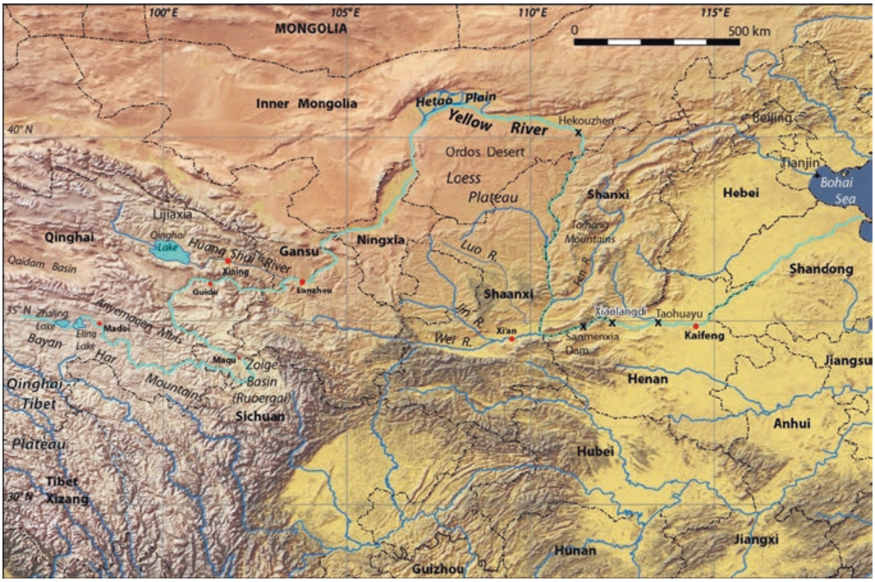

Fig. 1.6 A geographic overview of the Yellow River Basin

October, reflecting a strong monsoon-driven influence. The name ‘Yellow’ refers to the perennial colour of the muddy river water in the middle-lower reaches. Indeed, the traditional Mongolian name for the middle course was the ‘Black River’, in reference to high sediment loads. This is one of the most sediment-laden rivers in the world, with concentrations as high as 920 kg m^{-3} and annual sediment loads of around 1.6×10^9 tons (a peak of 3.9×10^9 tons was estimated for 1933). Although the Yellow River ranks 26th in the world in terms of drainage area, it is second only to the Amazon in terms of sediment delivery to the oceans.

Two major steps demarcate pronounced changes in topographic gradient along the course of the Yellow River: between the Qinghai–Tibet Plateau and the Loess Plateau upstream of Lanzhou and between the Loess Plateau and the North China Alluvial Plain near Xiaolangdi (Fig. 1.7). This book is concerned solely with the area above the first step, at the margins of and atop the Qinghai–Tibet Plateau.

From its source at an elevation of around 4600 m, the Upper Yellow River first flows east through a series of basins and deep gorges and then turns north-east at the city of Lanzhou in Gansu Province (Figs. 1.6 and 1.7). Officially, the Upper Yellow River extends from the river source to Hekouzhen in Inner Mongolia Autonomous Region at an elevation of 1000 m (see Section 1.3; Fig. 1.6; IRTCES 2005). Based on this designation, the Upper Yellow River contributes about 56 % of the total run-off but only 10 % of sediment load of the whole river basin (Huang et al. 2016, Chap. 4; Wang et al. 2006; Xu et al. 2007). Unlike middle and lower reaches, the upper section of the river has been subjected to limited flow regulation impacts. However, dam developments in various gorges at the margins of the Qinghai–Tibet Plateau are placing increasing pressure upon the flow and sediment regimes of the Upper Yellow River. Because of the low population numbers and densities, the extensive nature of farming practices, and the lack of industrial development, water quantity remains abundant in this region, and water quality is good (Ouyang et al. 2010). The river flows clear for large parts of the year, with low levels of sediment concentration and pollutants, only earning its ‘Yellow’ name in middle and lower reaches. The local Tibetan name for the upper river is Ma Chu (river of the peacock).

In contrast to the upper course, much of the middle and lower courses of the Yellow River has been subjected to intensive human disturbance throughout its long history, including deforestation, land reclamation, dam construction, and levee building (see Brierley et al. 2016a, b, Chaps. 3 and 15). Beyond Lanzhou, the river flows for many hundreds of kilometres through the Ordos Desert, an easterly extension of the Gobi Desert in Ningxia and Inner Mongolia, and the Loess Plateau (Fig. 1.6). As early as in the Qin Dynasty, from 245 to 206 B.C, ancient irrigation canals were built along the wide alluvial plains in this area. Subsequent water resource developments have greatly altered flow and sediment dynamics in this reach. Officially, the 1200 km middle reach of the Yellow River extends from Hekouzhen to Taohuayu in Henan Province, decreasing in elevation from 1000 to 110 m (Fig. 1.6; IRTCES 2005). This reach passes through the Loess Plateau, the primary source of the high sediment load of the river, the Ordos Plateau, Hetao Plain, and the Taihang Mountains. About 30 % of total run-off and nearly 90 % of total sediment load come from the middle reach. Low run-off and high sediment loads result in hyperconcentrated flows.

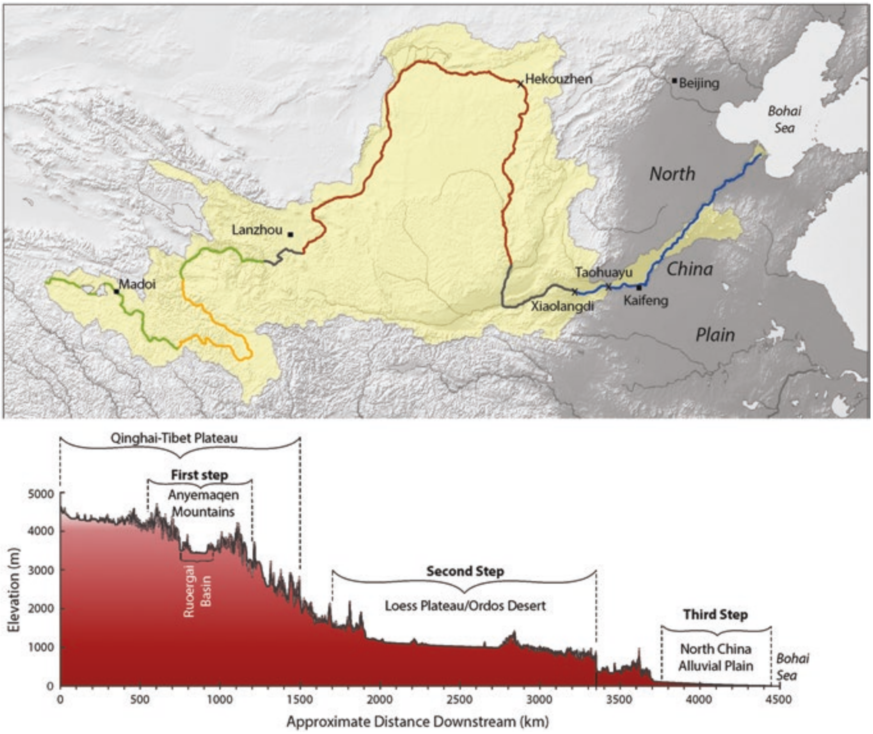

Fig. 1.7 The three topographic steps that make up differing altitudinal and landscape zones of the Yellow River across China. The *upper basin* lies predominantly atop the Qinghai–Tibet Plateau, the margins of which lie just to the west of Lanzhou. The *middle course* drains the Loess Plateau, from where large sediment loads are derived (hence the name of the river). The *lower course* extends over a wide lowland plain and has been characterized by major avulsions and associated hazards throughout historical time. We thank Tami Nicoll for assistance in developing this diagram

The second step at the margin of the Loess Plateau and the North China Plain marks the beginning of the lowland alluvial plain near Xiaolangdi (Figs. 1.6 and 1.7). Officially, the 768 km long lower reach of the Yellow River extends from Taohuayu east of the Taihang Mountains to the Bohai Sea, with elevation decreasing from 110 m to sea level (IRTCES 2005). The river enters the plains at the city of Kaifeng, where it changes from a torrent to a broad meandering stream that has now been enclosed by dikes. From west to east, the alluvial plain is made up primarily of alluvial fan, floodplain, and estuarine delta plain deposits. Rapid delta growth, along with changing sedimentation patterns and subsidence during the Quaternary, has exerted a primary control upon migration patterns of the Lower Yellow River, shifting the position of the river mouth. Hyperconcentrated flows have induced serious sedimentation and flood protection problems in this area. Major aggradation and levee development have perched the active channel zone above the adjacent plain. At Kaifeng, the lower course of the Yellow River lies

10 m above the adjacent floodplains. This area has a long history of flood disasters—a situation that has been recurrently exploited at times of war. Reduced sediment loads along the Yellow River in recent decades reflect the combined impact of flow regulation, climate change (reduced precipitation, especially in middle and lower reaches), and the influence of land use programmes (especially soil and water conservation projects; see Wang et al. 2015).

1.3 Defining the Yellow River Source Zone

Specifying the boundaries of the Yellow River Source Zone is a contentious issue, with little consensus regarding the definition of the geographical scope of the region. The catchment area and administrative districts of the Yellow River Source Zone are shown in Fig. 1.8. Differing authors have used at least five different interpretations of the boundaries of this zone:

- Pan and Liu (2005) stated that Yellow River Source Zone is the hinterland of Qinghai–Tibet Plateau, located in the south of Qinghai Province, including Madou, Maqin, Chengduo, Qumalai, Dari, and Gande Counties and covering a total area of 64,700 km^2.

Fig. 1.8 The catchment area and administrative districts of the Yellow River Source Zone. The catchment area is from Blue et al. (2013). Districts for the 19 counties are derived from the administrative maps of Qinghai, Sichuan, and Gansu provinces

- Some researchers indicated that the Yellow River Source Zone extends from the upper area of the Riyue Mountains east of Qinghai Lake and includes Longyangxia Dam. The geographical scope of this region covers an area of 92,000 km^2 (Feng et al. 2004).
- A biophysical, catchment-framed approach views the Yellow River Source Zone as comprising the administration districts upstream of Longyangxia Reservoir in the north-eastern section of the Qinghai–Tibet Plateau (Blue et al. 2013; Nicoll et al. 2013). This area includes 19 counties, with 15 counties in Qinghai (Qumalai, Chengduo, Madou, Dari, Gande, Banma, Jiuzhi, Henan, Zeku, Maqin, Tongde, Xianghai, Guinan, Gonghe, and Guide); three counties in Sichuan (Aba, Hongyuan, and Ruoergai); and one county in Gansu (Maqu). The geographical scope of this region covers a total area of 177,162 km^2.
- In the official designation used by IRTCES (2005), there are three sections of the Upper Yellow River atop the Qinghai–Tibet Plateau, and a fourth section of the Upper Yellow River extends downstream to Hekouzhen in the Inner Mongolia Autonomous Region.
- Finally, the Yellow River Source Zone can be described solely in relation to administrative districts within Qinghai Province. In this definition, the Yellow River Source Zone refers to 15 counties, with six counties in Golou, four counties in Huangnan, and five counties in Hainan Prefectures, and covers a total area of 137,700 km^2 (see NDRC 2014).

Different chapters in this book refer to differing geographic areas across the region. Some chapters incorporate comment on the Qinghai–Tibet Plateau and adjacent mountain ranges (Han et al. 2016, Chap. 12), while others refer to the Sanjiangyuan (Three River Source Zone, including headwater areas of the Yellow, Yangtze, and Lancang (Mekong) Rivers, e.g. McGregor 2016, Chap. 2; Li et al. 2016b, Chap. 9). Most chapters refer specifically to the catchment-framed delineation of the Upper Yellow River within the confines of the Qinghai–Tibet Plateau, setting the downstream boundary of the region at the margins of the plateau close to the provincial boundary between Qinghai and Gansu. This area includes three counties in Sichuan and one county in Gansu (these counties are located at the First Great Bend of the Upper Yellow River; see Fig. 1.8). In the socio-economic chapter (Ran et al. 2016, Chap. 14), analysis is restricted to data derived solely from administrative counties within the Yellow River Source Zone that lie within Qinghai Province. The specific area that is considered is outlined at the beginning of each chapter.

1.4 An Introduction to the Geography of the Upper Yellow River

1.4.1 Geology

Uplift of the Himalayas and the Qinghai–Tibet Plateau as a result of the collision of the Indian and Asian continents has been the most prominent tectonic event in the world over the last 40–50 million years. By about 50 million years ago, the fast north-moving Indo-Australian plate (15 cm/year) had completely closed the Tethys Ocean. The relatively light sedimentary rocks from the former ocean floor were readily crumpled into the mountain ranges that now form the Himalaya. The geologic base of the Qinghai–Tibet Plateau is comprised of Precambrian metamorphic rocks with an overlying complete stratigraphic sequence from lower Palaeozoic rocks upwards (Liu et al. 1980).

The plateau was formed in several uplift phases, with progressive stepwise uplift of distinct blocks towards the north-east (Li et al. 2014a, b; Liu-Zeng et al. 2008; Tapponnier et al. 2001). As the Indo-Australian plate continues to be driven horizontally below the Qinghai–Tibet Plateau (at about 50 mm per year), the plateau continues to be forced upwards. However, the surface is currently being eroded at about the same rate, such that total elevation increase in actively growing mountain ranges is around 1 mm per year (Lehmkuhl and Owen 2005). About 1.8 million years ago, dramatic adjustments to river courses in the eastern and south-eastern edge of the plateau created the contemporary courses of the Upper Yellow and Yangtze rivers (Craddock et al. 2010; Li et al. 2014a, b).

Uplift of the plateau was accompanied by a series of large strike–slip faults that run north-west–south-east through the region and associated extensional normal faulting. Current slip rates on these faults average 1–20 mm per year (Tapponnier et al. 2001). Many of the internally drained basins on the plateau are related to these fault systems, either directly by creation as a pull-apart basin (e.g. the Kunlun fault complex; Fu and Awata 2007), or as past foreland basins that eventually cut off former river outlets due to tectonic uplift of the surrounding ranges (e.g. the Qinghai Lake Basin; Colman et al. 2007; Tapponnier et al. 2001). Strong structural control has offset some rivers by up to 90 km (Fu and Awata 2007). Stream networks at the south-eastern plateau margin, where incision has created gorges more than 2 km deep, have a distinct tectonically induced asymmetry, with all major rivers having a parallel north-west to south-east alignment, and more than 90 % of the drainage lying the western side of the river (Wang et al. 2010).

The Upper Yellow River drains the north-eastern part of the Qinghai–Tibet Plateau. The present configuration of the basin developed around 1.8 million years ago, evolving to its present pattern through stepwise incision of knickpoints in response to the stepwise uplift of the plateau. Incision proceeded rapidly, at an average rate of ~350 km per million years (Craddock et al. 2010). Major sedimentary basins in this area (Zoige, Gonghe, Tongde) likely originated as fault basins during uplift of the plateau (Wang et al. 1995) and are currently separated from each other by actively growing mountain ranges (Craddock et al. 2010). These basins gradually infilled over time to create the low-relief landscapes present today, primarily through lacustrine deposits in the case of Zoige Basin (Wang et al. 1995) and fluvial aggradation in the Tongde and Gonghe basins (Harkins et al. 2007). Basin evolution occurred in a similar manner to 'bathtub infilling', with sediments flooding the closed basins created by uplift of the bordering mountain ranges (Nicoll et al. 2013). The pathway of incision has cut through these various bedrock sections and basin fills. The most recent phase of uplift-induced incision

(~0.03 million years ago) dissected the Nanshan Mountains of Guinan County and the western Qilian Mountains, thereby connecting with the Ruoergai Basin (Li et al. 1996; Harkins et al. 2007). Although river incision through the basin fills may have been a response to ongoing tectonic uplift (Harkins et al. 2007), some contend that it may reflect a climatic trigger (Craddock et al. 2010; Perrineau et al. 2011; Li et al. 2014a, b).

Much of the source region of the Yellow River is underlain by sedimentary rocks (especially sandstone red beds, with some dolomitic limestone), minor volcanic rocks, and occasional granite. Weathering of sedimentary rocks generates soils with a high content of hydromica and chlorite minerals. Loess is widely distributed across the north-eastern corner of the plateau, while evaporite deposits are prominent in many inland lakes.

1.4.2 Climate

Tectonic factors have exerted a key influence upon climatic and environmental conditions across the region. Uplift of the Qinghai–Tibet Plateau created drier and colder conditions. It brought about and intensified the Asian monsoon. The plateau is seasonally buffeted both by the summer monsoons from the south-east and south, the northerly winter monsoon, and the westerly winds from central Asia (McGregor 2016, Chap. 2, see Fig. 1.9). The Asian monsoon can be divided into the dry winter component driven by the large Siberian anticyclone, and the wet Indian and East Asian summer monsoons. The seasonal monsoon wind shift and weather associated with the heating and cooling of the Tibetan plateau is the strongest monsoon on Earth.

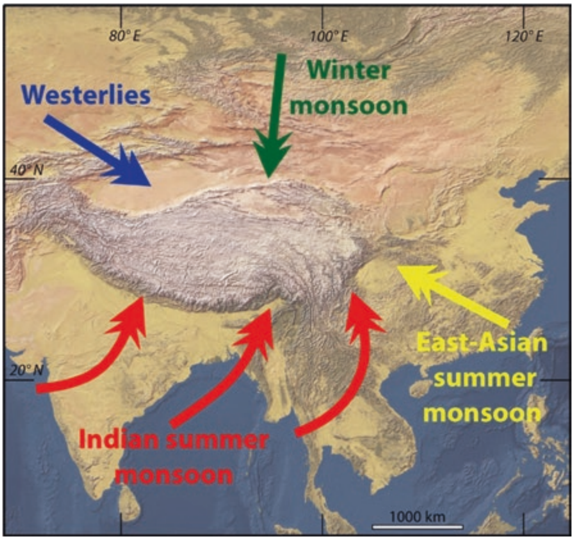

Fig. 1.9 Dominant weather systems in Qinghai Province

Due to its high altitude, the Qinghai–Tibet Plateau has a cold and dry alpine (high-altitude, semi-arid steppe) climate, with an annual mean temperature of −2.3 °C. Mean precipitation ranges from 100 to 500 mm per annum in different parts of the plateau, increasing from the north-west to the south-east of the Upper Yellow River Basin. The alpine continental climate is characterized by clear separation of dry and wet seasons. The cold season is controlled by high-pressure systems over Mongolia. Northerlies prevail, and the climate is dry and cold. In summer, the subtropical high-pressure systems of the west Pacific become strong, with warm, wet air masses gradually displacing the Mongolian high. The south-west monsoon brings warmer low-pressure systems with abundant water vapour that creates more precipitation. Summers are cool and humid. July is generally the hottest month of the year. About 70–75 % of the annual precipitation falls during the rainy season from June to September. Radiation is very intense, with more than 2500 sunshine hours per year. The snow cover is distributed primarily above 4000 m in the Anyemaqen Mountains from early October to mid-April, with the snow line rising to around 4700 m in late May. The coincidence of snowmelt with an increase in precipitation results in an abrupt rise in river run-off in June. The annual potential evapotranspiration is around 1400 mm. Given the high altitude and very thin air, the growing period is short and there is no absolute frost-free period. Major windstorms induce significant aeolian activity. Global warming in recent decades has induced warmer regional temperatures, especially in winter, but there has been marked regional variability in precipitation changes.

1.4.3 Geomorphology and Palaeoenvironments of the Upper Yellow River Basin

The Qinghai–Tibet Plateau covers most of the Tibet Autonomous Region and Qinghai Province, as well as parts of Ladakh in Jammu and the state of Kashmir in India. Elevations are greater than 4500 m in the interior and 3000 m on the peripheries. Towering mountain ranges surround this vast plateau (Fig. 1.1). The plateau itself is not flat. Indeed, tectonic uplift, river incision, and the imprint of palaeoenvironmental conditions have created a wide range of landscapes that include snow-capped mountains and glaciers, high plateaus, intermontane basins, wide valleys, and extensive lakes. China's largest extant closed-basin lake, Qinghai Lake, is located on the north-eastern margins of the plateau. Proceeding to the north and north-west, the plateau becomes progressively higher, colder, and drier.

Landscape diversity in the Upper Yellow River Basin reflects the imprint of climatic signals superimposed upon a tectonic template. Active feedback between tectonic processes and incision preferentially concentrates erosion along the eastern margin of the Qinghai–Tibet Plateau. Strong uplift and associated river incision denuded the mountains and created extensive gully networks on the plains. The interior of the plateau is essentially shielded, despite regionally variable tectonic and drainage network activity, with low-relief landscapes characterized by low erosion rates. Given the active tectonic setting and variable climate conditions, the region is prone to significant natural hazards associated with earthquakes, hillslope instability, floods and droughts, windstorms, and permafrost-related processes.

The source of the Yellow River lies in the Yueguzonglie Basin in the Bayan Har Mountains, at an elevation of 4600 m (Fig. 1.1). The mean altitude of the Upper Yellow River above Lanzhou is around 3600 m. Several wide basins are separated by major mountain ranges along the course of the Upper Yellow River: the Bayan Har Mountains define the southern edge of the Yellow River catchment, and the Anyemaqen Mountains run WNW-ESE through the middle of the upper catchment. The north-west boundary is demarcated by the Chaka sub-basin, an internally drained basin that is generally considered to be part of the larger Qaidam Basin. The Qilian Mountain and the Huang Shui, the largest tributary of the Upper Yellow River, mark the margin between the Qinghai–Tibet Plateau and the Inner Mongolia Plateau. To the south and west of the Yellow River watershed, tributaries to the Yangtze cut down through the plateau margin to the Sichuan Basin.

Glaciers within the Upper Yellow River Basin were limited in extent during the Last Glacial Maximum and reached their maximum extent well prior to that time (Heyman et al. 2011; Lehmkuhl and Owen 2005; Owen et al. 2003, 2005, 2006). Multiple phases of glaciation are evident, with local ice caps covering entire elevated mountain areas at the maximum extent. However, absence of glacial traces in intervening lower-lying plateau areas suggests that local ice caps did not merge to form a regional ice sheet around the Bayan Har Mountains. Rather, glacial landforms are restricted to mountain blocks that protrude above the surrounding plateau area (Heyman et al. 2008, 2009). Complex glacial histories in this region through the mid-Late Quaternary reflect the role of two climatic systems: periods of strong monsoons and mid-latitude westerlies (Murari et al. 2014; Owen and Dortch 2014).

Permafrost extends over an area of around 1.5 million km^2 of the Qinghai–Tibet Plateau (i.e. more than 70–80 % of the plateau interior; Jin et al. 2007). The present distribution of permafrost was established when most of the plateau had reached its present general elevation in the Late Pleistocene. During the Holocene (about 10,800 years B.P. to present), a general warming trend has induced degradation and shrinkage in the areal extent of permafrost, inducing extensive settling of the ground surface and desertification. However, a periglacial climate has been retained across much of the region during this period. A complex history of changes in depth and areal extent of permafrost, fashioned largely by elevation, has accompanied phases of climate change (Jin et al. 2007).

Quaternary sediments are abundant across the Upper Yellow River Basin, with extensive lacustrine and river deposits, and localized aeolian (sand dune and loess) sequences. Changing environmental conditions associated with tectonic uplift, denudation processes, climate change, and alterations to the hydrologic regime have brought about remarkable shifts in lake levels. Maximum lake levels were reached during the most intense phase of the monsoon system, while lake lowstands have been associated with cool and dry phases during the Pleistocene.

Qinghai Lake has been a closed-basin lake (no river outlet) since 36,000 years ago (Yan et al. 2002). It is China's largest extant closed-basin lake. Lake highstands around 36 m above the modern lake level appear to date to 70–110,000 years ago, with Early Holocene highstands no more than ~12 m above modern (Rhode et al. 2010; Liu et al. 2011, 2012). Progressive lowering of the water level in Qinghai Lake during the last half century is mainly a result of negative precipitation–evaporation balance within the context of global warming (Colman et al. 2007).

Desert evolution in the Qaidam Basin, to the north-west of the Upper Yellow River Basin, was mainly controlled by shrinkage of the Asian summer monsoon and the strengthening influence of the westerlies which increased the aridity of the basin (Yu and Lai 2014). The effectiveness of aeolian processes and associated soil development has varied markedly over time. At Lake Donggi Cona (4090 m asl), lake highstand sedimentation and lake level changes also responded to changes in Asian monsoon variability (Dietze et al. 2010). Lake lowstands occurred during the cold and dry phases of the Pleistocene. The increase in monsoon-related precipitation caused the lake to rise during the Early to Mid-Holocene. The end of the subsequent highstand sedimentation marks the shift to a dry and cool period during the Late Holocene.

Synchronicity of cold and dry periods with sparse vegetation cover and abundant loose fine-grained materials promotes effective aeolian processes. Trapping of deposits, in turn, is conditional upon appropriate accommodation space with sufficient land surface roughness, such that wind speeds are diminished and deposition can occur. This may require sufficient precipitation to generate ground cover. Optimal conditions for aeolian processes are typically experienced during periods of deglaciation, as significant bodies of loose, fine-grained sediment are exposed, vegetated cover is negligible, and winds may be severe. Alternatively, high availability of materials may accompany drier phases when the fine-grained sediments of lake beds (or river systems) are exposed (IJmker et al. 2012; Lehmkuhl and Haselein 2000; Stauch et al. 2012). The development of lake-marginal dunes (lunettes), dune fields, and infilled plateau landscapes is the product of multiple phases of deposition, stabilization, and reworking.

Geochemical and sedimentological characteristics of widespread sand dune fields and sand sheets on the north-eastern Qinghai–Tibet Plateau are indicative of a local source (IJmker et al. 2012). Finer-grained loess materials have typically been transferred much greater distances. Aeolian sediments on the Qinghai–Tibet Plateau indicate two different climatic modes (IJmker et al. 2012). During the Early Holocene, wetter conditions supported the retention of aeolian sediments. The reactivation of sediment in the Late Holocene due to small-scale disturbances in the vegetation cover points to a cooler and drier climate. Local climatic conditions, especially related to effective moisture, have induced a complex history of well-sorted aeolian sand, palaeosols, and loess deposits in the Gonghe Basin (Qiang et al. 2013).

Warmer conditions and degradation of permafrost have influenced the origin, age, formation, and stability of periglacial sand sheets and dunes (Jin et al. 2007;

Zhang et al. 2005). In the recent period, since the Little Ice Age, increasingly arid and warmer climate conditions, alongside land use changes, have induced well-developed mobile sand dunes and ridges, with desertification processes burying highways, farmlands, and grasslands in some cases. Modern aeolian sediment transport on the plateau happens mostly during winter, when vegetation cover is reduced and air masses associated with the dry winter monsoon and westerlies prevail (IJmker et al. 2012). Intervening periods may be characterized by erosion (reworking and/or removal) of aeolian deposits (e.g. Stauch et al. 2012).

The largest Loess Plateau in the world is located just to the north-east of the Qinghai–Tibet Plateau. It covers an area over 400,000 km^2, extending from north-eastern Qinghai through Gansu and covering much of Shanxi, northern Henan, and Shaanxi (Fig. 1.1). Typical thickness of loess deposits ranges from 50 to 80 m, masking the detailed relief of the underlying surfaces. Gradual strengthening of the Asian winter monsoon combined with a global cooling trend underpinned the development of thick loess deposits across the north-eastern part of the plateau (An et al. 2001). As loess is homogeneous, fine-grained, and poorly consolidated, with its calcium carbonate cement being readily soluble in water, it is very erodible. Gully incision and channel network expansion within the extensive cover of loess deposits have created dissected hills and ridges and extremely high sediment yields. Multiple phases of gully development on the Loess Plateau reflect large-scale monsoonal climatic shift coincident with neo-tectonic uplift of the land mass (Huang et al. 2012). Historically, erosion has been accentuated by land use changes, but recent reforestation programmes have arrested this process.

The landscape classification scheme developed by Nicoll et al. (2013) differentiates among 10 landscape types in the Upper Yellow River Basin (Fig. 1.10). Areas classified as *palaeo glacial valleys* are concentrated in the south-west of the area, within the Anyemaqen and Bayan Har Mountains (Heyman et al. 2008; Stroeven et al. 2009). Subdued glacial landscapes are characterized by U-shaped glacial valleys up to 2 km wide, clustered around higher mountain massifs along with meltwater channels, large glacial outwash fans, and lakes formed within glacially scoured basins. Depositional features include moraines, hummocky terrain, and drumlins (Stroeven et al. 2009). Due to their high elevation, permafrost exists over much of the area, with wetlands prominent on the lower valley floors.

The *plateau uplands* cover nearly 25 % of the Upper Yellow River Basin. This high-elevation area is relatively cold and dry, with a mean annual temperature below freezing and precipitation of approximately 320 mm. Permafrost development is evidenced by periglacial landforms such as patterned ground and frost-heave mounds, as well as thaw-induced landslides on shallow hillslopes. Drainage is generally poor, and wetlands are dominant. The landscape is relatively low relief, with broad valleys and internal basins that have been infilled with lacustrine and alluvial deposits.

Moderate and steep hillslope landscape classes are primarily located within the Bayan Har and Anyemaqen mountain ranges. Overall, moderate and steep hillslopes cover 39 % of the Upper Yellow River Basin, with 23 % above the approximate 4100 m elevation limit of permafrost influence. The majority of these

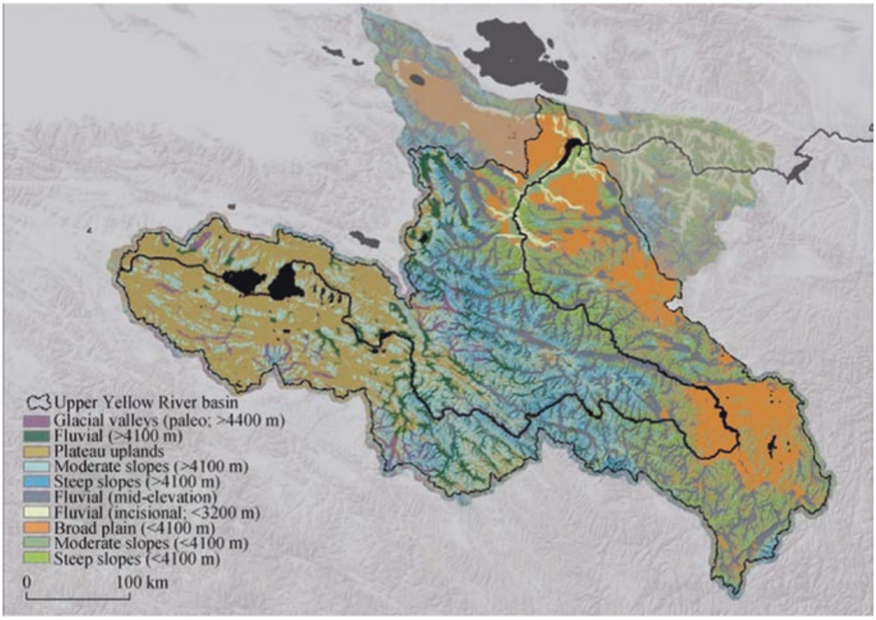

Fig. 1.10 Primary landscape types of the Upper Yellow River Basin (Nicoll et al. 2013)

hillslopes (28 %) are moderately sloping, with gradients less than 40 %. While hillslope instability is more prominent on steeper hillslopes, the combination of thin soils, sparse vegetation, widespread human influence, and freeze–thaw action induces greater instabilities than may be predicted based on gradient alone Hu et al. (2016, Chap. 5).

Fluvial landscapes make up 21 % of the Upper Yellow River Basin. Low gradients (<1 %) and wide valley floors of many headwater reaches on the upper plateau surface result in disconnected landscapes with an array of channel planform types and a multitude of wetlands (see Brierley et al. 2016a, Chap. 3; Li et al. 2016b, Chap. 9). Rates of fluvial erosion are relatively low. Many tributaries are disconnected from the mainstream and pond behind levees, developing a series of wetlands during the wet season. Structural controls are prominent within the mountain ranges downstream of the upper plateau, where bedrock gorges are common. Local transitions from confined to unconfined valley settings are accompanied by corresponding changes in channel planform and associated landforms (Yu et al. 2014a). Much of the available sediment load within this area may be due to direct or indirect glacial conditioning (Chen et al. 2011; Lehmkuhl and Owen 2005). Large alluvial fans composed primarily of glacial outwash materials now act both as sediment sources and confining features for many of the streams.

Incisional landscapes are located within tributary systems and the Yellow River itself downstream of the Anyemaqen Mountains. In these settings, fluvial valleys have cut down dramatically and are now relatively isolated from the main plateau surface.

Extensive terrace sequences in excess of 500 m high are evident in those areas where the river has cut through extensive basin-fill deposits (Harkins et al. 2007).

Alongside this tectonic control, the elevation-induced climate gradient has resulted in pronounced variability in the influence of vegetation upon channel planform types along the Upper Yellow River (Brierley et al. 2016b, Chap. 15; Yu et al. 2014). The *broad plain* landscape class covers 15 % of the Upper Yellow River Basin and consists of wide, relatively flat plains that are below the lower limit of permafrost (Nicoll et al. 2013). The geographic extent of this class largely covers three main sedimentary basins: the Zoige (Ruoergai) Basin near the first bend of the Yellow River, the Tongde basin downstream of the Anyemaqen Mountains, and the Gonghe Basin, bordered to the north-west by the Qaidam Basin. There is a significant climatic gradient between these basins. The Zoige Basin has a wetter climate, with much of the area covered by the Ruoergai wetland (Li et al. 2015). In contrast, the Tongde and Gonghe basins are semi-arid, with aeolian processes forming both vegetated and active (unvegetated) dune fields. As the trunk stream of the Yellow River has incised through the basin fills, changing base levels have triggered secondary incision of tributary systems.

1.4.4 Vegetation

Vegetation cover in the Yellow River Source Zone includes alpine and sub-alpine meadows, steppes, coniferous forest, broadleaf forest, needle-leaf forest, swamp and aquatic vegetation, cushion plants, shrub, and zones of sparse vegetation (Fig. 1.11). Alpine and sub-alpine meadows (grasslands) are dominant, with isolated remnants of montane and sub-alpine broadleaf and conifer forest on steep hillslopes and remote areas up to 4500 m high (Herzschuh et al. 2010). The grasslands are comprised of low-productive, cold-tolerant perennial plants such as kobresia (*Kobresia* spp.), needlegrass (*Stipa* spp.), sedge (*Carex* spp.), saussurea (*Saussurea* spp.), roegneria (*Roegneria* spp.), bluegrass (*Poa* spp.), wild ryegrass (*Elymus* spp.), and speargrass (*Achnatherum* spp.). The height of forage is low, ranging between 10 and 30 cm. Notable variability in radiation on north- and south-facing hillslopes also induces significant variability in patterns of plant communities. Regional vegetation patterns are shown in Fig. 1.12.

Tectonic uplift and geological isolation played important roles in shaping species diversity across the region. Some species likely retreated to the plateau edge during the glacial ages and then recolonized the platform during the interglacial ages and/or at the end of last glacial maximum (Liu et al. 2014). In contrast, other species survived the conditions experienced at the last glacial maximum in multiple refugia, even at the high-altitude platform. Indeed, some cold-preferring conifers might have expanded their distributional ranges during the Last Glacial Maximum. The largest glaciation, rather than the Last Glacial Maximum, was probably the key determinant of the distributional ranges, genetic diversity, and intraspecific divergences of the current species (Liu et al. 2014). Many plant

Coniferous forest — *Broad-leaf forest*

Needle-leaf forest — *Shrub vegetation*

Alpine meadow vegetation — *Alpine steppe vegetation*

Cushion plant — *Swamp and aquatic vegetation*

Fig. 1.11 Vegetation diversity in the Yellow River Source Zone

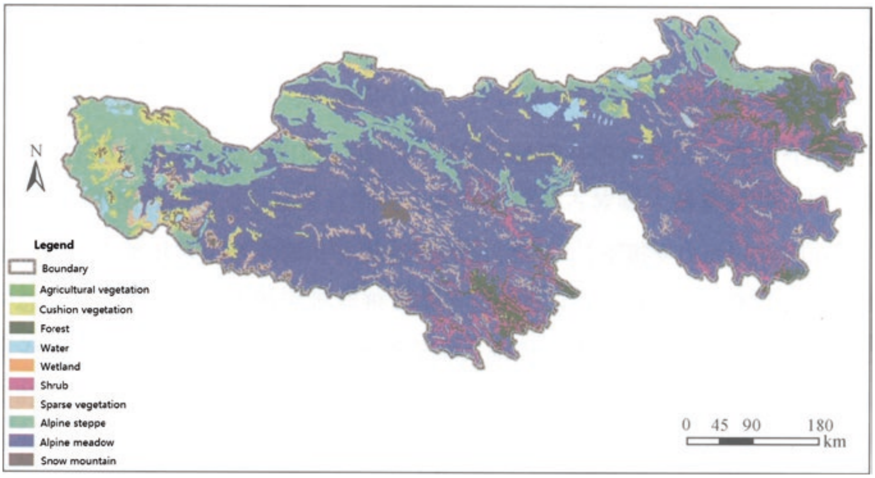

Fig. 1.12 Spatial distribution of vegetation cover types in the Sanjiangyuan region

species have adapted their reproductive strategies to meet the challenges posed by the harsh environmental conditions on the Qinghai–Tibet Plateau.

1.4.5 Fauna

Several parts of the source region of the Yellow River lie within the Sanjiangyuan National Nature Reserve, which boasts 93 species of animals, 255 species of birds, 18 species of amphibious reptiles, and at least 90 genera of insects and soil fauna (Chen et al. 2007). Many of these animals are endemic to the region and are rare or threatened. Indeed, 69 species found in this region are on the list of 'protected wildlife of national importance', of which 16 are in the first class (including the iconic Tibetan antelope (*Pantholops hodgsoni*), wild yak (*Bos mutus*), and snow leopard (*Panthera uncia*)) and 53 species are in the second class (including the blue sheep (*Pseudois nayaur*) and the Tibetan gazelle (*Procapra picticaudata*)) (Fig. 1.3).

Native small mammals on the grasslands in the Upper Yellow River, such as plateau pikas (*Ochotona curzoniae*), Chinese zokor (*Eospalax fontanierii*), and Brandt's vole (*Lasiopodomys brandtii*), are ecosystem engineers in their respective ecosystems. They contribute significantly to the preservation of native biodiversity of plants and animals as well as preserving important ecosystem functions. Their burrows offer shelter for other small mammals such as toads, lizards, insects, and other invertebrates and even provide breeding habitats for burrow-nesting birds (Lai and Smith 2003). These small mammals also introduce heterogeneity into the grasslands, generating a mosaic of different habitats that increase plant species diversity (Bagchi et al. 2006) as well as providing food for native predators (including foxes, weasels, and small cats and birds such as hawks, falcons, eagles, and owls; Samjaa et al. 2000). The small mammals also promote the recycling of nutrients and aeration of the soil (Zhang et al. 2004) and may even reduce the risk of soil erosion. To date, limited research has systematically assessed species diversity and ecological functionality in lakes, rivers, wetlands, and soils of the region.

1.5 Structure of the Book

Three critical themes fashion core threads of enquiry for this book:

(a) The development of practical (applied) research that relates specifically to landscape diversity in efforts to protect the distinctive landscapes and ecosystems of the Upper Yellow River and improve environmental conditions in areas subjected to degradation. Appropriate documentation of key resources and distinctive attributes (the values we seek to protect) and effective understanding of underlying processes that threaten ecosystem values are required to provide a starting point for appropriately informed and targeted management interventions.
(b) Increasing development pressures in the region require the adaption of precautionary approaches to environmental management that build upon coherent scientific guidance, in which field-based understandings are related directly to remotely sensed applications (and vice versa).
(c) Emphasis upon 'place' and the 'local' appropriately highlights the fundamental importance of people as part of ecosystems. Effective uptake of best available understandings builds upon coproduced knowledge of biophysical-and-cultural landscapes, providing a basis to establish common platforms for shared commitments to environmental decision-making (see Wilcock et al. 2013).

The book is structured as follows. Chapter 2 provides an overview of spatial and temporal variability in the climate of the Upper Yellow River Basin. The hydrologic regime and river diversity of the Upper Yellow River are assessed in Chaps. 3 and 4. Hillslope forms and processes in the region are appraised in Chap. 5. Human impacts upon environmental systems are assessed in terms of grassland resources (Chaps. 6 and 7), desertification issues (Chap. 8), wetland resources (Chaps. 9 and 10), and fish resources (Chap. 11). The land use history of the region, human–environmental interactions, and socio-economic considerations are summarized in Chaps. 12, 13, and 14, respectively. Chapter 15 provides a synthesis of prospective environmental futures in the region, emphasizing choices to be made in moves towards sustainable environmental management.

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References

Aldenderfer, M., & Yinong, Z. (2004). The prehistory of the Tibetan Plateau to the seventh century AD: perspectives and research from China and the West since 1950. *Journal of World Prehistory, 18*, 1–55.

An, Z. S., Kutzbach, J. E., & Prell, W. L. (2001). Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since late Miocenetimes. *Nature, 411*, 62–66.

Bagchi, S., Namgail, T., & Ritchie, M. E. (2006). Small mammalian herbivores as mediators of plant community dynamics in the high-altitude arid rangelands of trans-Himalaya. *Biological Conservation, 127*, 438–442.

Blue, B., Brierley, G. J., & Yu, G. (2013). Geodiversity in the Yellow River Source Zone. *Journal of Geographical Sciences*, *23*, 775–792.

Brantingham, P. J., & Xing, G. (2006). Peopling of the northern Tibetan Plateau. *World Archaeology, 38*, 387–414.

Brierley, G. J., Yu, G. A., Li, Z. W. (2016a). Geomorphic diversity of rivers in the upper Yellow River basin. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 59–77). Berlin: Springer.

Brierley, G. J., Cullum, C., Li, X. L., et al. (2016b). Conclusion: Environmental futures of the upper Yellow River basin. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 353–369). Berlin: Springer.

Chen, Y., Li, Y., Zhang, Y., Zhang, M., et al. (2011). Late quaternary deposition and incision sequences of the golmud river and their environmental implications. *Quaternary International, 236*, 48–56.

Chen, B., Zhang, X., Tao, J., et al. (2014). The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agricultural and Forest Meteorology, 189*, 11–18.

Colman, S. M., Yu, S. Y., An, Z., et al. (2007). Late cenozoic climate changes in China's western interior: A review of research on lake Qinghai and comparison with other records. *Quaternary Science Reviews, 26*, 2281–2300.

Craddock, W. H., Kirby, E., Harkins, N. W., et al. (2010). Rapid fluvial incision along the Yellow River during headward basin integration. *Nature Geoscience, 3*, 209–213.

Dietze, E., Wünnemann, B., Diekmann, B., et al. (2010). Basin morphology and seismic stratigraphy of Lake Donggi Cona, north-eastern Tibetan Plateau China. *Quaternary International, 218*, 131–142.

Elvin, M., & Liu, C. (Eds). (1998). *Studies in environment and history: Sediments of time: environment and society in Chinese history*. Cambridge University Press. 544 pp.

Fan, J. W., Shao, Q. Q., Liu, J. Y., et al. (2010). Assessment of effects of climate change and grazing activity on grassland yield in the three rivers headwaters region of Qinghai-Tibet Plateau China. *Environmental Monitoring and Assessment, 170*, 571–584.

Feng, J. M., Wang, T., Xie, C. W., et al. (2004). A case study on the eco-environmental degradation in the source region of the Yellow River, Northeast Qinghai-Xizang Plateau. *Progress in Geography, 23*, 56–62. (In Chinese with English Abstract).

Fu, B., & Awata, Y. (2007). Displacement and timing of left-lateral faulting in the Kunlun Fault Zone, northern Tibet, inferred from geologic and geomorphic features. *Journal of Asian Earth Sciences, 29*, 253–265.

Gao, J. G. (2016). Wetland and its degradation in the Yellow River Source Zone. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 209–232). Berlin: Springer.

Han, M. Q., Brierley, G. J., Cullum, C., et al. (2016). Climate, vegetation and human land use interactions on the Qinghai-Tibet Plateau through the Holocene. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 253–274). Berlin: Springer.

Harkins, N., Kirby, E., Heimsath, A., Robinson, R., & Reiser, U. (2007). Transient fluvial incision in the headwaters of the Yellow River, northeastern Tibet, China. *Journal of Geophysical Research, 112*(F3), F03S04: 1–21.

Harris, R. B. (2010). Rangeland degradation on the Qinghai-Tibetan plateau: A review of the evidence of its magnitude and causes. *Journal of Arid Environments, 74*, 1–12.

Harris, R. B., Wenying, W., Smith, A. T., et al. (2015). Herbivory and competition of Tibetan steppe vegetation in winter pasture: effects of livestock exclosure and plateau pika reduction. *PLoS ONE, 10*(7), e0132897.

Herzschuh, U., Birks, H. J. B., Liu, X., et al. (2010). What caused the mid-Holocene forest decline on the eastern Tibet-Qinghai Plateau? *Global Ecology and Biogeography, 19*, 278–286.

Heyman, J., Hattestrand, C., & Stroeven, A. P. (2008). Glacial geomorphology of the Bayan Har sector of the NE Tibetan Plateau. *Journal of Maps, 4*, 42–62.

Heyman, J., Stroeven, A. P., Alexanderson, H., et al. (2009). Palaeoglaciation of Bayan Har Shan, northeastern Tibetan Plateau: Glacial geology indicates maximum extents limited to ice cap and ice field scales. *Journal of Quaternary Science, 24*, 710–727.

Heyman, J., Stroeven, A. P., Caffee, M. W., et al. (2011). Palaeoglaciology of Bayan Har Shan, NE Tibetan Plateau: Exposure ages reveal a missing LGM expansion. *Quaternary Science Reviews, 30*, 1988–2001.

Hu, X. S., Brierley, G. J., Cullum, C., et al. (2016). Hillslope stability in the Yellow River source region. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 101–115). Berlin: Springer.

Huang, C. C., Pang, J., Zha, X., et al. (2012). Development of gully systems under the combined impact of monsoonal climatic shift and neo-tectonic uplift over the Chinese Loess Plateau. *Quaternary International, 263*, 46–54.

Huang, H. Q., Liu, X. F., Brierley, G. J., et al. (2016). Hydrology of the Yellow River Source Zone. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 79–99). Berlin: Springer.

IJmker, J., Stauch, G., Pötsch, S., et al. (2012). Dry periods on the NE Tibetan Plateau during the late quaternary. *Palaeogeography, Palaeoclimatology, Palaeoecology, 346*, 108–119.

IRTCES. (2005). *Case study on the Yellow River sedimentation*. Beijing: International Research and Training Center on Erosion and Sedimentation. 126 pp.

Jin, H. J., Chang, X. L., & Wang, S. L. (2007). Evolution of permafrost on the Qinghai-Xizang (Tibet) Plateau since the end of the late Pleistocene. *Journal of Geophysical Research: Earth Surface, 112*(F2).

Kang, S., Xu, Y., You, Q., et al. (2010). Review of climate and cryospheric change in the Tibetan Plateau. *Environmental Research Letters*, *5*(1), 015101.

Lai, C. H., & Smith, A. T. (2003). Keystone status of plateau pikas (Ochotona curzoniae): Effect of control on biodiversity of native birds. *Biodiversity & Conservation*, *12*(9), 1901–1912.

Lehmkuhl, F., & Haselein, F. (2000). Quaternary paleoenvironmental change on the Tibetan Plateau and adjacent areas (Western China and Western Mongolia). *Quaternary International, 65–66*, 121–145.

Lehmkuhl, F., & Owen, L. A. (2005). Late Quaternary glaciation of Tibet and the bordering mountains: A review. *Boreas, 34*, 87–100.

Li, J. J., Fang, X. M., & Ma, H. Z. (1996). Geomorphological and environmental evolution in the upper reaches of the Yellow River during the late Cenozoic. *Science in China (Series D), 39*(4), 380–390.

Li, X., Brierley, G. J., Shi, D., et al. (2012). Ecological protection and restoration in Sanjiangyuan Natural Reserve, Qinghai Province, China. In: Higgitt, D. (Ed.), *Perspectives on Environmental Management and Technology in Asian River Basins*. SpringerBriefs in Geography, Netherlands. 93–120.

Li, J., Fang, X., Song, C., et al. (2014a). Late Miocene-Quaternary rapid stepwise uplift of the NE Tibetan Plateau and its effects on climatic and environmental changes. *Quaternary Research, 81*, 400–423.

Li, X. L., Perry, G. L. W., Brierley, G. J., et al. (2013). Restoration prospects for Heitutan degraded grassland in the Sanjiangyuan. *Journal of Mountain Science*, *10*, 687–698.
Li, X. L., Perry, G. L. W., Brierley, G. J., et al. (2014b). Quantitative assessment of degradation classifications in degraded alpine meadows (Heitutan), Sanjiangyuan, western China. *Land Degradation & Development, 25*, 417–427.
Li, Y. F., & Wang, Z. Y. (2016). Modeling vegetation-erosion dynamics in the Mugetan Desert, Yellow River Source Zone. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 167–182). Berlin: Springer.
Li, Z. W., Wang, Z. Y., Brierley, G., et al. (2015). Shrinkage of the Ruoergai Swamp and changes to landscape connectivity, Qinghai-Tibet Plateau. *Catena, 126*, 155–163.
Li, X. L., Perry, G., & Brierley, G. J. (2016a). Grassland ecosystems of the Yellow River Source Zone: degradation and restoration. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 137–165). Berlin: Springer.
Li, Z. W., Wang, Z. Y., & Pan, B. Z. (2016b). Wetland ecosystems of the Yellow River Source Zone. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 183–207). Berlin: Springer.
Liu, J. Q., Duan, Y. W., Hao, G., et al. (2014). Evolutionary history and underlying adaptation of alpine plants on the Qinghai-Tibet Plateau. *Journal of Systematics and Evolution, 52*, 241–249.
Liu, X., Lai, Z., Madsen, D., et al. (2011). Lake level variations of Qinghai Lake in northeastern Qinghai-Tibetan Plateau since 3.7 ka based on OSL dating. *Quaternary International, 236*, 57–64.
Liu, X., Lai, Z., Yu, L., et al. (2012). Luminescence chronology of aeolian deposits from the Qinghai Lake area in the Northeastern Qinghai-Tibetan Plateau and its palaeoenvironmental implications. *Quaternary Geochronology, 10*, 37–43.
Liu, Z. Q., Yu, X. J., Xu, X., et al. (1980). The basic geological characteristics of the Qinghai-Tibet Plateau. *Bulletin of Chinese Academy of Geological Sciences, 2*, 23–47. (in Chinese).
Liu-Zeng, J., Tapponnier, P., Gaudemer, Y., et al. (2008). Quantifying landscape differences across the Tibetan plateau: Implications for topographic relief evolution. *Journal of Geophysical Research: Earth Surface, 113*(F4).
McGregor, G. R. (2016). Climate variability and change in the Sanjiangyuan region. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 35–57). Berlin: Springer.
Miehe, G., Miehe, S., Bach, K., et al. (2011). Ecological stability during the LGM and the mid-Holocene in the Alpine Steppes of Tibet? *Quaternary Research, 76*, 243–252.
Miehe, G., Miehe, S., Böhner, J., et al. (2014). How old is the human footprint in the world's largest alpine ecosystem? A review of multiproxy records from the Tibetan Plateau from the ecologists' viewpoint. *Quaternary Science Reviews, 86*, 190–209.
Miehe, G., Miehe, S., Kaiser, K., et al. (2008a). Status and dynamics of the *Kobresia pygmaea* ecosystem on the Tibetan plateau. *Ambio, 37*, 272–279.
Miehe, G., Miehe, S., Kaiser, K., et al. (2009). How old is pastoralism in Tibet? An ecological approach to the making of a Tibetan landscape. *Palaeogeography, Palaeoclimatology, Palaeoecology, 276*, 130–147.
Miehe, G., Miehe, S., Will, M., et al. (2008b). An inventory of forest relicts in the pastures of Southern Tibet (Xizang A.R., China). *Plant Ecology, 194*, 157–177.
Mueller, E. N., Wainright, J., Parsons, A. J., et al. (2014). Land degradation in drylands: an ecogeomorphological approach. In E. N. Mueller, J. Wainright, A. J. Parsons, et al. (Eds.), *Patterns of land degradation in drylands: Understanding self-organised ecogeomorphic systems* (pp. 1–9). Dordrecht: Springer.
Murari, M. K., Owen, L. A., Dortch, J. M., et al. (2014). Timing and climatic drivers for glaciation across monsoon-influenced regions of the Himalayan-Tibetan orogen. *Quaternary Science Reviews, 88*, 159–182.

NDRC (National Development and Reform Commission, China). (2014). The second phase for the ecological protection and restoration of Sanjiangyuan. http://www.sdpc.gov.cn/zcfb/zcfbghwb/201404/W020150203319341893483.pdf. (In Chinese).

Nicoll, T., Brierley, G. J., & Yu, G. (2013). A broad overview of landscape diversity of the Yellow River Source Zone. *Journal of Geographical Sciences, 23*, 793–816.

Ouyang, W., Skidmore, A. K., Toxopeus, A. G., et al. (2010). Long-term vegetation landscape pattern with non-point source nutrient pollution in upper stream of Yellow River basin. *Journal of Hydrology, 389*, 373–380.

Owen, L. A., & Dortch, J. M. (2014). Nature and timing of Quaternary glaciation in the Himalayan-Tibetan orogen. *Quaternary Science Reviews, 88*, 14–54.

Owen, L. A., Finkel, R. C., Barnard, P. L., et al. (2005). Climatic and topographic controls on the style and timing of late Quaternary glaciation throughout Tibet and the himalaya defined by 10Be cosmogenic radionuclide surface exposure dating. *Quaternary Science Reviews, 24*, 1391–1411.

Owen, L. A., Finkel, R. C., Haizhou, M., et al. (2006). Late Quaternary landscape evolution in the Kunlun mountains and Qaidam Basin, Northern Tibet: A framework for examining the links between glaciation, lake level changes and alluvial fan formation. *Quaternary International, 154*(155), 73–86.

Owen, L. A., Finkel, R. C., Ma, H., et al. (2003). Timing and style of late Quaternary glaciation in northeastern Tibet. *Geological Society of America Bulletin, 115*, 1356–1364.

Pan, J. H., & Liu, J. L. (2005). Land use change and its impact in the eco-environment on the Yellow River source region during the past 15 years. *Journal of Arid Land Resources and Environment, 19*, 69–74. (in Chinese).

Perrineau, A., Van Der Woerd, J., Gaudemer, Y., et al. (2011). Incision rate of the Yellow River in northeastern Tibet constrained by ^{10}Be and ^{26}Al cosmogenic isotope dating of fluvial terraces: implications for catchment evolution and plateau building. In: R. Gloaguen, & L. Ratschbacher (Eds.), *Growth and collapse of the Tibetan Plateau: Geological Society of London Special Publication* (Vol. 353, pp. 189–219).

Piao, S., Cui, M., Chen, A., et al. (2011). Altitude and temperature dependence of change in the spring vegetation green-up date from 1982 to 2006 in the Qinghai-Xizang Plateau. *Agricultural and Forest Meteorology*, *151*(12), 1599–1608.

Qi, D. (2016). Fish of the Upper Yellow River. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 233–252). Berlin: Springer.

Qiang, M., Chen, F., Song, L., et al. (2013). Late Quaternary aeolian activity in Gonghe Basin, northeastern Qinghai-Tibetan Plateau China. *Quaternary Research, 79*, 403–412.

Qiao, Y. M., & Duan, Z. H. (2016). Understanding alpine meadow ecosystems. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 117–135). Berlin: Springer.

Qin, Z., Yang, Y., Kang, L., et al. (2010). A mitochondrial revelation of early human migrations to the Tibetan Plateau before and after the last glacial maximum. *American Journal of Physical Anthropology, 143*, 555–569.

Qiu, J. (2008). The third pole. *Nature, 454*(7203), 393–396.

Ran, Y. C., Xie, J. X., & Li, X. L. (2016). Socio-economic development and its effects on the ecological environment of the Yellow River Source Zone. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 331–351). Berlin: Springer.

Rhode, D., Haizhou, M., Madsen, D. B., et al. (2010). Paleoenvironmental and archaeological investigations at Qinghai Lake, western China: Geomorphic and chronometric evidence of lake level history. *Quaternary International, 218*, 29–44.

Samjaa, R., Zöphel, U., & Peterson, J. (2000). The impact of the vole *Microtus brandti* on Mongolia steppe ecosystems. *Marburger Geographische Schriften, 135*, 346–360.

Schlütz, F., & Lehmkuhl, F. (2009). Holocene climatic change and the nomadic Anthropocene in Eastern Tibet: palynological and geomorphological results from the Nianbaoyeze mountains. *Quaternary Science Reviews, 28*, 1449–1471.

Stauch, G., IJmker, J., Pötsch, S., et al. (2012). Aeolian sediments on the north-eastern Tibetan Plateau. *Quaternary Science Reviews, 57*, 71–84.

Stroeven, A. P., Hattestrand, C., Heyman, J., et al. (2009). Landscape analysis of the Huang He headwaters, NE Tibetan Plateau: patterns of glacial and fluvial erosion. *Geomorphology, 103*, 212–226.

Tane, H. (2011). The Yellow River watershed in Qinghai's Sanjiangyuan region. In G. Chen, X. L. Li, J. Gao, et al. (Eds.), *Wetland types and evolution and rehabilitation in the Sanjiangyuan region* (pp. 92–110). Xining: Qinghai People's Publishing House.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) headwaters. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 275–330). Berlin: Springer.

Tapponnier, P., Zhiqin, X., Roger, F., et al. (2001). Oblique stepwise rise and growth of the Tibet Plateau. *Science, 294*, 1671–1677.

UNCCD. (1994). *United Nations Convention to Combat Desertification (UNCCD)*. New York: United Nations.

Wang, Y., Wang, S., & Xia, W. (1995). Sedimentary mineralogy and environment interpretation of core RH from Zoige Basin. In Qinghai-Tibet Project Experts Committee (Ed.), *Formation, evolvement, environmental variance, and ecosystem research of the Qinghai-Tibetan Plateau*. Beijing: Science Press.

Wang, H., Yang, Z., Saito, Y., et al. (2006). Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: connections to impacts from ENSO events and dams. *Global and Planetary Change, 50*, 212–225.

Wang, Z., Yu, G., Brierley, G. J., et al. (2010). Stream networks and knickpoints in the Sanjiangyuan region. *Annals of Warsaw University of Life Sciences—SGGW, Land Reclamation, 42*, 79–91.

Wen, L., Dong, S. K., Li, Y. Y., et al. (2013). The effects of biotic and abiotic factors on the spatial heterogeneity of alpine grassland vegetation at a small scale on the Qinghai-Tibet Plateau (QTP) China. *Environmental Monitoring and Assessment, 185*, 8051–8064.

Wilcock, D., Brierley, G. J., & Howitt, R. I. (2013). Ethnogeomorphology. *Progress in Physical Geography*, *37*, 573–600.

Wohl, E. (2013). Wilderness is dead: whither critical zone studies and geomorphology in the Anthropocene? *Anthropocene, 2*, 4–15.

Wu, J., Zhang, X., Shen, Z., et al. (2013). Grazing-exclusion effects on aboveground biomass and water-use efficiency of alpine grasslands on the northern Tibetan Plateau. *Rangeland Ecology & Management, 66*, 454–461.

Xu, Z. X., Li, J. Y., & Liu, C. M. (2007). Long-term trend of major climate variables in the Yellow River basin. *Hydrological Processes, 21*, 1935–1948.

Yan, J. P., Hinderer, M., & Einsele, G. (2002). Geochemical evolution of closed-basin lakes: general model and application to Lakes Qinghai and Turkana. *Sedimentary Geology, 148*, 105–122.

Yao, T., Thompson, L. G., Mosbrugger, V., et al. (2012). Third pole environment (TPE). *Environmental Development, 3*, 52–64.

Yu, G., Brierley, G. J., Huang, H. Q., et al. (2014a). An environmental gradient of vegetative controls upon channel planform in the source region of the Yangtze and Yellow Rivers. *Catena, 119*, 143–153.

Yu, L., & Lai, Z. (2014). Holocene climate change inferred from stratigraphy and OSL chronology of aeolian sediments in the Qaidam Basin, northeastern Qinghai-Tibetan Plateau. *Quaternary Research, 81*, 488–499.

Yu, L., Lai, Z., An, P., et al. (2014b). Aeolian sediments evolution controlled by fluvial processes, climate change and human activities since LGM in the Qaidam basin Qinghai-Tibetan Plateau. *Quaternary International, 372*, 22–32.

Zhang, H., Gilbert, B., Wang, W., et al. (2013). Grazer exclusion alters plant spatial organization at multiple scales, increasing diversity. *Ecology and Evolution, 3*, 3604–3612.

Zhang, Y., Gao, Q., Dong, S., et al. (2015). Effects of grazing and climate warming on plant diversity, productivity and living state in the alpine rangelands and cultivated grasslands of the Qinghai-Tibetan Plateau. *The Rangeland Journal, 37*, 57–65.

Zhang, Y., Liu, J., & Du, Y. (2004). The impact of plateau zokor *Myospalax fontanierii* burrows on alpine meadow vegetation on the Qinghai-Xizang (Tibetan) plateau. *Acta theriologica, 49*, 43–51.

Zhang, W., Wang, T., Qu, J., et al. (2005). Developmental characteristics of aeolian dunes and environmental changes in the adjoining region of Puruogangri ice sheet, North Tibetan Plateau. *Environmental Geology, 48*, 15–24.

Chapter 2
Climate Variability and Change in the Sanjiangyuan Region

Glenn R. McGregor

Abstract Described as the "water tower" of Asia, the Sanjiangyuan region contains the headwaters of the Mekong, Yangtze and Yellow rivers. Climate variability and change in this region therefore has fundamental impacts on a range of climate-related ecosystem services. This chapter presents an overview of the climate controls and the characteristics of the Sanjiangyuan region as well as the nature of observed climate variability and change. The climate of the Sanjiangyuan region is the outcome of both regional and distant climate processes. The region lies in a transitional zone between semi-arid and sub-humid climate conditions, the result of geographical and seasonal contrasts in moisture receipt from distant source areas over the Indian and Pacific oceans and the South China Sea. In addition to marked temperature and precipitation seasonality, inter-annual climate variability and extremes are marked features of the region's climate. Despite the paucity of observational data, it is clear that the Sanjiangyuan region is experiencing pronounced changes in climate, the origins of which are yet to be established unequivocally. The advance of rapid economic development against a backdrop of a highly variable climate resource and an uncertain climate future raises the spectre of ecosystem service degradation and the challenge of managing climate-related ecosystem services. An improved understanding of Sanjiangyuan region climate-forcing factors at the regional to global scale, regional climate characteristics and the possible consequences of human-induced climate change will assist with meeting this challenge, as will building capacity in climate risk management.

Keywords China climate · Climate controls · Climate resources · Inter-annual variability · Climate extremes · Climate change · Climate risk management

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2.1 Introduction

Covering an area of 360,000 km^2 and located on the Qinghai–Tibetan Plateau in the southern and eastern parts of Qinghai Province, the Sanjiangyuan region delivers significant ecosystem services. Often described as the "water tower" of Asia, the Sanjiangyuan region contains the headwaters of three major rivers: the Mekong (Lancang), Yangtze and Yellow rivers. Changes and variability in climate have a fundamental impact on the delivery of ecosystem services, ecosystem health and environmental stability and thus livelihood sustainability. The purpose of this chapter is to present an overview of the climate controls and characteristics of the Sanjiangyuan region as well as to outline the nature of observed climate variability and change.

2.1.1 Climate Controls

Controls on the climate of the Sanjiangyuan region occur at a range of scales from the continental scale of atmospheric circulation over East Asia, to the regional scale of the high and vast Qinghai–Tibet Plateau and local scales of landform and relief variations across the region.

2.1.2 Atmospheric Circulation Over East Asia

The climate of the Sanjiangyuan region is a result of the interaction between a number of components of the atmospheric circulation system of the broader East Asian region (Ding and Chan 2005; Wang and Chen 2012). These are illustrated schematically in Fig. 2.1. Chief among these are the East Asian summer and winter monsoons.

The East Asian summer monsoon flows are a product of the convergence of air from three high-pressure systems:

- the Mascarene high over the southern Indian Ocean which produces south-westerly flows over the Bay of Bengal and western parts of Southeast Asia,
- the wintertime high-pressure system over Australia and associated cross-equatorial flows from the south over Southeast Asia and
- the western Pacific subtropical high which brings moist unstable south-easterly air from the China Sea and Pacific Ocean.

All three flows converge to produce moist, unstable, generally southerly streams of air over the Sanjiangyuan region that result in elevating atmospheric moisture and precipitation levels during the summer months. For some areas of the Sanjiangyuan region, the total annual precipitation is almost wholly dependent on

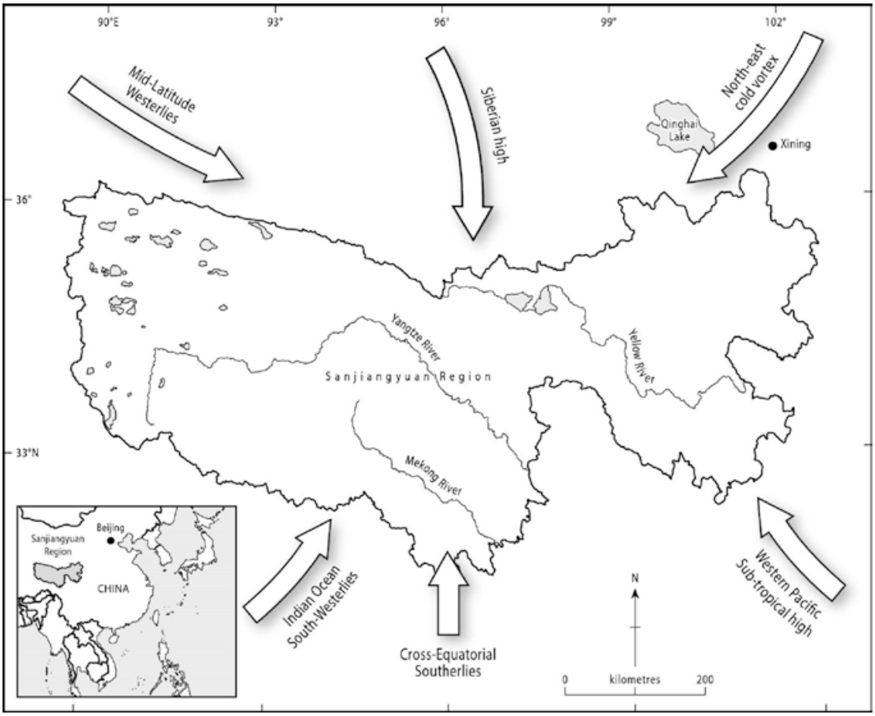

Fig. 2.1 Main air masses influencing the Sanjiangyuan region. Moist, unstable air masses of the Indian Ocean south-westerlies, cross-equatorial southerlies and the western Pacific Subtropical high merge to form the East Asian summer monsoon, which brings summer moisture and precipitation to the Qinghai–Tibet Plateau. The winter monsoon is associated with the northerly Siberian High, which brings sub-zero temperatures to the Sanjiangyuan region, suppressing precipitation. The mid-latitude westerlies and the north-east cold vortex are physically steered by the sheer bulk of the Qinghai–Tibet Plateau (*Source* Adapted from Ding and Chan 2005)

the East Asian summer monsoon. East of the Sanjiangyuan region, the flows of moist unstable air from the south converge with cold air from the middle to high latitudes, emanating from the region of a cold vortex over the north-west Pacific, to form the Meiyu front, a major feature of the East Asian monsoon.

Although a significant component of the East Asian climate system, the East Asia winter monsoon has received much less attention in the literature compared to its summer counterpart from both physical process and societal impact perspectives (Chen et al. 2014a, b, c; He and Wang 2013; Li et al. 2014). The term winter monsoon describes the movement of cold air in a south and eastward direction over eastern and southern China (Fig. 2.1). Such flows make their way across the equator to form the summer monsoon over the Maritime Continent and northern Australia. The winter monsoon period is characterised by not only sub-zero temperatures in the Sanjiangyuan region but also cold air outbreaks over eastern

China (sometimes referred to as cold northerly surges), explosive cyclogenesis off the coast of East Asia and coastal weather disturbances that propagate along the coast of East China (Chan and Li 2004). The winter monsoon owes its origins to the wintertime development of the Siberian High (Fig. 2.1). This is a cold-core high-pressure system which represents a shallow but extensive layer of very cold air that develops over the continental middle latitudes in the region of Siberia–Mongolia. As such, it is extremely stable with the result that local precipitation generation processes are suppressed and flows of moist air from any direction are blocked. In the eastern parts of the Sanjiangyuan region, surges of cold air can have two origins, namely from the north-east due to anticyclonic flow on the eastern flanks of the Siberian High, and from the west as cold air slides off the plateau where air takes on the climate characteristics of the very cold-extensive high-elevation snow- and ice-covered surfaces.

2.1.3 The Qinghai–Tibet Plateau as a Barrier to Air Movements

The Qinghai–Tibet Plateau, often referred to as the "roof of the world", is a massive elevated surface that stands at more than 4000 m above sea level. The climate effects of the plateau are wide ranging. It acts as a barrier to air mass movement and physically steers the mid-latitude upper westerly winds. The Plateau is a heat sink in the winter and a heat source in the summer. It also plays a role in the formation and dynamics of the South Asian High, and winter snow extent and depth across the plateau appear to have an effect on spring and summer rainfall for a number of regions across China.

The shear physical size and elevation of the Qinghai–Tibet Plateau present a physical barrier to flows of air from the south, west and north and to a lesser extent from the east where elevations are lower. The barrier effect of the Qinghai–Tibet Plateau is demonstrated effectively by Xu et al. (2011) in a study on precipitable water with the southern Plateau noted as wetter than the central area because of the blocking effect of the plateau on the monsoon. In winter, the plateau plays an important role in steering the Asian subtropical jet stream to the south and accelerating the westerly winds on its southern flanks. During this season, because of steep south-to-north temperature gradients, wind speeds high in the jet stream tend to accelerate to the east of the plateau. The position of the upstream entrance region of the subtropical jet stream is important for wintertime precipitation over south-eastern China. This is because acceleration of air into the jet stream creates a region of strong ascending motion and thus precipitation south of the jet entrance region (Molnar et al. 2010). As a result, some of the more eastern parts of the Sanjiangyuan region (east of around 98–100°E) are affected by jet stream-related precipitation processes. Furthermore, the large amounts of condensation that occur associated with precipitation in this region generate diabatic heating and thus atmospheric instability. This, in combination with the orographic effects of the Plateau and attendant ascending motion, creates low-level flow in the subtropics. As a result, moist air from the south moves in a north-westerly direction. Some of this moisture manages to penetrate into the south-eastern parts of the Sanjiangyuan region, contributing to the relatively high-wintertime precipitation totals found here in comparison with the more western parts of the Sanjiangyuan region. With the onset of the northern hemisphere spring and summer, the temperature gradient between the equator and high latitudes decreases. Consequently, the jet stream tends to weaken and move over the Qinghai–Tibet Plateau and Sanjiangyuan region during spring and further north by mid-summer, taking with it its attendant zones of ascending motion. The northward movement of the jet stream, in combination with the arrival of moist unstable flows of monsoonal air from the south, announces the arrival of the East Asian summer monsoon and increasing the levels of summer precipitation over the Sanjiangyuan region. In addition to its effects on the subtropical jet stream, it has been suggested that the Qinghai–Tibet Plateau plays an important role in acting as an obstacle to southward flows of cold–dry air from higher latitudes. From a geologic perspective, this may well have been important in influencing the development of the Asian monsoon (Boos and Kuang 2010; Song et al. 2010).

As the Qinghai–Tibet Plateau can be both a heat sink and a heat source it has the potential to alter atmospheric temperature and pressure patterns. Notwithstanding some of the debates relating to the importance of Plateau heating for the generation of the summer monsoon, seasonal heating and cooling of the atmosphere over the Sanjiangyuan region have important regional climate effects. In the summer, convective heating of the atmosphere can lead to summer time convective storms and intense rainfall over valleys and high ground. In the winter, atmospheric cooling facilitates the development of intense inversions and very stable air, especially over valley surfaces, the consequence of which is cold-air ponding. Studies on the seasonal march of heating and cooling indicate that from late February, the more southern parts of the Qinghai–Tibet Plateau in the south of the Sanjiangyuan region begin to heat (Xu and Zhang 2008; Wonsick and Pinker 2014). By May, most of the Plateau has become a heat source for the atmosphere with maximum atmospheric heating reached over the eastern parts of the Sanjiangyuan region in July. From late August, there is a gradual demise in heating. By October, the eastern regions of the Plateau, including the Sanjiangyuan region, begin to act as a cold source which intensifies through to January (Xu and Zhang 2008). Variations in seasonal heating over the plateau and associated impacts on cyclonic activity to the north-east of the plateau appear to play a role in the sign of precipitation anomalies over east China (Wang et al. 2014a, b). Heating in spring over the Plateau is important for summer rainfall in the wider Sanjiangyuan region (Duan et al. 2013a, b).

The South Asian High is an area of high pressure in the stratosphere that lies above the Qinghai–Tibet Plateau in summer (Xu and Zhang 2008). The South Asian High has a large spatial extent at this time of the year stretching west over the Iranian Plateau (50–70°E). The section of the South Asian High lying over the Plateau (80–100°E) is often referred to as the Tibetan High. Heating of the

Qinghai–Tibet Plateau during summer has been suggested as one of the principal factors in the establishment of the South Asian High/Tibetan High. Strong ascending motion, because of surface summer heating, results in high geopotential heights and an area of divergence in the upper troposphere above the Qinghai–Tibet Plateau. In terms of climate effects, the South Asian High is crucial for the onset of the Asian summer monsoon (Qian et al. 2005). Summer precipitation in northern China is closely associated with the longitudinal position of the South Asian High/Tibetan High in June, as opposed to the intensity of the South Asian High/Tibetan High (Huang and Qian 2003). In years with positive (negative) precipitation anomalies over northern China, the centre of South Asian High/Tibetan High moves west and north (south and east) of its climatological position.

2.1.4 Climate Effects of Local Variations in Landforms and Relief

Other elevation effects on climate include decreasing temperatures and in some cases increasing precipitation totals with altitude. While the inverse elevation temperature relationship holds for most areas across the Qinghai–Tibet Plateau and Sanjiangyuan region, precipitation dependence on altitude varies spatially. Generally, on the southern flanks of the Sanjiangyuan region, which face into the moist summer monsoon flows, there is a clear increase in precipitation with elevation due to orographic forcing (Domros and Gongbing 1988). However, in northern high-elevation parts of the Sanjiangyuan region, this association breaks down due to a combination of distance from moisture source and rain shadow effects. Further, because of the varied topography of the Sanjiangyuan region, aspect or orientation plays an important role in creating steep precipitation gradients across orographic barriers with upwind slopes wetter than their downwind equivalents (Chen and Bordoni 2014; Shi et al. 2008). At the daily timescale, local topographic effects and landscape, rather than large-scale synoptic weather systems, play an important role in determining the nature of the diurnal cycle of precipitation. For example, for hilly regions, there is a daytime precipitation peak, whereas over lakes and valleys, there are evening to nocturnal peaks (Guo et al. 2014). Similarly, there are contrasts over mountain ridges and valleys, with the former displaying morning or early afternoon precipitation peaks, while the latter tend to have late afternoon or evening peaks, as might be expected with mountain–valley local circulations (Guo et al. 2014). The diurnal variation of precipitable water over the Qinghai–Tibet Plateau is multifarious because of its topographic complexity (Xu et al. 2011).

2.2 Climate Characteristics

With the use of the terminology associated with the widely accepted Köppen–Geiger Classification (Peel et al. 2007), the climate of the Sanjiangyuan region falls broadly into the category of "arid steppe cold (BSk)". This classification is broadly in line with the climate types identified in a number of studies specifically focused on China, as discussed in Domros and Gongbing (1988) and McGregor (1993). Frustratingly, the lack of long-term observed climate data, at a suitable spatial resolution, hinders the description of possible climate sub-types within the Sanjiangyuan region. However, as more climate information becomes available, there is emerging evidence of a variety of climate sub-types across the broader Sanjiangyuan region (Geng et al. 2014; Lu et al. 2008). Given its considerable longitudinal range and the presence of significant topographic barriers, it is perhaps no surprise that available temperature and precipitation observations reveal considerable variation in climate resources across the Sanjiangyuan region. This is clearly seen when climagraphs for a number of climate stations, either within or lying just beyond the margins of the Sanjiangyuan region, are inspected (Fig. 2.2). Three broad climate sub-types are apparent: arid (Fig. 2.2a–c), semi-arid (Fig. 2.2d–f) and sub-humid (Fig. 2.2g, h).

The effects of the East Asian summer monsoon are clearly manifest in the pronounced seasonal distribution of rainfall in all three climate sub-types. For example, Yushu (Fig. 2.2g), which has a sub-humid climate, receives over 90 % of its annual total precipitation of 484 mm within the summer months. Stations further to the north and east, such as Tongde (Fig. 2.2e) and Xining (Fig. 2.2d), demonstrate similar seasonality, but decreasing precipitation amounts with annual totals of 428 and 369 mm, respectively. Greater Qaidam, Golmud and Dulan (Fig. 2.2a–c) have precipitation regimes that typify the arid regions of the wider Sanjiangyuan region with respective annual precipitation totals of 83, 38 and 181 mm, largely concentrated in the months of May to September. Stark seasonal contrasts in temperature are also evident, a result of strong summer radiation heating and advection of heat via summer monsoon flows. There is little heating in the winter due to the seasonal shift of the zone of maximum radiative heating south and outflows of cold–dry northerly continental air from the Siberian High during the winter monsoon. Overall, mean annual temperature is closely related to altitude.

While climatologists have traditionally relied on station data to gain insights into climate characteristics and resources, the availability of a range of climate re-analysis products and gridded climate data sets has made it possible to gauge the nature of climate for regions where few conventional observations are available (Tong et al. 2014a, b; You et al. 2013, 2014a, b; Zhang et al. 2013). Figure 2.3a, b shows the spatial distribution of mean January and July temperatures across the Sanjiangyuan region for the period of 1971–2013 based on mapped outputs from the NCEP/NCAR re-analysis project (Kanamitsu et al. 2002; Saha et al. 2010).

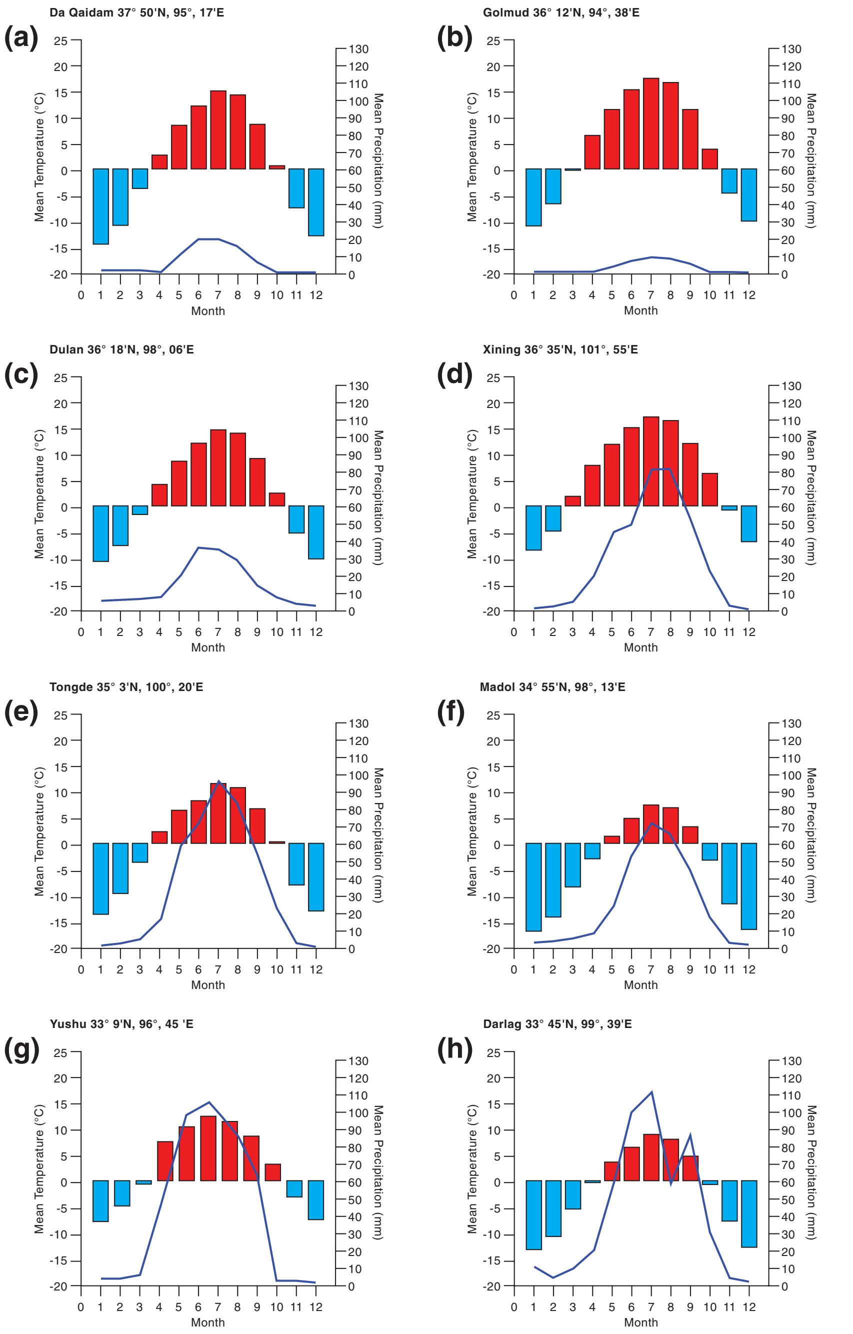

Fig. 2.2 Climagraphs for selected locations across the broader Sanjiangyuan region. *Bars* indicate temperature, while precipitation is shown as a *solid line*. Arid zones are exemplified in **a**–**c**, semi-arid zones in **d**–**f**, and sub-humid zones in **g**–**h** (*Data source* Domros and Gongbing 1988)

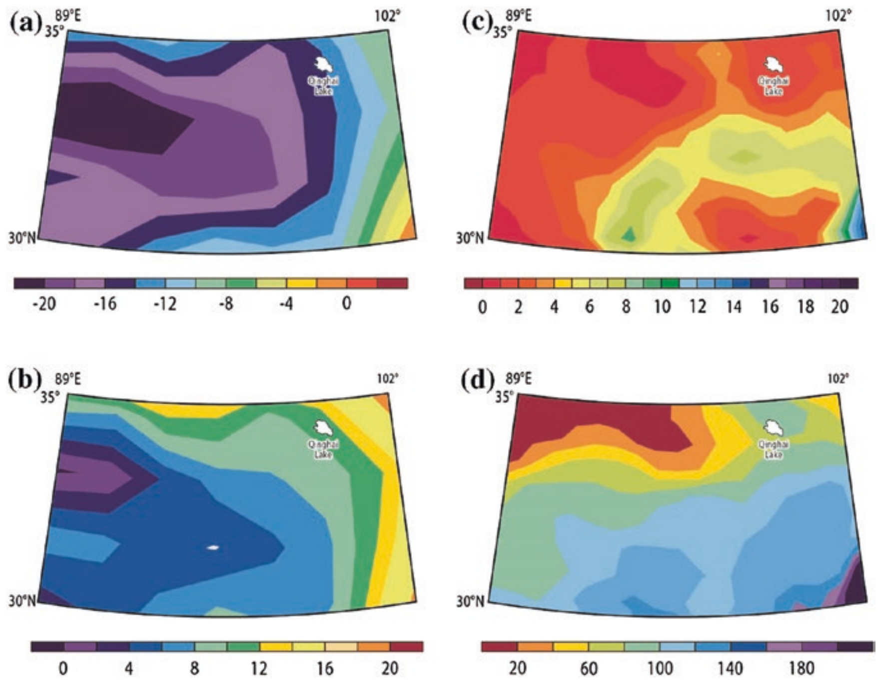

Fig. 2.3 Spatial distribution of mean temperature in °C (**a**, **b**) and precipitation in mm (**c**, **d**) for January (**a**, **c**) and July (**b**, **d**) during 1972–2012. Plots are based on twentieth-century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, at http://www.esrl.noaa.gov/psd/

Similarly, precipitation products from the Global Precipitation Climatology Centre (Schneider et al. 2014) have been used to construct precipitation maps for the same months and period (Fig. 2.3c, d).

Temperature in both January and July demonstrates a strong west-to-east gradient of increase (Fig. 2.3a, b), reflecting elevation control with western high-elevation areas possessing lower temperatures than the eastern parts of the Sanjiangyuan region. Such strong longitudinal temperature differences across the broader Sanjiangyuan region may influence the magnitude of summer rainfall over some parts of China (Zhu et al. 2010). Climatologically, the entire Sanjiangyuan region experiences sub-zero temperatures in the core winter month of January, while in July, temperatures in the east of the Sanjiangyuan region can range between 12 and 16 °C on average (Fig. 2.3a, b). During winter, cold and dry continental air, mass-related stable atmospheric conditions, in combination with the high relative relief, produce severe inversions. This can lead to very poor air quality in valley settings where there is significant urban development (e.g. Xining). As evident from the climagraphs, a comparison of the January and July temperature maps indicates significant seasonal contrasts in temperature across the Sanjiangyuan region, with seasonal ranges in the order of 20–30 °C.

A noteworthy feature of the precipitation climatology of the Sanjiangyuan region, as hinted at by the climagraphs, is the almost region-wide extremely low winter precipitation totals. This is clearly demonstrated by the mapping for the core winter month of January (Fig. 2.3c). Low totals are the result of the outflow of cold–dry polar continental air from the region of the Siberian High to the north. Any precipitation that falls is usually in the form of snow due to the low temperatures and the result of the penetration of weather disturbances from the east emanating from the area of the north-east cold vortex over the North Pacific (Fig. 2.2). These disturbances are steered by the topography. Hence, most winter precipitation is restricted to the lower elevation areas, as can be seen for the crescent-shaped area of relatively high precipitation in the south-eastern sector of the Sanjiangyuan region (Fig. 2.3c). In stark contrast to January, precipitation totals for July are significant (Fig. 2.3d). The spatial distribution of precipitation in this month reflects elevation, topographic barriers and distance from moisture source effects. The general south-east-to-north-west decrease in precipitation reflects the distance of areas within the Sanjiangyuan region from the Indian Ocean/Bay of Bengal, equatorial and western Pacific moisture sources (Fig. 2.1). Not only is there a general south-to-north precipitation gradient but also a noticeable west-to-east precipitation decrease is evident. This is due to the high elevation of the south-western parts of the Sanjiangyuan region which prevents moisture reaching elevated plateau surfaces as the majority of moisture in the summer monsoonal flows is carried below 3500 m. Further, the Qinghai–Tibet Plateau steers moist monsoonal flows originating from the Bay of Bengal region in an eastward direction. The Qaidam Basin, which lies to the north of the wider Sanjiangyuan region, is an area of persistent winter to summer low precipitation totals. Indeed, this is one of the driest areas in China. The Qaidam Basin has a typical continental intermontane desert climate, resulting from rain shadow effects. Flows of moist air are generally prevented from entering the basin due to topographic blocking by the Kunlun Mountains to the south. However, disturbances associated with the East Asian Summer Monsoon do provide limited moisture to the area during the summer months of May to September. Total annual precipitation at Greater Qaidam is only 83 mm (Fig. 2.2a). Annual precipitation for inner parts of the Qaidam Basin can be as low as 25 mm. Due to the high elevation of the basin, summer precipitation is often in the form of snow. However, the number of annual snow days remains low at around 12–13, compared to 37–38 snow days a year in the subhumid locations in the south of the Sanjiangyuan region such as Yushu (Domros and Gongbing 1988).

2.3 Climatic Variability

Climatic variability in the Sanjiangyuan region can manifest itself in a number of ways such as anomalously warm/cold and/or dry/wet summers or winters and climate extremes (Wang et al. 2012a, b). Such anomalies are often due

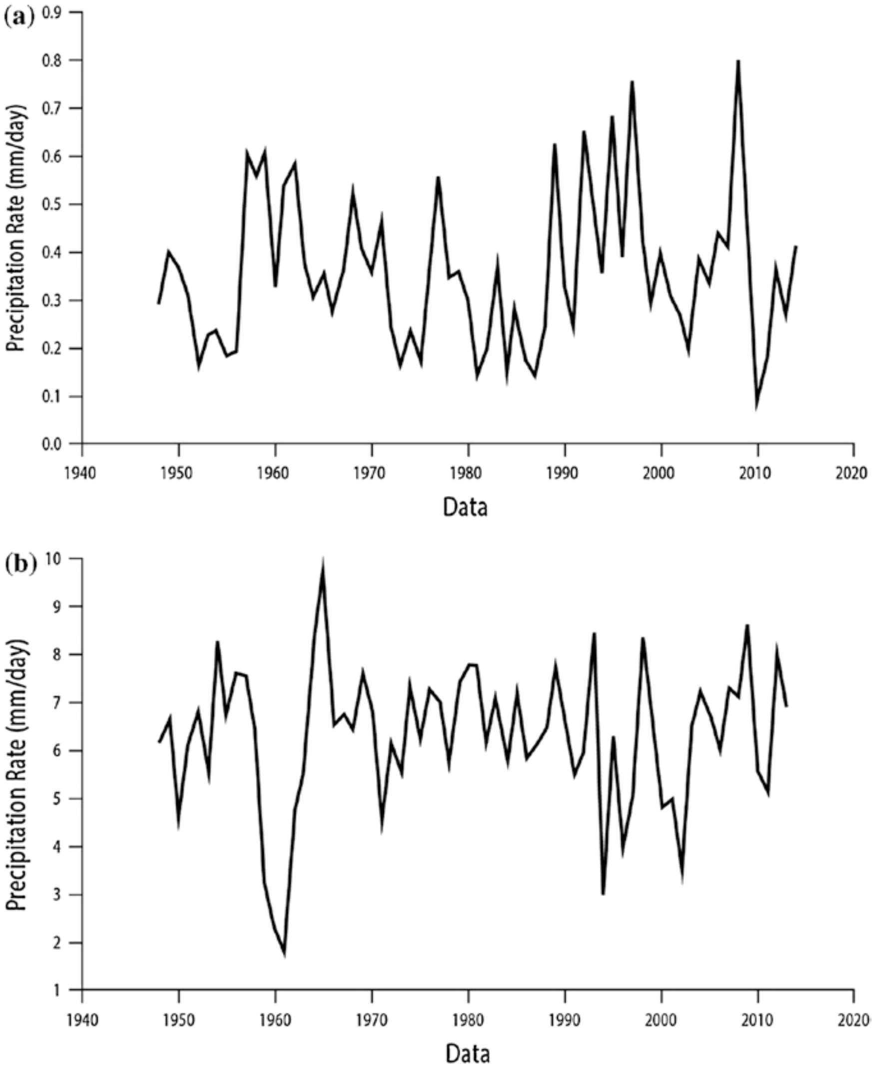

Fig. 2.4 Mean January (**a**) and July (**b**) precipitation in the Sanjiangyuan region expressed as mm per day. The mean total precipitation for January and July can be established by multiplying the mm day^{-1} numbers on the vertical axis by the number of days for January and July. Plots are based on twentieth-century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, at http://www.esrl.noaa.gov/psd/

to inter-annual variations in the atmospheric circulation patterns that influence an area. Considerable inter-annual climatic variability is apparent from time series plots of January and July precipitation rate expressed as millimetres per day for the eastern part of the Sanjiangyuan region (Fig. 2.4a, b). Notwithstanding the large differences in precipitation rate between the core winter and summer months, high inter-annual precipitation variability is evident. In terms of ecosystem services, summer precipitation is of particular interest (Mou et al. 2013; Shen et al. 2011), with clear evidence for both anomalously dry and wet summers. Of particular note are the low precipitation rates in the early 1960s which equate with a period of widespread famine in China associated with monsoon-related crop failures. Anomalously dry summers also occurred in 1992, 2002 and 2010–11.

From a climate risk management perspective, knowing the likelihood of upcoming climate anomalies a season ahead can help significantly with advanced planning in climate sensitive sectors of the economy and society, especially those exposed to extreme events such as droughts or floods. Accordingly, there has been an increasing interest in seasonal climate prediction (Lee et al. 2013), including some analyses for the Qinghai–Tibet Plateau (Hartmann et al. 2008). The scientific basis of such predictions depends on developing an understanding of the way in which a number of large-scale modes of atmospheric and oceanic circulation variability may influence climate on a range of timescales (Sun and Zhan 2012). Much effort has been invested in exploring how potential drivers of climate variability, such as the El Niño–Southern Oscillation (ENSO), may influence climate over the Qinghai–Tibet Plateau (e.g. Fan et al. 2012; Ha et al. 2012). Relationships between local/regional climate and variations in the components of the global atmospheric or oceanic circulation system over great distances are often referred to as teleconnections. Several examples are outlined below.

2.3.1 Variations in Temperature Associated with Changes in Atmospheric Pressure Patterns

In an analysis of temperature variability, both positive and negative temperature anomalies were found to be associated with departures of pressure patterns from the long-term mean (Yin et al. 2000). Different pressure–height anomaly patterns were found for the cold (October–March) and warm (April–September) seasons. Key regions where variations in atmospheric pressure patterns appear to influence temperature variability over the Qinghai–Tibet Plateau include Eurasia and the western Pacific. ENSO events were also found to be significantly correlated with temperature anomalies (Yin et al. 2000).

2.3.2 Variations in Precipitation Associated with Changes in Atmospheric Pressure Patterns

Variations in moisture flux from the Bay of Bengal, the South China Sea and North China are critical for determining winter and spring precipitation anomalies

(Wu et al. 2013a, b). It is noted that teleconnections play a role in drought and flood occurrence, such that sea surface temperature anomalies in the equatorial Pacific give rise to periods of drought or flood over extensive parts of southern China by influencing variations in atmospheric moisture transport and thus precipitation anomalies. Although focused on the Mei-Yu front, the work of Kosaka et al. (2011) highlights atmospheric processes and teleconnections over East Asia that may well be pertinent to the Sanjiangyuan region. Kosaka et al. (2011) found that precipitation anomalies over the Mei-Yu region are associated with anomalies of mid-tropospheric horizontal temperature advection. Anomalous warm (cool) advection causes increased (decreased) Mei-Yu precipitation via prompting adiabatic ascent (descent). The anomalous precipitation either bolsters or suppresses vertical motion, through positive feedback. In addition to these local processes, a number of teleconnection patterns appear important, including the Pacific–Japan teleconnection pattern, ENSO and the so-called Silk Road pattern which is the pattern of atmospheric disturbance along the summertime Asian jet. The importance of the Southern Oscillation, the atmospheric component of ENSO, for determining the nature of extreme monthly precipitation over the Qinghai–Tibet Plateau and the seasonal dependence of the relationship has been highlighted by Wan et al. (2013).

Not only do teleconnections to the east over the wider Pacific Basin play a role in precipitation variability, but those upwind to the west also appear important (Liu and Yin 2001). For example, in investigating the relationship between the summer North Atlantic Oscillation and East Asian summer rainfall, Sun and Wang (2012) found that changes in the summer North Atlantic Oscillation pattern can have fundamental impacts on atmospheric flow divergence, vertical motion, water vapour transport, total cloud cover and thus rainfall anomalies over central and northern Asia. Focusing on extreme dryness and wetness on the Qinghai–Tibet Plateau, Bothe et al. (2010) found that extreme cases of drought and wetness can be associated with circulation anomalies in the North Atlantic/European sector and associated downwind atmospheric disturbances across the Eurasian continent. In the case of drought, an intense high-pressure anomaly over Scandinavia, associated with a marked negative surface temperature anomaly, alters North Atlantic storm tracks so that cyclonic systems follow a more south-west-to-north-east route than usual. This generates disturbances over Eurasia which, on reaching south-eastern Asia, suppress moisture supply from the Bay of Bengal and hence enhance dryness over the Qinghai–Tibet Plateau. In contrast, Qinghai–Tibet Plateau wetness is associated with Atlantic storm tracks that take a more west-to-east trajectory across Central Europe. These ultimately interact with atmospheric moisture flows from the Bay of Bengal to guarantee generous moisture supply to the Qinghai–Tibet Plateau (Bothe et al. 2010). Similarly, but at a shorter timescale, eastward propagating areas of anomalous convection associated with the 30–60 day Madden Julian Oscillation influence precipitation at the intra-seasonal timescale (Jia et al. 2011). The main influence of the Madden Julian Oscillation is to modulate moisture transport from the Bay of Bengal, the South China Sea and the western Pacific subtropical high, thus impacting upon summer rainfall totals and monsoon active and break phases.

Precipitation exerts a primary control upon discharge variability in rivers (see Huang et al. 2016, Chap. 4) and the functionality of wetlands (see Li et al. 2016, Chap. 9; Gao 2016, Chap. 10). Accordingly, because of the importance of summer stream flow for providing water resources for economic development dependent on irrigation and power generation, there has been a focus on how variations in large-scale atmospheric and oceanic circulation patterns might influence water resource availability in the wider Sanjiangyuan region. For example, variations in stream flow in the upper Yangtze Basin are associated with sea surface temperatures in the eastern Indian Ocean "Indian dipole" and western Pacific Ocean "ENSO" regions via their influence on precipitation patterns and spring snowmelt (Xu et al. 2007). Positive (negative) ENSO and Indian Ocean dipole episodes are important for severe dryness (wetness) over the Qinghai–Tibet Plateau (Bothe et al. 2010), while the interplay between the Indian Ocean Dipole and El Nino Modoki events can influence the strength of the East Asian monsoon (Feng and Chen 2014).

2.3.3 Decadal-Scale Variations in Teleconnection Patterns

Beyond the intra-seasonal and inter-annual timescales, there is emerging evidence of possible decadal-scale variations in teleconnection patterns which may well impact the climate and thus shape ecosystem and landscape processes over the broader Sanjiangyuan region. For example, the meridional teleconnection over the western North Pacific and East Asia changed around the 1970s (Lin et al. 2010). This period has also been highlighted as significant for an alteration of the position and intensity of the summer North Atlantic Oscillation with consequent effects on precipitation in those areas influenced by weather patterns from the west (Sun and Wang 2012). The non-stationary relationship between the summer North Atlantic Oscillation and rainfall and snowfall over China points to decadal-scale sea surface temperature anomalies in the North Pacific and North Atlantic as important for moderating summer North Atlantic Oscillation precipitation relationships (Chu et al. 2008; Gu et al. 2009). However, the impact of inter-decadal variations in ocean–atmosphere process on summer precipitation in China cannot be ignored, as manifest by Pacific Decadal Oscillation (Ding et al. 2009; Duan et al. 2013a, b; Mao et al. 2011). Decadal-scale changes in aridity and drought occurrence are attributed to Pacific Decadal Oscillation phases, together with possible influences from the Atlantic Meridional Oscillation (Fang et al. 2010; Li and Bates 2007; Qian and Zhou 2014).

2.3.4 Wider Effects of Climate Variability on the Qinghai–Tibet Plateau

Through inter-annual variations in the amount of winter snow, the Qinghai–Tibet Plateau can have a fundamental effect on the intensity of the summer monsoon, and thus, precipitation totals over some parts of eastern China (Liu and Wang 2011; Wu et al. 2012; Xu et al. 2013). When there are positive winter snow depth anomalies over the eastern parts of the Qinghai–Tibet Plateau/southern parts of the Sanjiangyuan region (between 90°E and 102°E, centred on 30°N), precipitation is greater than normal in eastern China south of the Yangtze River and across north-east China north of around 45°. The aforementioned areas of above normal precipitation are matched with an intervening area of below normal spring precipitation which equates with the north-eastern parts of the Sanjiangyuan region. In terms of effects of Qinghai–Tibet Plateau winter snow cover on summer precipitation, there are some subtle differences to that of spring precipitation such that positive snow anomalies in the northern parts of the Sanjiangyuan region between 90°E and 103°E centred along 35°N are associated with negative precipitation anomalies in the Yellow River Basin, northern China and southern China. At the same time, positive precipitation anomalies are experienced in the Yangtze River Basin.

2.4 Climate Trends and Climate Change

The spectre of human-induced climate change has provided impetus to the search for evidence of trends in a range of climate variables as well as stimulating climate change modelling studies and impact assessments.

2.4.1 Climate Trends on the Qinghai–Tibet Plateau

Observational studies of climate trends reveal a range of alterations in temperature and precipitation characteristics and climate-related phenomena. The climate of the Qinghai–Tibet Plateau experienced moisturising and warming over the period of 1961–2007 in five climate zones covering alpine grassland meadow and desert areas (Li et al. 2010). Warm and wet events have increased, while cold and dry events have decreased. The most significant changes are in winter and autumn, with northern Qinghai exhibiting the greatest and most significant decrease in the frequency of extremely low-temperature events. Unlike temperature, the trend in wetness is spatially heterogeneous and seasonally dependent, with increases in precipitation days and amount evident for all climate zones in winter and spring, while summer and autumn display a weak but statistically insignificant decrease in these precipitation metrics. Of all the climate zones considered, south-eastern Tibet was found to demonstrate the largest decrease in the frequency of severely dry events (Li et al. 2010). Similar directions of change in climate variables have also been found in the Sanjiangyuan region where minimum, maximum and mean air temperature as well as precipitation all showed significant increases from 1960 to 2009 (Liang et al. 2013).

In the Qaidam Basin immediately to the north of the Three Rivers Region, climate warmed significantly at an average rate of 0.53 °C per decade over the period of 1961–2010 (Wang et al. 2014a, b). Seasonally, the greatest warming (0.43–1.01 °C per decade) was found for winter. Annual precipitation has increased at a rate of 7.38 mm per decade with summer demonstrating the greatest increases of around 4 mm per decade.

In addition to mean, maximum and minimum temperature trends, intra-annual temperature variability for the eastern and south-eastern areas of the Qinghai–Tibet Plateau has shown a significant decreasing trend over the period of 1960–2008 (Song et al. 2014a, b). In contrast, a significant increase in inter-annual temperature variability is observed. Interestingly, increases in inter-annual temperature appear to be associated with changes in the frequency of cold/warm nights and warm days, whereas intra-annual variability is associated with an upward (downward) trend in cold (warm) extremes. Significant increases in precipitation in the upper Yangtze region for June, July and August are related to changes in intense precipitation such that more precipitation falls in intense events as opposed to moderate and weak events (Jiang et al. 2008).

Apart from temperature and precipitation, potential evaporation and sunshine hours in the Sanjiangyuan region have increased, while relative humidity and wind speed decreased (Liang et al. 2013). Such changes have profound implications for the effectiveness of aeolian processes and associated desertification processes (see Li and Wang 2016, Chap. 8). Mean annual ground surface temperatures over the period of 1980–2007 increased at greater rates than mean annual air temperature (Wu et al. 2013a, b), while the lower altitudinal limit of permafrost has risen by 25 m in the north and between 50 and 80 m in the south of the Qinghai–Tibet Plateau over the last 20–30 years (Cheng and Wu 2007). Such trends have broader implications for degraded permafrost across the Qinghai–Tibet Plateau (Jin et al. 2008; Yang et al. 2010). Chen et al. (2014a, b) also note the importance of soil freeze–thaw processes for the climate of the Qinghai–Tibet Plateau. As lake levels are generally responsive to changes in climate, some attention has been given to the analysis of limited lake records for the Sanjiangyuan region (Bianduo et al. 2009; see Li et al. 2016, Chap. 9). To the north of the Sanjiangyuan, there has been an overall decrease in the level of Qinghai Lake, despite some short-term but unsustained peaks (Zhang et al. 2011a, b). Analyses of lake level in terms of variations in precipitation, evaporation and run-off reveal that decreasing lake levels (−0.7 m per decade) are associated with rising temperatures at a rate of 0.3 °C per decade. The period of high lake levels between 2004 and 2009 may be due to accelerated glacier and snow cover melt in preceding years (Zhang et al. 2011a, b). In addition, glacier retreat will have grave implications for hydrological processes across the Qinghai–Tibet Plateau (Yao et al. 2007).

2.4.2 Hypotheses to Explain Observed Climate Trends

A variety of explanations have been put forward for the observed changes in temperature and precipitation over the Qinghai–Tibet Plateau (Guo and Wang 2012;

Zhu et al. 2011). Wang et al. (2014a, b) contend that pollution emissions from industrial processes and urbanisation are the main factors contributing to climate warming over the Qaidam Basin, along with a weakening of zonal wind speed (You et al. 2014a, b). Guo and Wang (2012) suggest that the significant warming in northern parts of the Qinghai–Tibet Plateau may be related to pronounced stratospheric ozone depletion, via its influence on radiative and dynamical heating. In terms of variations and trends in East Asian monsoon precipitation, Xu et al. (2013) and Wen et al. (2010) consider that observed changes in summer precipitation can be explained by changes in the apparent heat source over the Qinghai–Tibet Plateau.

A widely invoked explanation for observed trends in climate and climate-related ecosystem services is human-induced climate change at the global scale. While for the Qinghai–Tibet Plateau, no specific climate change attribution experiments have been conducted, Wen et al. (2013) demonstrate that there are greenhouse gas-related anthropogenic effects in daily extreme temperature for China at large. At the regional level, some modelling studies have raised the possibility of the role of changing land use and land surface climatology in observed temperature changes via altering land–atmosphere energy exchanges (Chen et al. 2014b; Chen and Wu 2007; Li and Xue 2010; Lian and Shu 2009). There are a burgeoning number of climate change simulations for China as a whole, but uncertainty exists around the regional specificity and nature of change, especially relating to precipitation projections (e.g. Chen and Sun 2013; Kusonoki and Arakawa 2012; Seo et al. 2014; Shi et al. 2011; Song et al. 2014a, b; Sun et al. 2010; Wei and Bao 2012; Xin et al. 2013a, b; Xu et al. 2009).

Relatively speaking the number of studies addressing the impact of climate change on the Qinghai–Tibet Plateau and more specifically the Sanjiangyuan region is meagre in comparison with elsewhere in China (Wang et al. 2013). Notwithstanding this, there is a growing literature on climate impacts, especially relating to vegetation and grassland health (Chen et al. 2013; Fan et al. 2010; Piao et al. 2012; Qin et al. 2014; Wang et al. 2011; Xu et al. 2008; Zhang et al. 2010) and water resources (Tong et al. 2014a, b; Zhang et al. 2011a, b, 2012). These studies point to potential detrimental changes to a range of ecosystem services, a major concern given the significance of such services for sustainable development and poverty alleviation (Beardsley 2014; Gosling 2013; Howe et al. 2013; Munang et al. 2013; Rodriguez-Labajos 2013; Zhang et al. 2014; Zhao et al. 2013).

2.5 Concluding Remarks

The climate of the Sanjiangyuan region is the outcome of both regional and distant climate processes with marked seasonality in temperature and precipitation. The region lies in a transitional zone between semi-arid and sub-humid climate conditions, the result of geographical contrasts in moisture receipt from distant source areas over the Indian and Pacific Oceans and the South China Sea. In addition to marked seasonality, inter-annual climate variability and extremes are marked features of the region's climate. This poses challenges for managing human activities that are climate sensitive. Despite the paucity of observational data, it is clear that the Sanjiangyuan region is experiencing pronounced changes in climate, the origins of which are yet to be established unequivocally. The advance of rapid economic development and associated landscape transformation, against a backdrop of a highly variable climate resource and an uncertain climate future, raises the spectre of ecosystem service degradation in the wider Sanjiangyuan region. While regional development is inevitable, the risk posed by a variable climate resource can be reduced through an improved understanding of Sanjiangyuan region climate-forcing factors at the regional to global scale and assessing the possible consequences of human-induced climate change. To achieve this, not only are improvements in climate monitoring, analysis and modelling required, but it is also imperative to build capacity in terms of trained climate risk managers who understand the complexity of environmental risk and the extent to which climate variability and change might alter that risk.

References

Beardsley, T. M. (2014). Can ecosystem services thinking help with climate change? *Bioscience, 64*, 371.

Bianduo, B., Li, L., Wang, W., et al. (2009). The response of lake change to climate fluctuation in north Qinghai-Tibet Plateau in last 30 years. *Journal of Geographical Sciences, 19*, 131–142.

Boos, W. R., & Kuang, Z.-M. (2010). Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. *Nature, 463*, 218–222.

Bothe, O., Fraedrich, K., & Zhu, X. H. (2010). The large-scale circulations and summer drought and wetness on the Tibetan Plateau. *International Journal of Climatology, 30*, 844–855.

Chan, J. C. L., & Li, C. (2004). The East Asia winter monsoon. In C. P. Chang (Ed.), *East Asian monsoon*. World Scientific Series on Meteorology of East Asia (Vol. 2, pp. 54–106). Singapore: World Scientific Press.

Chen, J., & Bordoni, S. (2014). Orographic effects of the Tibetan Plateau on the East Asian summer monsoon: an energetic perspective. *Journal of Climate, 27*, 3052–3072.

Chen, B. L., Luo, S. Q., Lu, S. H., et al. (2014a). Effects of the soil freeze-thaw process on the regional climate of the Qinghai-Tibet Plateau. *Climate Research, 59*, 243–257.

Chen, H., & Sun, J. (2013). Projected change in East Asian summer monsoon precipitation under RCP scenario. *Meteorology and Atmospheric Physics, 121*, 55–77.

Chen, Z., Wu, R., & Chen, W. (2014b). Impacts of autumn arctic sea ice concentration changes on the East Asian winter monsoon variability. *Journal of Climate, 27*, 5433–5450.

Chen, B. X., Zhang, X. Z., & Tao, J. (2014c). The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agricultural and Forest Meteorology, 189*, 11–18.

Chen, H., Zhu, Q. A., Peng, C. H., et al. (2013). The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau. *Global Change Biology, 19*, 2940–2955.

Cheng, G., & Wu, T. (2007) Responses of permafrost to climate change and their environmental significance Qinghai-Tibet Plateau. *Journal of Geophysical Research-Earth Surface, 112*, F02S03

Chu, G. Q., Sun, Q., Wang, X. H., et al. (2008). Snow anomaly events from historical documents in eastern China during the past two millennia and implication for low-frequency variability of AO/NAO and PDO. *Geophysical Research Letters, 35*, L14806.

Ding, Y. H., & Chan, J. C. L. (2005). The East Asian summer monsoon: An overview. *Meteorology and Atmospheric Physics, 89*, 117–142.

Ding, Y., Sun, Y., Wang, Z., et al. (2009). Inter-decadal variation of summer precipitation in China and its association with decreasing Asian summer monsoon part II: Possible causes. *International Journal of Climatology, 29*, 1926–1944.

Domros, M., & Gongbing, P. (1988). *The Climate of China* (p. 357). Berlin: Springer.

Duan, W. S., Song, L. Y., & Li, Y. (2013a). Modulation of PDO on the predictability of the interannual variability of early summer rainfall over south China. *Journal of Geophysical Research-Atmospheres, 118*, 13008–13020.

Duan, A. M., Wang, M. R., Lei, Y. H., et al. (2013b). Trends in summer rainfall over china associated with the Tibetan Plateau sensible heat source during 1980–2008. *Journal of Climate, 26*, 261–275.

Fan, K., Liu, Y., & Chen, H. P. (2012). Improving the prediction of the East Asian summer monsoon: new approaches. *Weather and Forecasting, 27*, 1017–1030.

Fan, J. W., Shao, Q. Q., Liu, J. Y., et al. (2010). Assessment of effects of climate change and grazing activity on grassland yield in the Three Rivers Headwaters region of Qinghai-Tibet Plateau, China. *Environmental Monitoring and Assessment, 170*, 571–584.

Fang, K. Y., Gou, X. H., Chen, F. H., et al. (2010). Reconstructed droughts for the southeastern Tibetan Plateau over the past 568 years and its linkages to the Pacific and Atlantic Ocean climate variability. *Climate Dynamics, 35*, 577–585.

Feng, J., & Chen, W. (2014). Influence of the IOD on the relationship between El Nino Modoki and the East Asian-western North Pacific summer monsoon. *International Journal of Climatology, 34*, 1729–1736.

Gao, J. G. (2016). Wetland and its degradation in the Yellow River Source Zone. In G.J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 209–232). Berlin: Springer.

Geng, Q., Wu, P., Zhao, X., et al. (2014). Comparison of classification methods for the divisions of wet/dry climate regions in Northwest China. *International Journal of Climatology, 34*, 2163–2174.

Gosling, S. N. (2013). The likelihood and potential impact of future change in the large-scale climate-earth system on ecosystem services. *Environmental Science & Policy, 27*, S15–S31.

Gu, W., Li, C., Li, W., et al. (2009). Interdecadal unstationary relationship between NAO and east China's summer precipitation patterns. *Geophysical Research Letters, 36*, L13702.

Guo, D., & Wang, H. (2012). The significant climate warming in the northern Tibetan Plateau and its possible causes. *International Journal of Climatology, 32*, 1775–1781.

Guo, J., Zhai, P., Wu, L., et al. (2014). Diurnal variation and the influential factors of precipitation from surface and satellite measurements in Tibet. *International Journal of Climatology, 34*, 2940–2956.

Ha, K.-J., Heo, K.-Y., Lee, S.-S., et al. (2012). Variability in the East Asian monsoon: a review. *Meteorological Applications, 19*, 200–215.

Hartmann, H., Becker, S., & King, L. (2008). Predicting summer rainfall in the Yangtze River basin with neural networks. *International Journal of Climatology, 28*, 925–936.

He, S., & Wang, H. (2013). Oscillating relationship between the East Asian winter monsoon and ENSO. *Journal of Climate, 26*, 9819–9838.

Howe, C., Suich, H., van Gardingen, P., et al. (2013). Elucidating the pathways between climate change, ecosystem services and poverty alleviation. *Current Opinion in Environmental Sustainability, 5*, 102–107.

Huang, H. Q., Liu, X. F., & Brierley, G. J., et al. (2016). Hydrology of the Yellow River Source Zone. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 79–99). Berlin: Springer.

Huang, Y., & Qian, Y. F. (2003). Relationships between South Asian high and summer rainfall in North China. *Plateau Meteorology, 22*, 602–607.

Jia, X. L., Chen, L. J., Ren, F. M., et al. (2011). Impacts of the MJO on winter rainfall and circulation in China. *Advances in Atmospheric Sciences, 28*, 521–533.

Jiang, T., Kundzewicz, Z. W., & Su, B. (2008). Changes in monthly precipitation and flood hazard in the Yangtze River basin, China. *International Journal of Climatology, 28*, 1471–1481.

Jin, H. J., Yu, Q. H., Wang, S. L., et al. (2008). Changes in permafrost environments along the Qinghai-Tibet engineering corridor induced by anthropogenic activities and climate warming. *Cold Regions Science and Technology, 53*, 317–333.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., et al. (2002). NCEP-DOE AMIP-II Reanalysis (R-2). *Bulletin of the American Meteorological Society, 83*, 1631–1643.

Kosaka, Y., Xie, S.-P., & Nakamura, H. (2011). Dynamics of interannual variability in summer precipitation over East Asia. *Journal of Climate, 24*, 5435–5453.

Kusunoki, S., & Arakawa, O. (2012). Change in the precipitation intensity of the East Asian summer monsoon projected by CMIP3 models. *Climate Dynamics, 38*, 2055–2072.

Lee, D.-Y., Ahn, J.-B., & Ashok, K. (2013). Improvement of multimodel ensemble seasonal prediction skills over East Asian summer monsoon region using a climate filter concept. *Journal of Applied Meteorology and Climatology, 52*, 1127–1138.

Li, S. L., & Bates, G. T. (2007). Influence of the Atlantic multidecadal oscillation on the winter climate of East China. *Advances in Atmospheric Science, 24*, 126–135.

Li, Y. F., & Wang, Z. Y. (2016). Modeling vegetation-erosion dynamics in the Mugetan Desert, Yellow River Source Zone. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 167–182). Berlin: Springer.

Li, F., Wang, H., & Gao, Y. (2014). On the strengthened relationship between the East Asian winter monsoon and Arctic oscillation: A comparison of 1950–70 and 1983–2012. *Journal of Climate, 27*, 5075–5091.

Li, Z. W., Wang, Z. Y., & Pan, B. Z. (2016). Wetland ecosystems of the Yellow River Source Zone. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 183–207). Berlin: Springer.

Li, Q., & Xue, Y. (2010). Simulated impacts of land cover change on summer climate in the Tibetan Plateau. *Environmental Research Letters, 5*, 015102.

Li, L., Yang, S., Wang, Z. Y., et al. (2010). Evidence of warming and wetting climate over the Qinghai-Tibet Plateau. *Arctic Antarctic and Alpine Research, 42*, 449–457.

Lian, L., & Shu, J. (2009). Simulation of effects of grassland degradation on regional climate over Sanjiangyuan Region in Qinghai-Tibet Plateau. *Acta Meteorologica Sinica, 23*, 350–362.

Liang, L., Li, L., Liu, C.-M., et al. (2013). Climate change in the Tibetan Plateau Three Rivers source region: 1960–2009. *International Journal of Climatology, 33*, 2900–2916.

Lin, Z. D., Lu, R. Y., & Zhou, W. (2010). Change in early-summer meridional teleconnection over the western North Pacific and East Asia around the late 1970s. *International Journal of Climatology, 30*, 2195–2204.

Liu, X. D., & Wang, Y. (2011). Contrasting impacts of spring thermal conditions over Tibetan Plateau on late-spring to early-summer precipitation in southeast China. *Atmospheric Science Letters, 12*, 309–315.

Liu, X., & Yin, Z. Y. (2001). Spatial and temporal variation of summer precipitation over the eastern Tibetan Plateau and the North Atlantic oscillation. *Journal of Climate, 14*, 2896–2909.

Lu, H., Shao, Q. Q., & Liu, J. Y. (2008). Cluster analysis on summer precipitation field over Qinghai-Tibet Plateau from 1961 to 2004. *Journal of Geographical Sciences, 18*, 295–307.

Mao, J., Chan, J. C. L., & Wu, G. (2011). Interannual variations of early summer monsoon rainfall over South China under different PDO backgrounds. *International Journal of Climatology, 31*, 847–862.

McGregor, G. R. (1993). Multivariate approach to the evaluation of the climatic regions and climatic resources of China. *Geoforum, 24*, 357–380.

Molnar, P., Boss, W., & Battisti, D. S. (2010). Orographic controls on climate and paleoclimate of Asia: Thermal and mechanical roles for the Tibetan Plateau. *Annual Review of Earth and Planetary Sciences, 38*, 77–102.

Mou, C., Sun, G., & Luo, P. (2013). Flowering responses of alpine meadow plant in the Qinghai-Tibetan plateau to extreme drought imposed in different periods. *Chinese Journal of Applied and Environmental Biology, 19*, 272–279.

Munang, R., Thiaw, I., Alverson, K., et al. (2013). The role of ecosystem services in climate change adaptation and disaster risk reduction. *Current Opinion in Environmental Sustainability, 5*, 47–52.

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrological and Earth System Science, 11*, 1633–1644.

Piao, S. L., Tan, K., Nan, H. J., et al. (2012). Impacts of climate and CO_2 changes on the vegetation growth and carbon balance of Qinghai-Tibetan grasslands over the past five decades. *Global and Planetary Change, 98*, 73–80.

Qian, Y. F., Zhang, Y., Jiang, J., et al. (2005). The earliest onset areas and mechanism of the tropical Asian summer monsoon. *Acta Meteorologica Sinca, 19*, 129–142.

Qian, C., & Zhou, T. (2014). Multidecadal variability of North China aridity and its relationship to PDO during 1900–2010. *Journal of Climate, 27*, 1210–1222.

Qin, Y., Yi, S., & Ren, S. (2014). Responses of typical grasslands in a semi-arid basin on the Qinghai-Tibetan Plateau to climate change and disturbances. *Environmental Earth Sciences, 71*, 1421–1431.

Rodriguez-Labajos, B. (2013). Climate change, ecosystem services, and costs of action and inaction: Scoping the interface. *Wiley Interdisciplinary Reviews-Climate Change, 4*, 555–573.

Saha, S., Moorthi, S., & Pan, H. (2010). The NCEP climate forecast system reanalysis. *Bulletin of the American Meteorological Society, 91*, 1015–1057.

Schneider, U., Becker, A., Finger, P., et al. (2014). GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. *Theoretical and Applied Climatology, 115*, 15–40.

Seo, K.-H., Ok, J., Son, J.-H., et al. (2014). Assessing Future changes in the East Asian summer monsoon using CMIP5 coupled models. *Journal of Climate, 26*, 7662–7675.

Shen, M. G., Tang, Y., Chen, J., et al. (2011). Influences of temperature and precipitation before the growing season on spring phenology in grasslands of the central and eastern Qinghai-Tibetan Plateau. *Agricultural and Forest Meteorology, 151*, 1711–1722.

Shi, Y., Gao, X. J., Wu, J., et al. (2011). Changes in snow cover over China in the 21st century as simulated by a high resolution regional climate model. *Environmental Research Letters, 6*, 045401.

Shi, X. Y., Wang, Y. Q., & Xu, X. D. (2008). Effect of mesoscale topography over the Tibetan Plateau on summer precipitation in China: A regional model study. *Geophysical Research Letters, 35*, L19707.

Song, J.-H., Kang, H.-S., Byun, Y.-H., et al. (2010). Effects of the Tibetan Plateau on the Asian summer monsoon: A numerical case study using a regional climate model. *International Journal of Climatology, 30*, 743–759.

Song, C., Pei, T., & Zhou, C. (2014a). The role of changing multiscale temperature variability in extreme temperature events on the eastern and central Tibetan Plateau during 1960–2008. *International Journal of Climatology, 34*, 3683–3701.

Song, F., Zhou, T., & Qian, Y. (2014b). Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophysical Research Letters, 41*, 596–603.

Sun, J. Q., & Wang, H. J. (2012). Changes of the connection between the summer North Atlantic oscillation and the East Asian summer rainfall. *Journal of Geophysical Research-Atmospheres, 117*, D08110.

Sun, J., Wang, H., Yuan, W., et al. (2010). Spatial-temporal features of intense snowfall events in China and their possible change. *Journal of Geophysical Research, 115*, D16110.

Sun, C., & Zhan, H. (2012). Interannual and interdecadal variability of East Asian monsoon and its relation to oceanic processes: A review. *Chinese Journal of Oceanology and Limnology, 30*, 905–907.

Tong, K., Su, F., Yang, D., et al. (2014a). Tibetan Plateau precipitation as depicted by gauge observations, reanalyses and satellite retrievals. *International Journal of Climatology, 34*, 265–285.

Tong, L. G., Xu, X. L., & Fu, Y. (2014b). Wetland changes and their responses to climate change in the "Three-River Headwaters" region of China since the 1990s. *Energies, 7*, 2515–2534.

Wan, S., Hu, Y., You, Z., et al. (2013). Extreme monthly precipitation pattern in China and its dependence on Southern oscillation. *International Journal of Climatology, 33*, 806–814.

Wang, G. X., Bai, W., Li, N., et al. (2011). Climate changes and its impact on tundra ecosystem in Qinghai-Tibet Plateau, China. *Climatic Change, 106*, 463–482.

Wang, H. J., & Chen, H. P. (2012). Climate control for southeastern China moisture and precipitation: Indian or East Asian monsoon? *Journal of Geophysical Research-Atmospheres, 117*, D12109.

Wang, Q., Chen, X., Yang, D. G., et al. (2012a). Paying for Tibet's environmental-ecosystem services. *Environmental Science and Technology, 46*, 5264.

Wang, Z. Q., Duan, A. M., & Wu, G. X. (2014a). Time-lagged impact of spring sensible heat over the Tibetan Plateau on the summer rainfall anomaly in East China: Case studies using the WRF model. *Climate Dynamics, 42*, 2885–2898.

Wang, H.-J., Sun, J.-Q., Chen, H.-P., et al. (2012b). Extreme climate in China: Facts, simulation and projection. *Meteorologische Zeitschrift, 21*, 279–304.

Wang, X., Yang, M., Liang, X., et al. (2014b). The dramatic climate warming in the Qaidam basin, northeastern Tibetan Plateau, during 1961–2010. *International Journal of Climatology, 34*, 1524–1537.

Wang, X. J., Yang, M. X., Wan, G. N., et al. (2013). Qinghai-Xizang (Tibetan) Plateau climate simulation using the regional climate model RegCM3. *Climate Research, 57*, 173–186.

Wei, K., & Bao, Q. (2012). Projections of the East Asian winter monsoon under the IPCC AR5 scenarios using a coupled model: IAP_FGOALS. *Advances in Atmospheric Sciences, 29*, 1200–1214.

Wen, L. K., Cui, P., Li, Y., et al. (2010). The influence of sensible heat on monsoon precipitation in central and eastern Tibet. *Meteorological Applications, 17*, 452–462.

Wen, Q. H., Zhang, X., Xu, Y., et al. (2013). Detecting human influence on extreme temperatures in China. *Geophysical Research Letters, 40*, 1171–1176.

Wonsick, M. M., & Pinker, R. T. (2014). The radiative environment of the Tibetan Plateau. *International Journal of Climatology, 34*, 2153–2162.

Wu, Z., Li, J., Jiang, Z., et al. (2012). Modulation of the Tibetan Plateau snow cover on the ENSO teleconnections: From the East Asian summer monsoon perspective. *Journal of Climate, 25*, 2481–2489.

Wu, W., Wen, Z. P., & Chen, Y. G. (2013a). Interannual variability of winter and spring precipitation in South China and its relation to moisture transport. *Journal of Tropical Meteorology, 19*, 322–330.

Wu, T., Zhao, L., Li, R., et al. (2013b). Recent ground surface warming and its effects on permafrost on the central Qinghai-Tibet Plateau. *International Journal of Climatology, 33*, 920–930.

Xin, X., Wu, T., Li, J., et al. (2013a). How well does BCC_CSM1.1 reproduce the 20th century climate change in China? *Atmospheric and Ocean Science Letters, 6*, 21–26.

Xin, X., Zhang, L., Zhang, J., et al. (2013b). Climate change projections over East Asia with BCC_CSM1.1 climate model under RCP scenarios. *Journal of the Meteorological Society of Japan, 4*, 413–429.

Xu, K., Brown, C., Kwon, H.-H., et al. (2007). Climate teleconnections to Yangtze river seasonal streamflow at the Three Gorges Dam, China. *International Journal of Climatology, 27*, 771–780.

Xu, X. K., Chen, H., & Levy, J. K. (2008). Spatiotemporal vegetation cover variations in the Qinghai-Tibet Plateau under global climate change. *Chinese Science Bulletin, 53*, 915–922.

Xu, G.-R., Cui, C.-G., Li, W.-J., et al. (2011). Variation of GPS precipitable water over the Qinghai-Tibet Plateau: Possible teleconnection triggering rainfall over the Yangtze River Valley and the surrounding area. *Terrestrial Atmospheric and Oceanographic Sciences, 22*, 195–202.

Xu, X. D., Lu, C. G., Ding, Y. H., et al. (2013). What is the relationship between China summer precipitation and the change of apparent heat source over the Tibetan Plateau? *Atmospheric Science Letters, 14*, 227–234.

Xu, Y., Xu, C.-H., Gao, X. J., et al. (2009). Projected changes in temperature and precipitation extremes over the Yangtze River basin of China in the 21st century. *Quaternary International, 208*, 44–52.

Xu, Z.-F., & Zhang, Y.-C. (2008). Effects of the Tibetan Plateau on the climate of China. In F. Congbin, J. Zhihong, G. Zhaoyong, et al. (Eds.), *Regional climate studies of China* (p. 472). Berlin: Springer.

Yang, M. X., Nelson, F. E., Shiklomanov, N. I., et al. (2010). Permafrost degradation and its environmental effects on the Tibetan Plateau: A review of recent research. *Earth Science Reviews, 103*, 31–44.

Yao, T. D., Pu, J. C., Lu, A. X., et al. (2007). Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding regions. *Arctic Antarctic and Alpine Research, 39*, 642–650.

Yin, Z.-H., Lin, Z., & Zhao, X. (2000). Temperature anomalies in central and eastern Tibetan Plateau in relation to general circulation patterns during 1951–1993. *International Journal of Climatology, 20*, 1431–1449.

You, Q., Fraedrich, K., Min, J., et al. (2014a). Observed surface wind speed in the Tibetan Plateau since 1980 and its physical causes. *International Journal of Climatology, 34*, 1873–1882.

You, Q., Fraedrich, K., Ren, G., et al. (2013). Variability of temperature in the Tibetan Plateau based on homogenized surface stations and reanalysis data. *International Journal of Climatology, 33*, 1337–1347.

You, Q., Jiao, Y., Lin, H., et al. (2014b). Comparison of NCEP/NCAR and ERA-40 total cloud cover with surface observations over the Tibetan Plateau. *International Journal of Climatology, 34*, 2529–2537.

Zhang, Z., Guo, W., Gong, D., et al. (2013). Evaluation of the twentieth century reanalysis dataset in describing East Asian winter monsoon variability. *Advances in Atmospheric Sciences, 30*, 1645–1652.

Zhang, Y., Wang, G., & Wang, Y. (2010). Response of biomass spatial pattern of alpine vegetation to climate change in permafrost region of the Qinghai-Tibet Plateau, China. *Journal of Mountain Science, 7*, 301–314.

Zhang, G. Q., Xie, H. J., Duan, S. Q., et al. (2011a). Water level variation of Lake Qinghai from satellite and in situ measurements under climate change. *Journal of Applied Remote Sensing, 5*, 053532.

Zhang, S. F., Zhang, S., Hua, D., et al. (2011b). Climate change and its driving effect on the runoff in the "Three-River Headwaters" region. *Journal of Geographical Sciences, 21*, 963–978.

Zhang, Y. Y., Zhang, S. F., Zhai, X. Y., et al. (2012). Runoff variation and its response to climate change in the Three Rivers source region. *Journal of Geographical Sciences, 22*, 781–794.

Zhang, Y. R., Zhou, D. M., Niu, Z. G., et al. (2014). Valuation of lake and marsh wetlands ecosystem services in China. *Chinese Geographical Science, 24*, 269–278.

Zhao, D., Wu, S., & Yin, Y. (2013). Dynamic responses of soil organic carbon to climate change in the Three-River Headwater region of the Tibetan Plateau. *Climate Research, 56*, 21–32.

Zhu, Y. L., Wang, H. J., Zhou, W., et al. (2011). Recent changes in the summer precipitation pattern in East China and the background circulation. *Climate Dynamics, 36*, 1463–1473.

Zhu, Y. F., Zhang, B., & Chen, L. X. (2010). Thermal difference between the Tibetan Plateau and the plain east of plateau and its influence on rainfall over China in the summer. *Chinese Science Bulletin, 55*, 1437–1444.

Chapter 3
Geomorphic Diversity of Rivers in the Upper Yellow River Basin

Gary John Brierley, Guo-an Yu and Zhiwei Li

Abstract The Yellow River is the third longest river in Asia and the sixth longest river in the world. The Upper Yellow River lies at the margins of and atop the Qinghai–Tibet Plateau, the highest plateau in the world with an average elevation of 4000 m above sea level and an area of about 2.6 million km^2. This area contributes about 56 % of the total run-off, but only 10 % of sediment load of the whole river basin. The river has a strong monsoon-driven seasonality in discharge, with around 60 % of annual run-off and 80 % of annual sediment discharge occurring during the flood season (June-September, especially July). Other than the impacts of a small (but increasing) number of dams along the trunk stream and tributaries close to the plateau margin, the flow regime of the Upper Yellow River is largely unregulated. Rivers of the Upper Yellow River Basin are globally significant examples of river response to tectonic uplift and incision. This chapter documents a 'journey along the Upper Yellow River', providing an account of river diversity and assessing controls upon the pattern of river types. Valley gradient and confinement are the primary controls on river diversity and evolution in this area. Adjacent to the Qinghai–Gansu border, tectonic uplift and climate changes have induced river

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bed incision via knickpoint retreat, cutting back through bedrock gorges and basin fills. An elevation (climate) induced gradient of riparian vegetation cover exerts a critical control upon the pattern of channel planform types along the river.

Keywords River diversity · Geomorphology · Alluvial river · Bedrock river · River pattern · River evolution · River management · Riparian vegetation

3.1 Introduction

> *Water, water, water … There is no shortage of water in the desert but exactly the right amount, a perfect ratio of water to rock.*
>
> Edward Abbey, *Wilderness Reader*

Rivers provide critical services for humans, including ready access to potable water, an easy means of transportation, fertile and replenished lands that are readily irrigated for agricultural use, a reliable source of renewable energy and food (fish), and many others. Beyond its importance in terms of drinking water, freshwater supports human well-being in many ways related to food and fibre production, hydration of other ecosystems used by humans, dilution and degradation of pollutants and cultural values. In many ways, rivers are the lifeblood of the land. As a consequence of their critical importance to human well-being, it is scarcely surprising that surface freshwaters—lakes, reservoirs and rivers—are among the most extensively altered ecosystems on Earth (Carpenter et al. 2011). In many instances, multiple stressors have transformed the morphology, hydrology, biogeochemistry, ecosystem metabolism and biodiversity of these systems (e.g. Dudgeon 2010). Flow regulation has fragmented almost all major river networks, impacting upon the transfer of mass and energy between continents and oceans. Few rivers retain their 'natural' riparian vegetation. Extensive sections of river have been channelized. Climate and land use changes have modified flow and sediment flux and altered the distribution and effectiveness of resistance elements upon valley floors. In many instances, rivers are adjusting to the legacy of past impacts. While these general assertions hold true for the middle and lower courses of the Yellow River, the Upper Yellow River is far less impacted. Given the pressure for the development in this area, for how long is this likely to be the case?

Management of water has exerted a critical influence upon economic and societal development in China. The emergence of hydraulic civilizations along river courses was closely tied to governance of water management that fashioned adequate supply of water of an appropriate amount and quality at the right time, meeting associated links for food production (Wittfogel 1956). All too often, however, historical efforts to meet societal needs have been addressed through a 'command and control' mindset with limited regard for ecosystem values (Holling and Meffe 1996). Security of supply and minimization of risk were the key challenges presented to engineers. Although these issues were addressed with considerable flair, undue emphasis upon short-term needs failed to address concerns for long-term sustainability which meets human needs while protecting environmental values. In simple terms, the quest for predictability and stability negates the inherent diversity and variability of natural systems. Requirements and commitments change as populations grow, climatic and environmental conditions change, and human needs/aspirations evolve. The quest for water of sufficient quantity and quality in the right place at the right time often conflicts with inherent variability and evolutionary traits. Social and economic collapse in response to environmental damage as a consequence of mismanagement is testimony to failed practices in the past (e.g. Diamond 2005; Wright 2005). In a sense, river health can be viewed as a barometer of the health of our society and our relationship to environmental systems, providing a measure of our commitment to sustainability.

Many challenges are faced in managing the shifting habitat mosaic of dynamic (living) rivers (Everard and Powell 2002). A harmonious approach to environmental management builds upon a solid understanding of the type of river under consideration, striving to work with its character, behaviour and evolutionary trajectory (Brierley and Fryirs 2005). Reach-scale understandings are framed in their catchment context, recognizing how adjustments to one section of river impact upon downstream or upstream reaches, thereby maintaining a 'balance' of flow and sediment fluxes. Balance does not equate to stability, or the spatial and temporal equivalence of erosional and depositional processes. Rather, it reflects the process regime for that section of river in its particular setting. Alterations to this process regime may have significant social, economic and environmental consequences. Indeed, history teaches us many lessons about the effectiveness and sustainability of river management practices and their impacts upon the flow-sediment regime of a river. For example, insightful management of the Min River at Dujiangyan in the upper Yangtze River Basin in Sichuan Province brought about practices that 'work with nature', such that this scheme has successfully provided flood protection and irrigated water supply for the area around the Chengdu plain for over 2000 years (Li and Xu 2006; Zhang et al. 2012). A quite different application and outcome has been achieved at the Sanmenxia Dam along the middle Yellow River, which was completed in 1960 (Wang et al. 2005, 2007). Untold damage has ensued.

This chapter provides an overview of the diversity, variability and evolutionary traits of river systems in the Upper Yellow River Basin. The rationale here is a simple one: we cannot manage rivers effectively until we can describe them in a meaningful way, interpret their behavioural regimes, and understand controls on where they are found and why, and explain how they are evolving. Much of the Upper Yellow River retains high ecological values (see Li et al. 2016b, Chap. 9). To protect and sustain these values into the future, the degradational or recovery trajectory of these systems must be understood before steps to improve (or maintain) their condition can be implemented.

The structure of this chapter is as follows. First, river diversity along the trunk stream is described through a 'journey along the Upper Yellow River'. This is

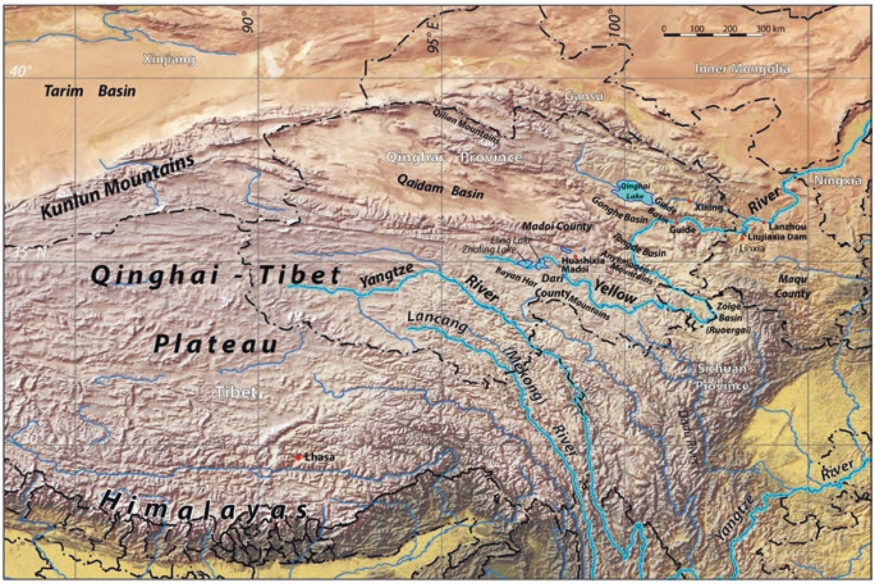

Fig. 3.1 Landscape setting of the Upper Yellow River atop the Qinghai–Tibet Plateau. Along with the headwaters of the Yangtze and Lancang (Mekong) rivers, this source zone is referred to as the Sanjiangyuan. The headwaters of the Yellow River are located upstream of the Zhaling and Eling lakes. The river flows initially in an east-south-east direction, before it takes a major turn to the north-west close to the margin of the Qinghai–Tibet Plateau at the First Great Bend (the Big Loop at Zoige (Ruoergai) Basin) in Sichuan Province. Downstream of this area, the river flows through a series of basin fills and gorges prior to descending from the plateau upstream of Lanzhou

followed by an assessment of controls upon the pattern of river types, including discussion of process relationships along the longitudinal profile of the river, tributary–trunk stream relationships and the imprint of evolutionary traits upon contemporary character and behaviour of the river. Finally, thoughts towards prospective river futures are briefly considered. For simplicity, the Upper Yellow River in this chapter is considered solely within Qinghai Province (Fig. 3.1). The drainage area of upper catchment of the Yellow River at Lanzhou is about 222,550 km^2.

3.2 A Journey Along the Upper Yellow River

The Yellow River flows across nine provinces and autonomous regions before emptying into the Yellow Sea north of the Shandong Peninsula. Based on the division used by the Yellow River Conservancy Commission, the upper reaches of the Yellow River extend from its source in the Bayan Har Mountains to Hekou Town in Inner Mongolia, just before the river makes a sharp turn to the south (see Fig. 3.1). This section of the river has a length of 3472 km, drains an area of 0.386×10^6 km^2 (51.4 % of the total basin area) and drops 3496 m (an average grade of 0.10 %).

From its source to Hekou Town, the Upper Yellow River has a length of 3471 km (63.5 % of the total river length; IRTCES, 2005). Along this section of the river, 43 tributaries drain an area >1000 km^2. The region encompasses a wide range of landscapes, from high-altitude broad plateaus underlain by permafrost, to broad deserts with high dunes, to steep mountain environments with cascading streams (Nicoll et al. 2013). The mean elevation above Lanzhou is around 3600 m. Along the course of the Upper Yellow River, several wide basins are separated by two major mountain ranges: the Bayan Har Mountain defines the southern edge of the Yellow River catchment, and the Anyemaqen Shan runs WNW-ESE through the middle of the upper catchment (Fig. 3.1). The north-west boundary is demarcated by the Chaka sub-basin, an internally drained basin considered part of the larger Qaidam Basin. The Qilian Mountain and the Huang Shui River, the largest tributary on the Upper Yellow River, mark the margin between the Qinghai–Tibet Plateau and the Inner Mongolia Plateau. To the south and west of the Yellow River watershed, tributaries to the Yangtze cut down through the plateau margin to the Sichuan Basin.

The Upper Yellow River contributes about 56 % of the total run-off and only 10 % of sediment load of the whole river basin (Xu et al. 2007; Wang et al. 2007). Steep rock hillslopes, low evaporation and high moisture retention atop the Qinghai–Tibet Plateau produce run-off coefficients that range from 30 to 50 %. There is a strong monsoon-driven seasonality in discharge (see Huang et al. 2016, Chap 4). Around 60 % of annual run-off and 80 % of annual sediment discharge occur during the flood season (June–September, especially July). Less than 1 % of the run-off in the Upper Yellow River Basin is generated from the glaciated area. Sediment discharge is highly correlated to run-off, with much more concentrated sediment load during summer months. Even then, the average suspended sediment concentration is less than 0.5 kg m^{-3}.

Valley gradient and confinement are the primary controls on the distribution of geomorphic process zones along rivers. The imprint of tectonic and incision histories varies markedly along the course of the Upper Yellow River. Adjacent to the Qinghai–Gansu border, tectonic uplift and climate changes have induced river bed incision, creating steep hillslopes and dissected landscapes. Very high erodibility and erosivity result in significant erosion and effective sediment delivery (i.e. these are highly connected landscapes). Incision processes via knickpoint retreat have extended upstream through bedrock gorges and basin fills. Beyond this area, low-relief plateau landscapes of former basin fills have highly disconnected process regimes (Nicoll et al. 2013). Hillslopes are disconnected from channel processes, with extensive sediment stores along valley floors. This gives considerable space for channels to adjust, creating a myriad of planform types. Fully self-adjusting alluvial reaches are separated by bedrock and/or terrace-confined valleys that constrain lateral and/or vertical channel adjustment. The channel bed along most of the Upper Yellow River is comprised of sand and fine-medium calibre gravels.

Significant transitions in valley width result in pronounced changes in river character and behaviour along the Upper Yellow River (see Figs. 3.2 and 3.3). In the sections that follow, river diversity is described for differing landscape compartments moving downstream from the river source.

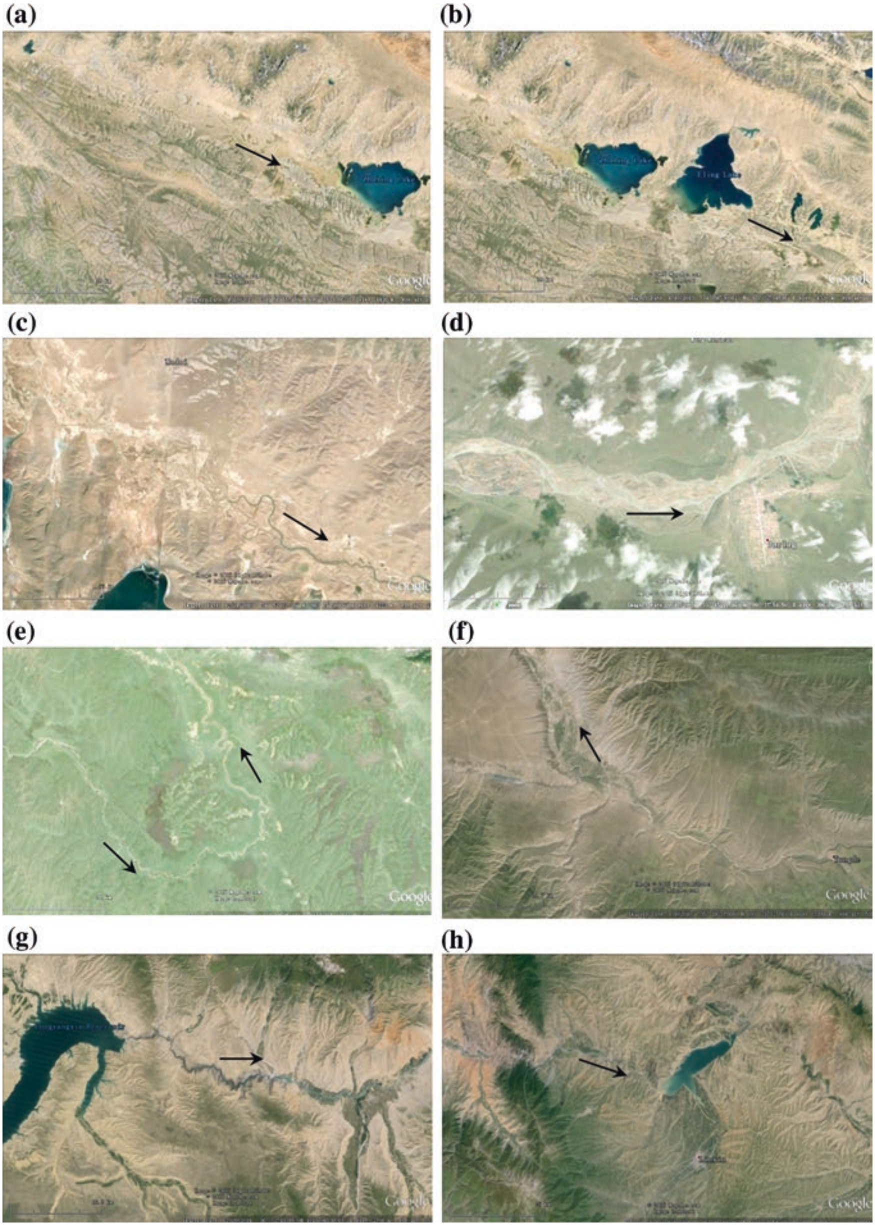

Fig. 3.2 Google Earth images of the river network of the Upper Yellow River. **a** Upstream of Zhaling Lake. **b** Zhaling/Eling lakes. **c**. Upper Yellow River near Madou. **d** Upper Yellow River near Dari. **e** Upper Yellow River at the Zoige Basin (Ruoergai). **f** Upper Yellow River in the Tongde Basin. **g** Upper Yellow River in the Guide Basin. **h** Upper Yellow River at Qingtong Gorge (Liujia)

Fig. 3.3 Photographs of the Upper Yellow River. **a** The Yellow River rises from Yagradagzê (5214 m) upstream of Zhaling Lake (H. Tane). **b** Zhaling Lake. **c** Upper Yellow River near Madou (4200 m). **d** Upper Yellow River near Dari. **e** Upper Yellow River at the Zoige (Ruoergai) Basin. **f** Upper Yellow River in the Tongde Basin. **g** Upper Yellow River in the Guide Basin. **h** Upper Yellow River at Liujiaxia Gorge (Liujiaxia Reservoir)

3.2.1 The Headwater Area: A Landscape of High-Elevation Lakes and Alluvial Plains

The source of the Yellow River lies in the Bayan Har Mountains (maximum elevation 5266 m asl) which divide the Upper Yellow and Yangtze rivers. The river originates in the Yueguzonglie Basin at an elevation of 4600 m, around 200 km upstream of Maduo. The climate is very cold and dry. The town of Maduo (4272 m), which lies at the centre of the Mountain River Lakes ecographic district, has a mean annual temperature of around −4 °C and an annual precipitation of around 320 mm (of which 240 mm falls between June and September). The relatively subdued mountains and valleys of this area bear the imprint of glaciation, with various erosional and depositional landforms such as U-shaped valleys and large moraines (Stroeven et al. 2009). In general terms, hillslopes of these low-relief landscapes rise less than 200 m above the plateau surface (see Brierley et al. 2016a, Chap 1; Nicoll et al. 2013). An intricate tapestry of wetlands and waterways makes up the plateau landscapes of this area, with alluvial plains and lakes separated by low rounded mountains. Beyond their origins in springs, streams wind their way through a mosaic of tarns and morainal deposits, prior to flowing through fluvial outwash formations with anabranching, braided and meandering channel planforms (Figs. 3.2a and 3.3a).

From the river source to Maduo, the river has a length of 370 km, drains an area of 20,930 km^2 and has three tributaries that drain an area >1000 km^2. This area is characterized by a chain of inter-montane basins that are linked west to east by the Upper Yellow River. The basins support extensive aquifers. This section of river flows through a series of swamps and grassland areas and traverses a series of major lakes. Zhaling and Eling lakes have capacities of 4.7 billion and 10.8 billion m^3, respectively (see Figs. 3.2b and 3.3b). Zhaling Lake (Gyaring Lake in Tibetan, meaning 'long grey lake') has an elevation of 4292 m. It covers an area of 526 km^2 (approximately 35 km × 15 km), drains an area of 8161 km^2 and has a mean depth of 8.9 m (maximum 13.1 m). Eling Lake (Ngorling Lake in Tibetan, meaning 'long blue lake') has an elevation of 4268 m. It covers an area of 611 km^2 (approximately 32 km × 19 km), drains an area of 18,188 km^2 and has a mean depth of 18.9 m (maximum 31.6 m). Indeed, Madou County is referred to as 'the county of thousand lakes', 15 of which are larger than 10 km^2. Valley floors of many rivers in this area are inset within deposits of formerly extensive lake networks. Extensive terraces are found beyond contemporary floodplain areas, with low-relief alluvial fans at valley margins. These features are comprised predominantly of coarse and silty sand with occasional gravel. Around Maduo, valleys are generally unconfined, with extensive floodplains, terraces and fans disconnecting sediment transfer from hillslopes to the stream network (Nicoll et al. 2013). The valley extends from 2 to 20 km wide. Given the average valley floor gradient of the upper Yellow River near Maduo of 0.0004, the channel has little energy to move sediment and deposits it midstream to create multiple channels. The channel adjusts laterally across shallow floodplains and is characterized by braided, anabranching and some meandering sections, with many floodplain wetlands (Figs. 3.2c and 3.3c).

As the average elevation of this area exceeds 4000 m, human activities are limited. Lush grassland pastures and vast expanses of open ground are found along river margins. However, due to the low temperatures and the location above the elevation-induced permafrost threshold, the growing season is very short. As a consequence, vegetation has little opportunity to stabilize channel bars, which are readily reworked to produce braided river morphologies (Yu et al. 2014).

3.2.2 Around Dari

From Maduo to Dari, the Upper Yellow River flows between the Bayan Har Mountains and the Anyemaqen Mountains. Beyond the low-relief upland area around Madou, the Yellow River enters the high relief topography of the Anyemaqen Mountains. Fluvial valleys begin to narrow, tributaries steepen, and hillslope processes begin to play a dominant role in the landscape. Numerous active fault complexes exert structural control upon the drainage network. The highest peak of the Upper Yellow River Basin, Maqinggangri (Maji Snow Mountain), extends to 6280 m, more than 2000 m above the adjacent valley floor. There are 57 glaciers within this range, covering an area of 126 km^2. Among these glaciers, Halong Glacier covers an area of 24 km^2. This is the largest and longest glacier in the Upper Yellow River drainage basin, extending over a vertical distance of 1800 m. Earlier phases of glaciation were much more substantive, extending hundreds of kilometres beyond contemporary glacial limits (see review in Nicoll et al. 2013). Extensive permafrost has created many periglacial landforms as products of frost heave, freeze–thaw and frost weathering. These features are more common in the humid east and south of the Upper Yellow River, but are relatively sparse in the arid north.

Dari (elevation 3968 m) is located at a strategic headland used for crossing the Yellow River. Local bedrock marks a constriction in valley width and a step along the course of the river, with a gorge (narrow, deep bedrock-controlled reach) downstream, and a shallow grade alluvial reach with wide and shallow channel cross sections upstream. A hilltop statue of King Gesar of Tibet who defeated the Tang Emperor's Army has a commanding view of the river at Dari County Town. Another statue on the floodplain shows the Tang Princess acknowledging her husband on the mountain top from the valley floor. Associated symbolism suggests that Tibetan shamanists rule the mountains, while Chinese animists rule the lowlands (Tane, personal communication, 2015).

Both mean annual temperature and precipitation at Dari are notably higher than upstream, at around 1 °C and 550 mm (of which around 400 mm falls between June and September). As Dari lies at an elevation close to the permafrost threshold, the growing season is slightly longer than in upstream (higher) areas. However, prevailing environmental conditions largely restrict human activities to animal husbandry in this area. Less severe climatic conditions relative to upstream areas play a significant role in supporting colonization of river bars by grasses and small shrubs during the summer months, despite higher flows at this time of year (Yu et al. 2013, 2014). This, in turn, promotes the development of an anabranching rather than a braided river. Multiple channels (including backchannels), bars and islands provide a wide array of hydraulic units, with some wetlands and ponds on floodplains (Figs. 3.2d and 3.3d). Valley width in this reach ranges from 500 to 2500 m with an average width of approximately 1000 m. The Upper Yellow River in this area has a slope of around 0.001. Aggradational floodplains have developed upstream of the bedrock constriction (pinch point) that has induced base level control at the knickpoint at Dari County Town (Yu et al. 2013, 2014).

3.2.3 Deep Valleys and Gorges Downstream of Dari

Downstream of Dari, the Upper Yellow River cuts through the rugged, finely dissected ranges of the Anyemaqen Mountains (elevation 3300–4500 m). Here, the river is characterized by deeply entrenched valleys and precipitous gorges. The valley is typically 15–300 m wide, with occasional or discontinuous floodplain pockets. There is limited space for sediment accumulations, even at tributary confluences, where relatively small alluvial fans are evident. Beyond Jiuzhi County Town, the river enters Sichuan Province at the First Great Bend (or the Big Loop), beyond which it turns sharply 180° to the north-west as it traverses the Anyemaqen Mountains, flowing through part of Gansu Province before returning to Qinghai Province (Li et al. 2013).

3.2.4 Around Maqu: Grasslands and Wetlands

Entry into the first major sedimentary basin marks an abrupt change in the landscape, from a region marked by strong structural control and steep, narrow valleys to the low-relief, poorly drained area of the Zoige Basin. The course of the Yellow River changes nearly 180° within this basin, likely reflecting deformation around the tip of the Kunlun fault complex (Harkins et al. 2007). Fluvial landscapes in this area are relatively unconfined, with wide valleys giving space for low-gradient, alluvial systems to develop. Many tributaries are disconnected from the main stem, ending in shallow lakes and swamps.

The Yellow River enters into Ruoergai grassland/wetland of the Zoige Basin at an altitude of ~3500 m, flowing across the broad and flat alluvial plain before finally moving into valleys near Maqu County at an altitude of ~3400 m. The Ruoergai Basin is largely comprised of grassland, low mountains, wide valleys and swamps. Quaternary sediments on the valley floor attain a thickness of around 200 m near Tangke Town in Zoige County. Mean annual temperature at Maqu (elevation 3471 m) is around 1.6 °C, while mean annual precipitation totals around 600 mm (of which 430 mm falls between June and September).

The Upper Yellow River near Maqu is predominantly a meandering–anabranching–anastomosing river (Figs. 3.2e and 3.3e). The knickpoint downstream, which represents the upstream extent of a phase of historical incision, acts as a local base level control, behind which valley infilling has generated valley floor slopes of approximately 0.0002. The low-energy channels have relatively stable banks, with a high proportion of vegetated mid-channel bars/islands. Many abandoned meanders on floodplains and adjacent terraces attest to a long-term history of lateral migration, avulsion and incision, with indications that the channel has straightened its course in the relatively recent past (Li et al. 2013). Floodplains, extensive backswamps and tributary fans store large volumes of sediment, disconnecting the river from the valley margins. Many tributaries such as Bai, Hei, Zequ and Nanmucuoqu Rivers have developed highly sinuous, meandering channels upstream of their confluences with the Upper Yellow River. Interestingly, braided–meandering and meandering–braided transitions are coincident with variable flow inputs from tributary rivers (Bai and Hei rivers, respectively; Li et al. 2013).

3.2.5 Incised, Confined and Meandering Reaches Beyond the Zoige Basin

Beyond Maqu County, the Upper Yellow River has incised through basin-fill deposits and intervening bedrock steps (gorges) and has a confined (imposed) meandering alignment. Tectonic controls likely induced the shift in river course at the First Great Bend, as the river re-enters the Anyemaqen Mountains before emerging within the Tongde Basin approximately 250 km downstream. Incision of the Upper Yellow River has fashioned these landscapes, as trunk and tributary systems have cut down through the broad Tongde and Gonghe sedimentary basins. Alluvial fans and terrace sequences are prominent. The boundaries of both the Tongde and Gonghe basins are delineated by narrow bedrock ranges, with the Yellow River flowing through a narrow bedrock gap (Craddock et al. 2010). Aeolian reworking of deposits creates some major sand dune fields in this area, especially adjacent to lakes and alluvial valley floors. Prominent examples include the dune field atop the Santala (three terraces) near Gonghe and the largest continuous dune field in the Yellow River Source Region at Mugetan (30 km long from west to east, 15 km wide from north to south; see Li and Wang 2016, Chap. 8).

The Lajia Mountains district (3000–4500 m) is a historic south and west crossing place on the Upper Yellow River. At Tongde (elevation 3289 m), the mean annual temperature and precipitation are 0.7 °C and 425 mm (of which around 310 mm falls between June and September). Adjacent to Xinghai in the Tongde Basin, the Upper Yellow River is terrace- and valley-confined, with little room to move (Figs. 3.2f and 3.3f). Rigid banks form narrow gorges and entrenched

Fig. 3.4 Telescopic fan at Tongde Basin

channels. The valley floor has a slope of around 0.002. River morphology in this reach is largely a product of knickpoint retreat through the basin fill. The combination of a lack of space and relatively high flow energy generally prevents the formation of mid-channel bars and secondary channels. As a result, the channel is relatively homogenous, cut off from its historical floodplains, leaving it with little room to adjust or deposit sediment. Sediment entering the channel from upstream or local tributaries is efficiently flushed through this reach because of the relatively steep gradient, lack of storage space and high stream power. Near Xinghai, a significant tributary drains from the north through a prominent inter-montane basin. However, tributaries are unable to exert a significant influence upon the Upper Yellow River trunk stream in this area, because valley confinement induces constraints on the capacity for lateral adjustment along the incised river. In some instances, however, telescopic alluvial fans have developed where there is sufficient space for differing phases of fan growth to be preserved (Fig. 3.4). In general terms, steep hills and dissected mountain blocks separate valley basins in this area, with deeply dissected rugged hills and mountains at elevations of up to 4400 m and broad valley basins at an elevation of around 3000 m. Majestic terraces record the long-term accumulation of lacustrine and alluvial deposits within the Gonghe Basin. Valley fills are up to 1 km deep, with terraces [locally referred to as the Santala (three levels)] extending over tens of kilometres wide.

Overall, the section of the Upper Yellow River from Madou to Longyangxia has a length of 1418 km, drains an area of 110,490 km^2 (cumulative area 131,420 km^2) and has 22 tributaries that drain an area >1000 km^2.

3.2.6 Moving Through the Margins of the Qinghai–Tibet Plateau: A Riverscape of Gorges, Terraces and Fans

The section of the Upper Yellow River from Longyangxia to Xiaheyan (Qingtongxia) has a length of 794 km, drains an area of 122,722 km^2 (cumulative area 254,142 km^2) and has eight tributaries that drain an area >1000 km^2. This section of river flows swiftly through multiple long gorges that alternate with 17 sections of wider valley. Bedrock confinement in narrow gorges creates opportunities for the development of hydroelectric plants. Beyond the Longyangxia Reservoir (storage capacity of 24.7 billion m^3, construction completed in 1992), the Upper Yellow River enters the Guide Basin, where basin-fill deposits create a major suite of terraces. Given the longer period since incision worked its way through this reach, the valley floor is much wider than upstream, with significant drapes of reworked alluvial and hillslope materials making up extensive fans at valley margins. These topographic considerations, along with more ameliorative climate conditions, present greatly enhanced prospects for agricultural and horticultural exploits. Indeed, local irrigation practices extract water from this anabranching section of river. Immediately, downstream of Guide Township, a left-bank tributary, cuts through a dissected sandstone (Danxia) landscape, creating a stunning backdrop to the river (Figs. 3.2g and 3.3g).

Liujiaxia Dam lies just downstream (construction completed in 1974). The section of river before the border with Gansu Province is characterized predominantly by the striking Liujia Gorge, with several major landslide scars indicating phases of hillslope collapse, temporarily damming the Upper Yellow River (Figs. 3.2h and 3.3h). Loess deposits form a dominant drape over much of this landscape.

3.3 Controls on the Patterns of River Types Along the Upper Yellow River

The topography of the Upper Yellow River Basin is dominated by the subdued relief of the plateau, which is made up of two components—the geologically controlled flatlands of headwater areas and large basin fills at Zoige, Tongde, Gonghe and Guide. Adjacent mountain ranges and ridge lands have more pronounced relief, with glacial features restricted to elevated parts of the Bayan Har Mountains. The accentuated relief at the plateau margin presents a stark contrast. A pronounced step on the longitudinal profile of the Upper Yellow River upstream of Lanzhou demacrates the transition from the Qinghai–Tibet Plateau to the Loess Plateau (Fig. 3.5). Upstream extension via knickpoint retreat has triggered dramatic incision through a series of bedrock steps (gorges), interspersed with terrace landscapes of incised basin fills. Tributary streams have adjusted to changing base level conditions, creating majestic alluvial fans at confluence zones (Fig. 3.4). Incision has limited the space over which channel adjustments can take place in these reaches.

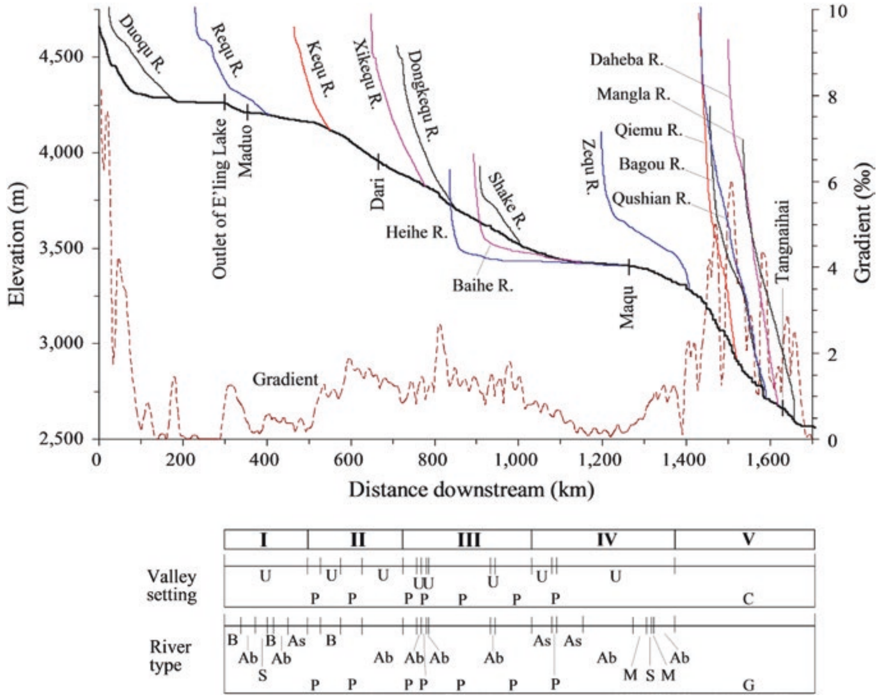

Fig. 3.5 Longitudinal profiles of the Upper Yellow River and key tributaries (modified from Yu et al. 2014). In terms of valley settings, a refers to unconfined, p to partly-confined, c to confined. In terms of river type, B refers to braided, Ab to anabranching, S to straight, As to anastomosing, P to partly-confined river, M to meandering, and G to gorge

Uplift of the plateau is thought to have begun about 50 million years ago, but the majority of its altitude has been formed since about 10 ± 8 million years ago (An et al. 2001; Harrison et al. 1992; Molnar et al. 1993) or more recently (e.g. Li et al. 1996). Spatially differentiated uplift rates ranged from 1 to 10 mm per annum, increasing from the north to the south of the plateau (Li et al. 1997; Zhang et al. 1991). Major east–west strike–slip faults and associated active normal faults developed in response to uplift; current slip rates on these faults average 1–20 mm per annum (Yin and Harrison 2000; Tapponnier et al. 2001). Regional metamorphism and igneous activity have accompanied these tectonic movements (Liu et al. 1980; Yin and Harrison 2000).

The upwardly convex longitudinal profiles of all the major rivers draining the eastern margin of the Qinghai–Tibet Plateau indicate that despite their extreme erosion rates, rates of channel incision are outpaced by tectonic forcing (i.e. incision is unable to match continued uplift; Aiken and Brierley 2013; Harkins et al. 2007). The Upper Yellow River established its present course in the Late

Overview of the Danxia landscapes at the mouth of the Garang River, a tributary of the Yellow River (in the foreground) near Guide

Dissected badland landscapes of the lower Garang Valley, a tributary that joins the Upper Yellow River just downstream of Guide

Fig. 3.6 Photographs from Garang Valley, a left-bank tributary of the Upper Yellow River immediately downstream of Guide

Pliocene–Early Pleistocene. Previously, inland-draining (endorheic) basins that had developed very thick fills of sediment from combinations of river and lake deposits, with some aeolian units, were incised by headward migration of a fluvial knickpoint that integrated these basins to create the modern course of the river (Craddock et al. 2010; Fang et al. 2003; Li et al. 1997; Nicoll et al. 2013; Perrineau et al. 2011). The longitudinal profile of the Upper Yellow River has at least four major knickpoints related to the history of basin excavation and drainage integration during the Quaternary (Fig. 3.5; Craddock et al. 2010). The discrete base levels observed along the longitudinal profile reflect waves of incision, with oversteepened reaches separating the basin fills (Fig. 3.5; Craddock et al. 2010). Changes to base level created highly connected landscapes with very high drainage densities along some tributary systems (e.g. Garang Valley immediately downstream of Guide; Nicoll and Brierley 2016; Fig. 3.6). Major landslide events have dammed the river in confined valley sections at the plateau margin (e.g. Guo et al. 2014; Ouimet et al. 2007). Breaching of these landslide-induced dams and their associated barrier lakes creates significant flood events.

A significant gradient of riparian vegetation cover is evident in the source region of the Yellow River (Yu et al. 2014). Downstream of Eling Lake at Maduo, vegetation cover on mid-channel bars, floodplains and hillslopes is restricted to grass and occasional low shrubs with an average height of less than 20 cm. Further downstream at Dari, conditions are much more amenable to vegetation growth, with significant shrub establishment on mid-channel bars. Maduo has only two months per year with a mean minimum temperature above freezing, whereas Dari and Maqu have 4–5 months per year above freezing. Around the First Great Bend of the Yellow River, mid-channel bars have an almost 100 % cover of *Salix Atopantha schneid*, with significant shrub and grass communities beneath the *salix* trees. The influence of riparian vegetation upon flow resistance characteristics and bank strength affects channel morphodynamics. In the absence of riparian vegetation and/or cohesive materials to stabilize the banks, variable, unconstrained flow over a non-cohesive bed generates laterally unstable multi-channelled rivers. Hence, braiding is the default channel planform morphology around Maduo. Although the high width-to-depth ratios and low topographic relief of braided channels make these areas susceptible to vegetative encroachment during low-flow conditions when large areas of the bed are exposed, the likelihood of vigorous vegetation growth is limited because ambient environmental conditions do not persist for a sufficient length of time to support vegetative establishment and reproduction. As these conditions are met further downstream, vegetation exerts a more substantive influence upon channel planform type, favouring the development of anabranching and meandering rivers (Yu et al. 2014).

In summary, while much of the Upper Yellow River has a forced morphology that has been induced by the geological history of the region, localized areas are truly alluvial with fully deformable boundaries. In the latter areas, the contemporary channel flows within older basin-fill deposits, with significant flights of terraces and fans at valley margins. Vegetation relations to channel morphodynamics fashion a distinct gradient of channel planform types in these alluvial reaches. This physical template fashions the nature and extent of human impacts upon the river, and resulting biophysical responses.

3.4 Human Impacts upon the Upper Yellow River

In global terms, the landscapes of the Upper Yellow River are sparsely populated and have been subjected to limited development pressures. This remains a relatively remote, high-elevation region with limited prospects for many human activities. However, the human history of the region spans many millennia (Han et al. 2016, Chap 12), and terrestrial systems have been transformed by vegetation clearance and overgrazing (Li et al. 2016a, Chap. 7; Tane et al. 2016, Chap. 13). Other than local impacts induced by dams adjacent to the plateau margin, human modification of flow and sediment regimes in the study area is limited. Channelization is restricted to very short sections of river adjacent to towns. Indeed, it could be contended that the physical template of the river (i.e. its geomorphic structure and diversity of physical habitat) has not been subjected to severe pressure or impacts. Having said this, there are not many channel banks that have not been trampled by yak (Tane et al. 2016, Chap 13). Although land use changes may have induced some changes to biogeochemical relationships and water quality, there is a lack of industrial pollutants in the area, and use of fertilizers and herbicides is extremely limited (agricultural practices are largely organic). In general terms, the aquatic ecosystems of the Upper Yellow River are much less impacted than other parts of the system. To date, however, we have limited understandings of human impacts upon species biodiversity and abundance along the Upper Yellow River (Pan et al. 2013; Qi 2016, Chap. 11).

3.5 Concluding Comment: Prospective River Futures for the Upper Yellow River

Rivers of the Upper Yellow River Basin are globally significant examples of river response to tectonic uplift and incision, with majestic gorges and deeply etched tributaries within extensive basin-fill deposits. Long-term geologic histories of river capture remain as elusive scientific debates that will likely be resolved through detailed field and remotely sensed analyses and chronological appraisals in coming years. Although we have good appreciation of river diversity and patterns in the region, our understandings of evolutionary traits and ecological relationships are limited. In terms of human impacts, rivers in the region are generally quite resilient to change, and they remain in good geomorphic condition, with reasonable prospects for recovery. Other than local hydropower developments, human activities have exerted a relatively small impact on river geodiversity. However, future hydropower developments may alter flow and sediment regimes, modifying patterns and rates of fluvial erosion and deposition, thereby affecting channel morphology and habitat relationships. Also, long-term impacts of climate change on vegetation cover and run-off relationships may induce changes to fluvial processes in alluvial reaches. The future of the river will depend largely upon efforts to protect and enhance the high-quality environmental values of the river (see Brierley et al. 2016b, Chap. 15).

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References

Aiken, S. J., & Brierley, G. J. (2013). Analysis of longitudinal profiles along the eastern margin of the Qinghai-Tibetan Plateau. *Journal of Mountain Science, 10*, 643–657.

An, Z. S., Kutzbach, J. E., Prell, W. L., et al. (2001). Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. *Nature, 411*, 62–66.

Brierley, G. J., & Fryirs, K. A. (2005). *Geomorphology and river management: Applications of the river styles framework*. Oxford: Blackwell Publications. 398 pp.

Brierley, G. J., Li, X., Cullum, C., et al. (2016a). Introduction: Landscape and ecosystem diversity in the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 1–34). Berlin: Springer.

Brierley, G. J., Cullum, C., Li, X. L., et al. (2016b). Conclusion: environmental futures of the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 353–369). Berlin: Springer.

Carpenter, S. R., Stanley, E. H., & Vander Zanden, M. J. (2011). State of the world's freshwater ecosystems: Physical, chemical, and biological changes. *Annual Review of Environment and Resources, 36*, 75–99.

Craddock, W. H., Kirby, E., Harkins, N. W., et al. (2010). Rapid fluvial incision along the Yellow River during headward basin integration. *Nature Geoscience, 3*, 209–213.

Diamond, J. M. (2005). *Collapse: How societies choose to fail or succeed*. New York: Viking.

Dudgeon, D. (2010). Prospects for sustaining freshwater biodiversity in the 21st century: Linking ecosystem structure and function. *Current Opinion in Environmental Sustainability, 2*, 422–430.

Everard, M., & Powell, A. (2002). Rivers as living systems. *Aquatic Conservation: Marine and Freshwater Ecosystems, 12*, 329–337.

Fang, X., Garzione, C. N., Van der Voo, R., et al. (2003). Flexural subsidence by 29 Ma on the NE edge of Tibet from magnetostratigraphy of Linxia Basin, China. *Earth and Planetary Science Letters, 210*, 545–560.

Guo, X., Lai, Z., Sun, Z., et al. (2014). Luminescence dating of Suozi landslide in the Upper Yellow River of the Qinghai-Tibetan Plateau, China. *Quaternary International, 349*, 159–166.

Han, M. Q., Brierley, G. J., Cullum, C., et al. (2016). Climate, vegetation and human land use interactions on the Qinghai-Tibet Plateau through the Holocene. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 253–274). Berlin: Springer.

Harkins, N., Kirby, E., Heimsath, A., et al. (2007). Transient fluvial incision in the headwaters of the Yellow River, northeastern Tibet, China. *Journal of Geophysical Research, 112*(F3), 1–21.

Harrison, T. M., Copeland, P., Kidd, W. S. F., et al. (1992). Raising Tibet. *Science, 255*, 1663–1670.

Holling, C. S., & Meffe, G. K. (1996). Command and control and the pathology of natural resource management. *Conservation Biology, 10*, 328–337.

Huang, H. Q., Liu, X. F., Brierley, G. J., et al. (2016). Hydrology of the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 79–99). Berlin: Springer.

Li, Y. F., & Wang, Z. Y. (2016). Modeling vegetation-erosion dynamics in the Mugetan Desert, Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 167–182). Berlin: Springer.

Li, K., & Xu, Z. (2006). Overview of Dujiangyan Irrigation Scheme of ancient China with current theory. *Irrigation and Drainage, 55*, 291–298.

Li, J. J., Fang, X. M., & Ma, H. Z. (1996). Geomorphological and environmental evolution in the upper reaches of the Yellow River during the late Cenozoic. *Science in China (Series D), 39*(4), 380–390.

Li, J. J., Fang, X. M., Voo, R. V., et al. (1997). Magnetostratigraphic dating of river terraces: rapid and intermittent incision by the Yellow River of the northeastern margin of the Tibetan Plateau during the Quaternary. *Journal of Geophysical Research: Solid Earth, 102*, 10121–10132.

Li, Z., Wang, Z., Pan, B., et al. (2013). Analysis of controls upon channel planform at the First Great Bend of the Upper Yellow River, Qinghai-Tibet Plateau. *Journal of Geographical Sciences, 23*, 833–848.

Li, X. L., Perry, G., & Brierley, G. J. (2016a). Grassland ecosystems of the Yellow River Source Zone: degradation and restoration. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 137–165). Berlin: Springer.

Li, Z. W., Wang, Z. Y., & Pan, B. Z. (2016b). Wetland ecosystems of the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 183–207). Berlin: Springer.

Liu, Z. Q., Yu, X. J., Xu, X., et al. (1980). The basic geological characteristics of the Qinghai-Tibet Plateau. *Bulletin of Chinese Academy of Geological Sciences, 2*, 23–47 (in Chinese).

Molnar, P., England, P., & Martiod, J. (1993). Mantle dynamics, uplift of the Tibetan Plateau and the Indian monsoon development. *Review of Geophysics, 34*, 357–396.

Nicoll, T., & Brierley, G. J. (2016). Within-catchment variability in landscape connectivity measures in the Garang Catchment, Upper Yellow River, Geomorphology. doi:10.1016/j.geomorph.2016.03.014.

Nicoll, T., Brierley, G. J., & Yu, G. A. (2013). A broad overview of landscape diversity of the Yellow River Source Zone. *Journal of Geographical Sciences, 23*, 793–816.

Ouimet, W. B., Whipple, K. X., Royden, L. H., et al. (2007). The influence of large landslides on river incision in a transient landscape: Eastern margin of the Tibetan Plateau (Sichuan, China). *Geological Society of America Bulletin, 119*, 1462–1476.

Pan, B., Wang, Z., Li, Z., et al. (2013). An exploratory analysis of benthic macroinvertebrates as indicators of the ecological status of the Upper Yellow and Yangtze Rivers. *Journal of Geographical Sciences, 23*, 871–882.

Perrineau, A., Van Der Woerd, J., Gaudemer, Y., et al. (2011). Incision rate of the Yellow River in northeastern Tibet constrained by ^{10}Be and ^{26}Al cosmogenic isotope dating of fluvial terraces: Implications for catchment evolution and plateau building. In R. Gloaguen, & L. Ratschbacher (Eds.), *Growth and collapse of the Tibetan Plateau* (Vol. 353, pp. 189–219). Geological Society of London Special Publication.

Qi, D. (2016). Fish of the Upper Yellow River. In: G. J. Brierley, X. Li, Cullum, C. et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 233–252). Berlin: Springer.

Stroeven, A. P., Hattestrand, C., Heyman, J., et al. (2009). Landscape analysis of the Huang He headwaters, NE Tibetan Plateau: Patterns of glacial and fluvial erosion. *Geomorphology, 103*, 212–226.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) Headwaters. In G. J. Brierley, X. Li, Collum, C. et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 275–330). Berlin: Springer.

Tapponnier, P., Xu, Z. Q., Roger, F., et al. (2001). Oblique stepwise rise and growth of the Tibet Plateau. *Science, 294*(5547), 1671–1677.

Wang, G., Wu, B., & Wang, Z. Y. (2005). Sedimentation problems and management strategies of Sanmenxia Reservoir, Yellow River, China. *Water Resources Research, 41*(9), W09501.

Wang, Z. Y., Wu, B., & Wang, G. (2007). Fluvial processes and morphological response in the Yellow and Weihe Rivers to closure and operation of Sanmenxia Dam. *Geomorphology, 91*, 65–79.

Wittfogel, K. A. (1956). Hydraulic civilizations. In W. L. Thomas Jr (Ed.), *Man's role in changing the face of the Earth*. Chicago: Wenner-Gren Foundation.

Wright, R. (2005). *A short history of progress*. New York: Carroll and Graf Publishers.

Xu, Z. X., Li, J. Y., & Liu, C. M. (2007). Long-term trend of major climate variables in the Yellow River basin. *Hydrological Processes, 21*, 1935–1948.

Yin, A., & Harrison, T. M. (2000). Geologic evolution of the Himalayan-Tibetan orogen. *Annual Review of Earth and Planetary Sciences, 28*, 211–280.

Yu, G. A., Liu, L., Li, Z. W., et al. (2013). Fluvial diversity in relation to valley setting in the source region of the Yangtze and Yellow Rivers. *Journal of Geographical Sciences, 23*, 817–832.

Yu, G., Brierley, G. J., Huang, H. Q., et al. (2014). An environmental gradient of vegetative controls upon channel planform in the source region of the Yangtze and Yellow Rivers. *Catena, 119*, 143–153.

Zhang, Q. S., Zhou, Y. F., Lu, X. S., et al. (1991). On the uplift rate of modern Qinghai-Tibet Plateau. *Chinese Science Bulletin, 36*, 529–531 (in Chinese).

Zhang, S., Yi, Y., Liu, Y., et al. (2012). Hydraulic principles of the 2,268-year-old Dujiangyan Project in China. *Journal of Hydraulic Engineering, 139*, 538–546.

Chapter 4
Hydrology of the Yellow River Source Zone

He Qing Huang, Xiaofang Liu, Gary John Brierley and Carola Cullum

Abstract Under the impact of climate change and human activities, water resources in the source zone of the Yellow River have decreased since the 1990s. At the same time, environmental deterioration, soil erosion, land desertification, shrinkage of wetlands and lakes, glacier ablation, deterioration of grasslands, rodent infestation, degradation of biological diversity and other environmental and ecological problems have arisen. As a result, the regional hydro-ecological system has become more and more vulnerable. Although the mean annual temperature in the region has increased by about 1.5 °C since the 1960s, the average annual precipitation since 2004 has exceeded the long-term average value, and the run-off at all hydrological sections on the main stream of the Yellow River has increased continuously since 2008, exceeding the long-term average. This may partly be due to the establishment of the Sanjiangyuan National Nature Reserve and the various soil and vegetation recovery programs undertaken since 2000. With the sharp decrease of run-off and sediment to the lower and estuarine reaches of the Yellow River, more effective measures for water and hydro-ecological systems conservation need to be implemented in the source zone.

Keywords Run-off · Precipitation · Temperature · Human impacts · Ecosystem conservation

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4.1 Introduction

Water is a vital resource, so water security is essential for the well-being of both humans and ecosystems. Water supply from the Yellow River is critical for the Chinese nation, supporting over 110 million people living within the river basin. Much of the rich biodiversity in the source area of the Yellow River is directly associated with water-dependent ecosystems, highlighting the fundamental importance of water conservation in this region (Zhao and Zhou 2005). The upper areas of the catchment are a very important part of the 'Water Tower of China'. However, in recent times, the Yellow River has experienced serious flow problems, especially in the last 30 years. In the lower and estuarine reaches, the river has completely dried up on occasion, causing both economic loss and ecological hazards (Liu and Chang 2005). Although much of the responsibility for these low flows has been attributed to over-allocation of water for irrigation in the middle reaches of the basin (Zheng et al. 2007), concern has also been expressed at reduced flows in the upper parts of the basin. Water volume in headwater areas of Qinghai Province has declined in recent years. Upper reaches of the Yellow River stopped flowing for the first time in recorded history in 1997 (Han 2004). Since 1990, water levels of Zhaling and Eling lakes have dropped by 2 m, and flow between the lakes stopped. Many small lakes have dried up in recent decades. Such concerns provided much of the impetus for the establishment of the Sanjiangyuan National Natural Reserve atop the Qinghai–Tibet Plateau (see, Brierley et al. 2016a, b, Chaps. 1 and 15; Ran et al. 2016, Chap. 14).

In the hydrological literature, the source zone of the Upper Yellow River is usually taken to include catchments above the Tangnaihai hydrological station in Xinghai County, covering an area of 121,972 km^2 (Fig. 4.1; see Chap. 1). Over 40 % of the total discharge of the river comes from the source zone, even though it only accounts for about 16 % of the total area of the basin. The elevation of the source zone ranges from the peak of Alnima at 6282 m to the valley of the Tongde Basin at 2665 m with an average elevation of 4000 m (Chen et al. 2008). A series of mountains stretch from the north-west to the south-east, with year-round snow and glaciers on the peaks.

The total discharge from this length of river averaged around 16.5 billion m^{3}year^{-1} in the 2000s—around 18 % less than in the 1950s–1960s (Miao et al. 2011). The reduced discharge is undoubtedly due to the combined effects of climate change and human activities, such as overgrazing and infrastructure development which have induced grassland and wetland degradation (Zhang et al. 2011). However, unravelling the effects of each of these factors and predicting possible outcomes under various scenarios is hugely challenging. Not only do the various components of the hydrological cycle (e.g. rainfall, snow, glacier and permafrost melting, infiltration into the soil and subsurface flows, interception by vegetation, evaporation from water bodies and many others) interact with each other, feedbacks, thresholds and sensitivity to initial conditions mean that this complex system cannot be described in terms of linear relationships and simple models based

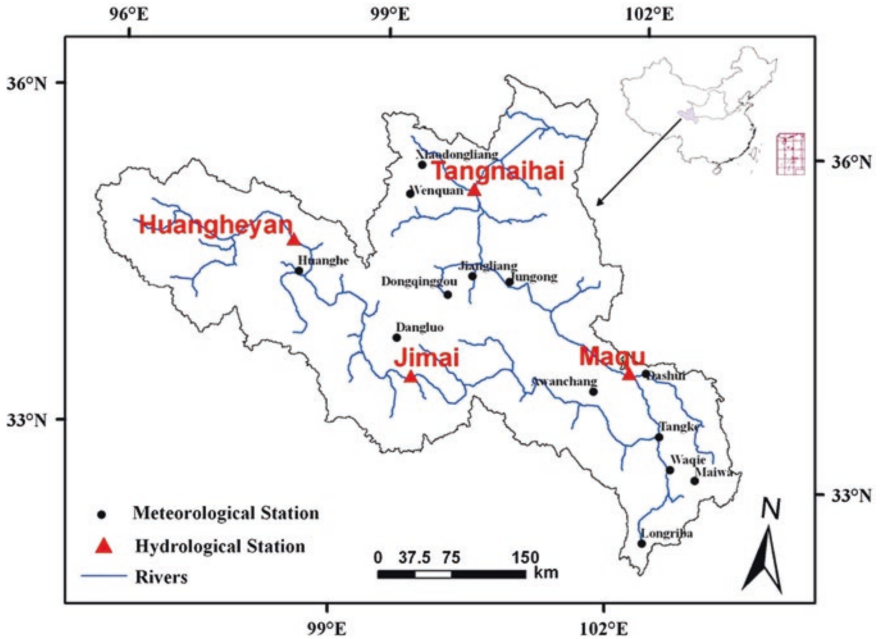

Fig. 4.1 Hydrological and meteorological stations in the source zone of the Yellow River (*Source* Zheng et al. 2009)

on empirical data. Not only are predictions surrounded by large amounts of uncertainty, but local differences in the key controls and drivers mean that different models are likely to apply with differing degrees of accuracy/reliability in different parts of the region.

The first steps in understanding and managing this complex system are to identify the various factors involved, to monitor changes and to appraise how interactions and outcomes might differ in various geoclimatic settings. In this chapter, we lay foundations for a systematic analysis of the hydrology of the region in both space and time.

We start by presenting a brief overview of the various factors that contribute to the variability of flow in the Upper Yellow River. We then consider trends in discharge and discuss the various factors responsible for these changes, dealing first with the effects of climate change and then with human impacts. Next, we consider local differences, suggesting that a better understanding of these variations is likely to improve our predictions for the future trajectory of discharge from the entire region. We conclude with reflections on future prospects for water supply from the Upper Yellow River.

4.2 The Hydrological Cycle

The amount of discharge at any time is dependent on interactions between a large number of components of the hydrological system (Zhang and Wang 2014). It has been estimated that over the course of an average year, 63 % of the streamflow in the source area of the Yellow River results from precipitation, 26 % from groundwater and 9 % from meltwater (Lan et al. 2010a, b; Liu et al. 2009). Change in streamflow reflects the combined effect of variability in precipitation and evaporation, while the meltwater contribution is caused primarily by seasonal snowpack trends and climate change.

Climate change (including changes in precipitation, temperature, air pressure and wind speed) alters streamflow both directly and indirectly (Dam 1999). Human activities that modify land use and land cover also impact upon streamflow via changes to the rates of infiltration and evapotranspiration, thereby altering run-off (Zhang et al. 2013).

4.2.1 Climate and the Hydrological Cycle

The hydrological cycle is broadly controlled by climate, so that changes in precipitation and temperature reverberate through the whole system.

The source area of the Yellow River has a monsoonal climate. In summer, the south-west monsoon produces a subtropical monsoon climate with abundant precipitation, while in winter the climate is controlled by cold anti-cyclonic conditions with scant precipitation (Huang and Zhou 2012; Lan et al. 2010a, b; Shi and Zhang 1995). Precipitation is controlled by the East Asian monsoons, which bring low temperature and dryness in winter and rains and warmth in summer (McGregor 2016, Chap. 2). Annual average daily temperature varies between −4 and 2 °C from the south-east to the north-west. The annual average precipitation is about 534 mm (Zheng et al. 2009). Precipitation tends to decrease from the south-east (~800 mm) to the north-west (~300 mm). Some 75–90 % of the precipitation falls between June and September. Around 71 % of the discharge of the Upper Yellow River is generated between July and October.

There is a close relationship between regional run-off and precipitation. In general terms, an increase of run-off is associated with an increase in precipitation, while a decrease of run-off occurs with a reduction in precipitation. Many studies have shown that 7- to 8-year cycles for both precipitation and run-off are related to the periodicity of atmospheric circulation patterns such as the El Nino Southern Oscillation (Dong et al. 2007; Huang and Zhou 2012; Lan et al. 2010a, b; Li et al. 2001; Xie et al. 2003, 2006).

The notion of a simple association between precipitation and run-off has been debated by some scientists. For example, Jiang and Li (2011) pointed out that run-off from the headwater catchments of the Yellow River is determined mainly by precipitation in the rainy season, but it is also influenced by the temperature regime in the dry season. However, because of the vast territory and local difference in precipitation, temperature, land cover and topography, the influence of precipitation on regional surface run-off and seasonal variation varies significantly across the region (e.g. Jia et al. 2008; Zhang et al. 2000).

Whereas rainwater passes relatively quickly through the system, some precipitation is stored in snow, glaciers and permafrost. The spring melting, which is accelerated by global warming, adds considerable flow to the high-altitude headwaters of the Upper Yellow River, augmenting both surface and subsurface flows. Indeed, spring and winter discharges consist mostly of meltwater, while summer run-off comes mostly from precipitation.

Some 130 km^2 of the Yellow River source area is covered by glaciers, while 43 % of the area lies above the lower elevation limit for permafrost (Chen et al. 2008). Both seasonal rises in temperature and long-term warming trends lead to melting of the permafrost (e.g. Jin et al. 2007; Zhang et al. 2004). As the soil thaws across greater areas and to deeper depths, more rainwater can infiltrate the soil, decreasing surface run-off and augmenting subsurface flows (Niu et al. 2011). More research is needed to estimate the likely future effects of increased melt flow on the volume of base flow contribution to the river.

Temperature rises also result in surface water losses, since evaporation from lakes and other water bodies increases and vegetation growth results in increased evapotranspiration.

4.2.2 Human Activities and the Hydrological Cycle

Human activities affect the hydrological cycle mainly through changes in land cover. Desertification, for example, increases the amount of water lost through interception and transpiration, but decreases losses from evaporation. Surface crusts may increase surface run-off immediately after rainfall. The overall effects are not easy to predict and are likely to vary significantly between seasons.

Degradation of alpine meadows and alpine steppe grasslands, and the associated impacts upon wetland areas significantly affect water storage capacity and surface run-off in the region. Alterations to surface conditions that modify run-off relationships in the source area of the Yellow River include: (1) human activities such as overgrazing (e.g. Ren and Lin 2005); (2) increasing seasonal melt of subsurface permafrost; (3) rodent infestation; and (4) severe soil erosion and degradation (Zhao et al. 1996; Chen et al. 1997; Zhou et al. 2003). Given the close link between surface and atmospheric processes, changes in land surface conditions affect surface exchanges of energy and water vapour, which in turn impact upon local climate (Huang 1987). For example, wetland reduction in the source area of the Yellow River has caused an increase in regional temperature and precipitation in summer, impact upon water resources (Ma et al. 2011).

To date, few successful attempts have been made to quantify how impacts of long-term land use change such as the transition from forest to grassland cover during the Holocene (Brierley et al. 2016b, Chap. 1; Han et al. 2016, Chap. 12) or changes to wetland areas (Gao 2016, Chap. 9; Li et al. 2016a, b, Chap. 10) have altered run-off and discharge characteristics of the Upper Yellow River. As such, detailed assessments of within- and between-regional variability in human impacts upon the hydrological cycle in the source zone of the Yellow River remain largely conjectural.

Impacts of flow regulation associated with dam construction and channelisation are very limited across most of the Upper Yellow River region, with the small control structure at Maduo being the only major obstruction for over 1000 km of river course before the sequence of dams on the trunk stream and some major tributaries at the margins of the Qinghai–Tibet Plateau (Brierley et al. 2016b, Chaps. 1 and 3). In addition, there is very little abstraction of flow for irrigation use, and effluent inputs are negligible, such that the Upper Yellow River currently flows clear with consistently good water quality.

4.3 Trends in Discharge from the Upper Yellow River

Both climate trends and consequent trends in discharge can be described at multiple spatial scales. It is challenging to separate long-term trends that are superimposed upon periodic cycles of varying lengths. In the face of this variability, one thing is clear—more than 70 % of the total annual precipitation falls in flood seasons from July to October (Li et al. 2001; Sun 2008).

Decadal variability in discharge at four gauging stations across the Upper Yellow River is summarised in Table 4.1 (the locations of stations are shown in Fig. 4.1). From 1956 to 2005, run-off had a yearly variation rate of 40.42 %, with an absolute variation of 0.13 billion m^3 per annum (Sun et al. 2009). From the middle of the 1950s to the end of the 1960s, run-off was generally low but displayed an upward tendency. From 1969 to 1975, however, it decreased to a low level again (Lan et al. 2006; Wang and Chen 2001; Wang and Li 2013; Zhang et al. 2004, 2013). From the mid-1970s to the middle of the 1980s, run-off was relatively high, and then it decreased again. In the beginning of the 1990s, it returned

Table 4.1 Inter-decadal variation of run-off in the source area of the Yellow River

Period	Huangheyan	Jimai	Maqu	Tangnaihai
1960–1969	0.637	4.01	15.4	21.6
1970–1979	0.927	4.29	14.5	20.4
1980–1989	0.108	4.76	16.8	24.1
1990–1999	0.501	3.37	12.8	17.6
2000–2009				16.5

(Unit: billion m^3; *Source* Yuan et al. 2015b) to a low regime, but after 2000 it increased once more. Over the whole period of the 1950s to the present, the highest regime of run-off occurred in the 1980s, while its lowest regime occurred in the 1990s (Zheng and Liu 2003; Chen and Liu 2007; Dong et al. 2007; Shi et al. 2007; Zheng et al. 2007; Yuan et al. 2015b). Changes in discharge can be related to changes in temperature and precipitation across the region, as summarised in Fig. 4.2.

There is considerable disagreement as to the existence and length of periodic cycles in the Upper Yellow River (Table 4.2). The variation of annual run-off in the source area of the Yellow River shows an alternating pattern of high and low regimes, in which low regimes are generally longer. More specifically, the variation of annual run-off is characterised by a frequent and multi-cycle alternation of high regime and low regime, within a complete period of about 20–30 years. It is likely that these cycles vary across the region, reflecting local impacts of the monsoons and local rain shadows cast by the mountains (see Yuan et al. 2015a, b).

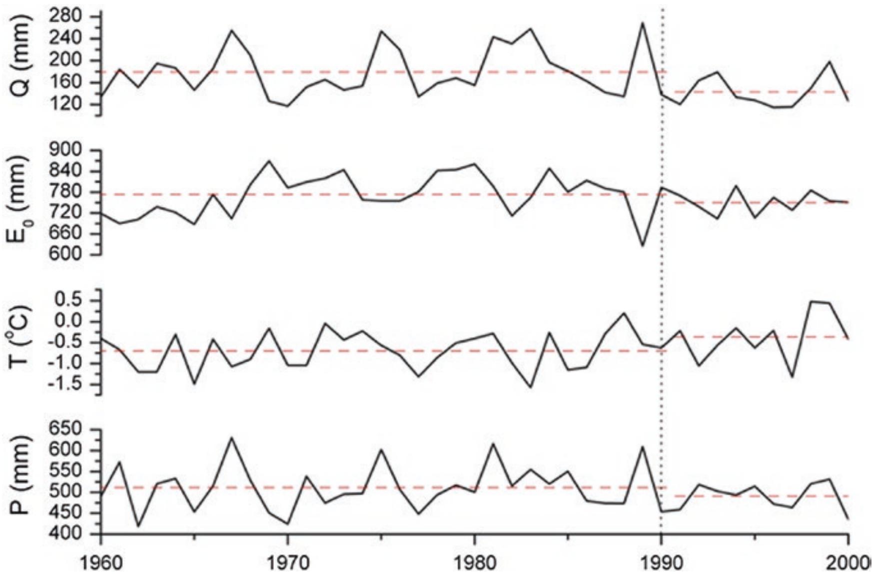

Fig. 4.2 Long-term variations in annual precipitation (*P*), temperature (*T*), potential evapotranspiration (E_0) and streamflow (*Q*) of the Yellow River Source Zone from 1960 to 2000. The means over this period are 507 mm, −0.36 °C, 768 and 171 mm, respectively (*Source* Zheng et al. 2009)

Table 4.2 Periodicity of annual run-off variation in the source area of the Yellow River

Hydrological station	Researcher	Method	Periodicity length	Time series
Huangheyan	Liang et al. (2007)	Wavelet	3–4a, 7–8a	1955–1999
	Li (2007)	Wavelet	6a, 10a, 14a	1956–2000
Jimai	Sun et al. (2010)	Wavelet	2–4a, 6–8a, 12–22a	1956–2005
	Yang et al. (2005)	Wavelet	4a, 5–6a, 10a, 22a	1959–2000
Maqu	Li (2007)	Wavelet	5a, 10a, 12a	1956–2000
	Yang et al. (2005)	Wavelet	4a, 5–6a, 8a, 10–11a, 21a	1960–2000
Tangnaihai	Li (2007)	Wavelet	5a, 10a	1956–2000
	Zhang and Wang (2014)	Spectrum	4a, 7–8a	1955–2008
	Zhao et al. (2010)	Wavelet	8a, 15a, 22a, 36a	1920–2007
	Yang et al. (2005)	Wavelet	4a, 5–7a, 8–9a, 16a	1959–2001

4.3.1 Climate Trends and the Hydrological Regime

Since the 1960s, the mean annual temperature in the source region of the Yellow River has increased by about 1.5 °C, with the trend accelerating sharply in the last decade (Yuan et al. 2015a, b). Although precipitation has steadily decreased over the same period, the trend is less distinct (Fig. 4.2).

Seasonal analysis has revealed that precipitation decreased mainly during the summer monsoon period (July–September), while temperature increased throughout the year (Yuan et al. 2015a, b). Given also that the majority of the discharge is associated with precipitation and surface run-off, rather than groundwater or meltwater (Lan et al. 2010a, b; Liu et al. 2009), it is not surprising that many studies have shown close links between the decline in discharge and falling levels of precipitation (e.g. Wang et al. 2004; Zheng et al. 2009).

Opinions are more divided concerning the effects of rising temperatures. Some scholars have proposed that the reduction of run-off since the 1990s in the source area of the Yellow River may be due to evaporation enhancement caused by an increase in temperature (Lai 1996; Zhang et al. 2004). Even if precipitation increases by 20 %, an increase of 2 °C in the regional temperature could still result in a decrease of 3 % in summer run-off (Shi and Zhang 1995). Others, however, have argued that the effects of reduced precipitation have contributed far more to falling discharge than any increases in evaporation (e.g. Lan et al. 2005). Indeed, Qiu et al. (2003) found that the slight increase in evaporation in the source area of the Yellow River between the 1960s and the 1990s was not statistically significant.

Further indirect effects of temperature change on evaporation may arise from feedbacks between temperate change and alteration of the land surface. For example, a rise in temperature may alter the condition of the ground, resulting in an increase in infiltration and/or evaporation, leading to a further reduction in run-off (Kang et al. 2005; Lan et al. 2006; Niu et al. 2011).

Rising temperatures also affect discharge by increasing spring and summer meltwaters from snow, glaciers and permafrost (Lv et al. 2011; Yang et al. 2003). Global warming is responsible for shrinking the area of the Anyemaqen Glacier by about 22 km^2 (17 %) between 1966 and 2000. However, while it is often assumed that glaciers have a wide geographical impact on meltwater and thus water resources, some researchers have pointed out that the effects of a change in temperature on the meltwater may be limited to only small tributaries in certain areas of the Yellow River source region (Xie et al. 2006; Guo et al. 2009). As shown by Yu et al. (2014), given the limited extent of glaciers in the Upper Yellow River, any changes in their magnitude have only a negligible impact on the flow regime, in stark contrast to the Upper Yangtze River.

4.3.2 Human Impacts on the Hydrological Regime

Although climate change has undoubtedly had a large impact on the discharge of the Upper Yellow River, several researchers have demonstrated that human activities have had a far greater impact. For example, Zheng et al. (2009) calculated that changing land cover in the Upper Yellow River was responsible for more than 70 % of the streamflow reduction in the 1990s, with climate change contributing less than 30 % to the overall reduction. These figures are startling, given the low population in this area, the relatively small amount of water abstraction and the absence of large dams in this region compared to the middle and lower reaches of the Yellow River.

The change in land cover associated with the reduced discharge is mostly related to decreases in the extent of grass cover in the grasslands of the region. Although this ‘desertification’ is also related to climate change, there is mounting evidence to suggest that overgrazing has contributed to the problem (see Qiao and Duan 2016, Chap. 6; Li et al. 2016a, Chap. 7; Li and Wang 2016, Chap. 8).

Although reduced cover in the herbaceous layer decreases transpiration losses and both surface run-off and infiltration are increased, water stored locally usually evaporates before it reaches the local channel (Ren and Lin 2005). In contrast, a dense herbaceous layer tends to store water on the surface, reducing evaporation and so increasing subsurface flows to the nearest stream.

Because of the close link between surface and atmospheric processes, changes in land surface conditions affect surface exchanges of energy and water vapour, which in turn impacts local climate (Huang 1987). Thus, reduced grass cover can locally accentuate the effects of a regional rise in temperature (e.g. Ma et al. 2011).

4.4 Local Variability of Factors Affecting the Hydrological Regime

The source region of the Yellow River is extremely diverse. The river descends from an altitudes over 5000 m in the Bayan Har Mountains, winding its way through wetlands, lakes, pastures and gorges before reaching Tangnaihai at an altitude of 2546 m (see, Brierley et al. 2016, Chap. 3). Land cover includes bare mountains, alpine steppe and alpine meadows, while the topography ranges from wide flat valleys to steep mountains (see Brierley et al. 2016b, Chap. 1). The configuration of the catchment influences the hydrological regime of the trunk stream, as catchment shape determines the pattern of tributary confluences and the associated areas that they drain. Overall, the topography and geology of the region induce a dendritic river pattern. Major tributaries of the river are summarised in Table 4.3. In addition, the flow regime is influenced greatly by regional variability in relief, as slope gradient and the degree of landscape dissection (i.e. drainage density and hydrological connectivity) fashion run-off generation and the conveyance of flow. Low-relief landscapes across basin fills and ancient lake/valley fills induce slow rates of water transfer across much of the region, with multiple lakes exerting a major constraint upon the flashiness of the discharge regime (Table 4.4, Fig. 4.3). Indeed, lakes and wetlands play an enormously important role in

Table 4.3 Major tributaries in the source area of the Yellow River

Tributary	Length (km)	Drainage area (km^2)	Average flow discharge (m^3/s)
Kariqu River	145.2	3157	5.61
Yueguzongliequ River	38.6	242	0.21
Zhaqu River	72	822	1.06
Duoqu River	159.7	6085	11.6
Lenaqu River	95.3	1678	2.39
Zoumaqu River	97	1183	1.47
Maqu River	310	28,000	19.1
White River	270	5488	63.1
Black River	456	7608	32.6

Table 4.4 Main lakes and their characteristics in the source area the Yellow River

Lake	Surface area (km^2)	Water level (m)	Length of lake (km)	Maximum width of lake (km)	Average width of lake (km)
Eling	610.7	4268.7	32.3	31.6	18.9
Zhaling	526.0	4292.0	35.0	21.6	15.0
Longrecuo	19.0	4213.0	9.4	4.1	2.02
Ayonggongmacuo	29.3	4220.0	13.5	4.1	2.17
Ayongwamacuo	37.6	4210.0	12.4	5.0	3.03
Ayonggamacuo	22.7	4200.0	8.9	4.8	2.55
Galalacuo	22.5	4412.0	7.4	4.6	3.04
Dongcaoalong	10.5	4180.0	4.5	4.0	2.33
Gangnagemacuo	33.1	4180.0	10.1	6.0	3.28
Rigecuo	15.0	4180.0	6.2	5.0	2.42
Hajiangyanchi	8.3	4235.0	4.6	3.1	1.8
Amucuo	2.8	4530.0	2.2	1.7	1.3

(*Source* Du 2000)

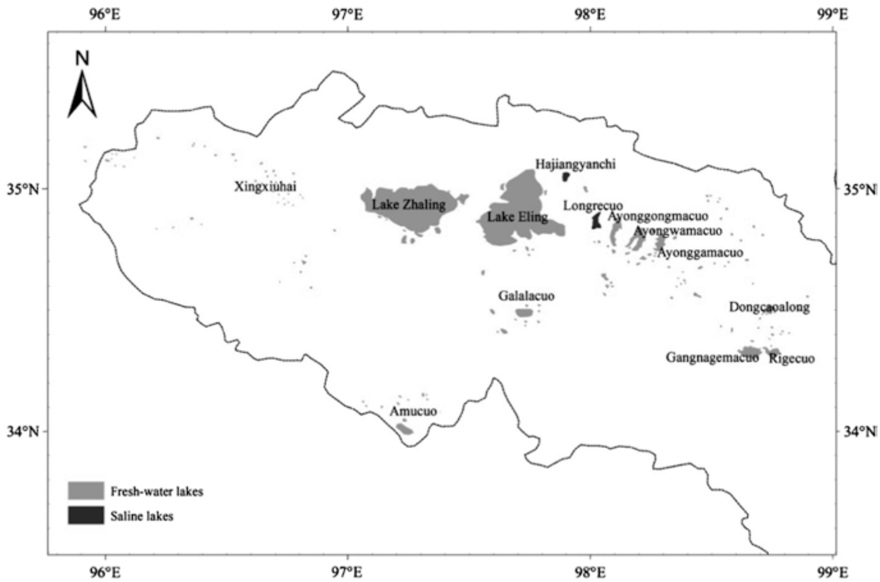

Fig. 4.3 Main lakes in the source area of the Yellow River

maintaining base flows in river systems—an attribute of vital importance in maintaining the ecological health of aquatic ecosystems (see Li et al. 2016b, Chap. 9; Qi 2016, Chap. 11).

The climate across the region varies considerably. Mean annual rainfall, for example, varies from 258 to 602 mm per year (Figs. 4.2 and 4.4). Among many factors, Yuan et al. (2015a, b) related regional variability in precipitation to different impacts of the weakening monsoon and local rain shadows effects, noting that the precipitation stations with significantly decreasing trends are all confined to the north-eastern parts of the region (Tongde, Zeku, and Maqu), whereas Maduo, which has experienced increasing rainfall, lies in the north-western part of the region (Fig. 4.4).

In the light of inconsistencies in reported variability in climate trends, it is vital to deepen our understanding of these regional differences in order to improve our

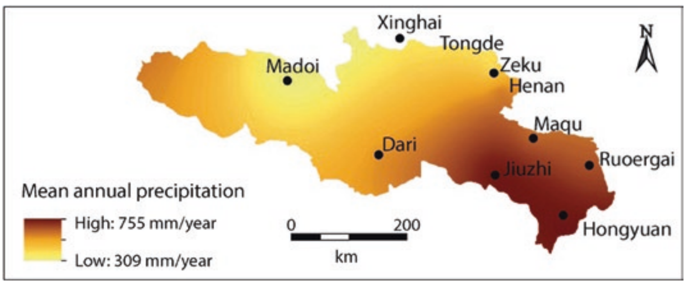

Fig. 4.4 Mean annual precipitation in the Upper Yellow River (*Source* Yuan et al. 2015a)

Table 4.5 Characteristics of different areas in the source zone of the Yellow River

	Area/river segment				
	Headwaters—above Huangheyan	Huangheyan–Jimai	Jimai–Maqu	Maqu–Tangnaihai	Total source area
Altitude (m)	4221	3969	3471	2546	
River length (km)	270	325	585	373	1553
Drainage area (km^2)	20,930	24,089	41,029	35,924	121,972
Mean annual precipitation (mm; 1956/9–2002[a])	310	537.4	602.2	258.1	584
Annual discharge (billion m^3)	0.67	3.3	10.43	5.9	20.3
Mean discharge (m^3/s)[b]	23.4	130.2	456.3	614.1	
Inter-annual coefficient of variation of run-off	0.83	0.78	0.26	0.27	
Run-off depth (mm)	32	133.8	255.4	163.2	163.8
% annual run-off during flood season	63.0	73.3	71.9	71.4	
Proportion of the total drainage area in the whole zone (%)	17.2 %	19.7 %	33.6 %	29.5 %	100 %
Proportion of the total discharge in the whole zone (%)	3.3 %	16.3 %	51.4 %	29.1 %	100

[a]Time series for Huangheyan and Tangnaihai are 1956–2002, and 1959–2002 for Jimai and Maqu
[b]Cited in Yuan et al. (2015b)
Data sources Yellow River Conservancy Commission (YRCC and the China Meteorological Administration (CMA)

ability to forecast future changes and their likely impact on discharge. As an initial step to address this issue, this chapter divides the Yellow River Source Zone into four areas with characteristic topography, vegetation and micro-climate, but most importantly with appropriate data with which to assess variability in run-off and discharge (Fig. 4.1 and Table 4.5).

4.4.1 Headwaters: Source to Huangheyan

Most of this area is situated at an altitude between 4100 and 4500 m. It is very cold and arid with a mean annual temperature of −3.89 °C and annual precipitation of 310 mm. The drainage area of this reach is about 21,000 km^2, with the mainstream covering a length of about 270 km.

Maduo County is often described as the 'county with thousands of lakes' (see Table 4.4; Fig. 4.3). It has 48 lakes with a surface area greater than or equal to 0.5 km^2. Among these, Longrecuo, Ayonggongmacuo, Ayongwamacuo and Ayonggamacuo lakes, located from the west to the east across the drainage basin, are usually called the 'four-sister lakes'. In addition, Galalacuo Lake is located on the northern slopes of the Bayan Har Mountains, while many small unnamed lakes are widespread throughout the Xingxiuhai Basin (Gao and Song 1984; Du 1999; Li 2005; Zhang 2006). All of these lakes are freshwater lakes except Longrecuo and Hajiangyanchi lakes.

Zhaling and Eling lakes are the two largest outflow freshwater lakes in this area. Water from the Zhaling Lake and its tributaries (mainly Duoqu River and Lenaqu River) converges into the Eling Lake in its south-west corner with an altitude of 4270 m, and further downstream drains into the Yellow River on the north side of the lake at 4254 m. Changes in the water level of the two lakes can cause considerable variations in the discharge observed at the Huangheyan hydrological station that is located downstream of the Eling Lake (Li 2005). These changes in water level are likely to be related to both changes in the rate of surface evaporation (linked to temperature) and the amount of meltwater from upstream snow, glaciers and permafrost as well as changes in precipitation. In relative terms, the coefficient of variation of run-off is quite high in this area (Table 4.5), with less run-off generation in summer months relative to other parts of the Upper Yellow River (63 %).

Although this area makes up 17 % of the source zone, it contributes just over 3 % of the discharge. This reflects the fundamental role of water storage in lakes (i.e. the disconnected nature of the drainage network in this area).

Mean discharge from this area was notably higher in the 1980s relative to other decades over the last 50 years (Fig. 4.5; Yuan et al. 2015a, b). The largest run-off at the Huangheyan hydrological station occurred in 1983 at 2.47 billion m^3, while the smallest run-off occurred in 1960 at 0.07 billion m^3 (Che et al. 2004; Li 2005; Sun 2008).

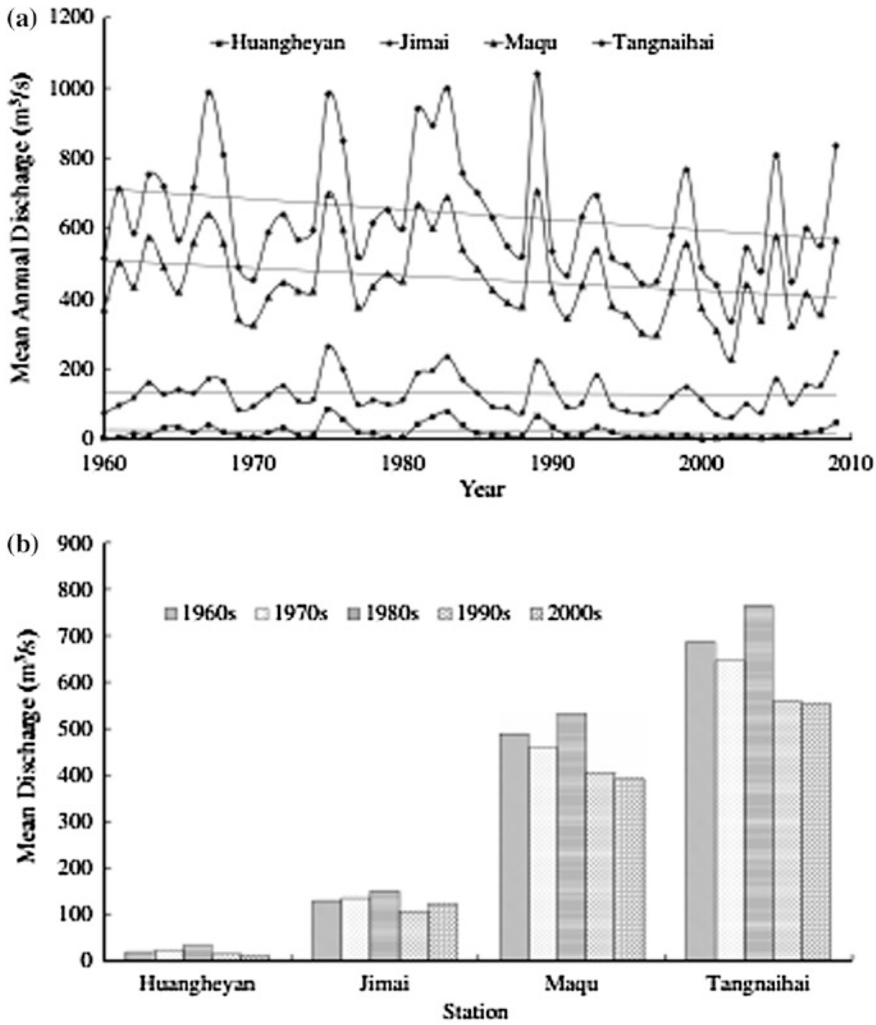

Fig. 4.5 Local differences in streamflow in the Upper Yellow River: **a** mean annual discharge; **b** decadal changes in mean annual discharge (*Source* Yuan et al. 2015a)

4.4.2 Huangheyan–Jimai

The river segment from Huangheyan to Jimai has a drainage area of about 24,000 km^2, with a river length of about 325 km. Immediately downstream of Huangheyan, the river lies in a wide valley with lakes and wetlands. Downstream, the main river channel narrows and deepens due to the constriction of the Bayan Har Mountains and the Anyemaqen Mountains (Brierley et al. 2016c, Chap. 3). Although there are many tributaries along this reach, the river water still remains clear and flows within a small range of variation. From Maduo County to the junction where the tributary Kequ River converges with the mainstream, the drainage system develops in a wide valley with star-studded lakes and swamps, such as Gangnagema, Dongcaoalong and Rigecuo lakes (Fig. 4.5a).

The coefficient of variation of run-off remains quite high in this area, reflecting the important regulatory role of the many lakes. The drainage area of this section makes up almost 20 % of the Upper Yellow River, but it contributes only 16.3 % of the flow at Tangnaihai. This marked proportional increase relative to the upstream area likely reflects the much greater precipitation in this area relative to the headwater zone itself (annual precipitation in this area is almost 540 mm, but it is only 310 mm upstream).

Notable decade-by-decade increases in mean discharge were experienced in this area from the 1960s through the 1970s to the 1980s. A marked decrease in discharge in the 1990s broke this trend, prior to a further reversal to an increasing trend in the 2000s (but not back to the discharge levels experienced in the 1960s, 1970s and 1980s; Fig. 4.5b). This recent increase in discharge is opposite to the three other sections of the Upper Yellow River, which all experienced a continued decline in discharge through to the 2000s.

4.4.3 Jimai to Maqu

The river segment from Jimai to Maqu is the largest of the four areas considered here, with a drainage area of about 41,000 km^2 and a river length of about 585 km. Two large tributaries, the Black River (Hei He) and White River (Bai He), join the river in this segment, which contributes the highest proportion of the total discharge in the Yellow River Source Zone. The reach from Dari County to Maqu County accounts for 33.6 % of the total drainage area of the Upper Yellow River, but it contributes 51.4 % of the total run-off upstream of Tangnaihai hydrological station. It is the largest run-off yield in the source area of the Yellow River, with an average run-off of about 10.43 billion m^3 (Sun 2008; Zhao et al. 2010).

The upper reaches of this segment are characterised by low mountains along both sides of the main channel and are dominated by alpine grasslands and meadow wetlands (see Brierley et al. 2016c, Chap. 3). By contrast, the lower reaches lie within a broad river valley. The area around the Zoige Basin (Ruoergai) is characterised by many wetlands which collectively extend over a total area of 4300 km^2 (Zhang and Xu 2002; see Li et al. 2016b, Chap. 9), but overall the landscape in this area is steeper, with more confined rivers than upstream areas (Brierley et al. 2016c, Chap. 3).

The inter-annual coefficient of discharge is much lower in this section relative to upstream areas (0.26 compared to around 0.8), likely as a result of more reliable (and higher) precipitation, the reduced influence of lakes and the associated increase in run-off depth (Table 4.5).

The inter-decadal variability of mean discharge at Maqu is more pronounced than at other gauge stations (Fig. 4.5b; Yuan et al. 2015a, b). The 1980s peak has been followed by a pronounced drop-off in flow of almost 30 %.

4.4.4 Maqu to Tangnaihai

This reach has a drainage area of about 36,000 km^2, with a river length of about 373 km. There are 40 glaciers spreading across the Anyemaqen Mountains on the left bank of the main river channel, with a total glacier area of about 120 km^2. Two large tributaries of the Qiemuqu River and Qushian River are sourced from these glaciers (Che et al. 2004, 2005).

Despite the variability of meltwater contributions to the discharge of the Upper Yellow River in this section, the inter-annual coefficient of variation in run-off remains low relative to headwater areas, likely as a result of the dependency of water supply from the Jimai to Maqu reach. The mean annual precipitation in this section is much lower than upstream, as this area lies in the rain shadow of the Anyemachen Mountains (mean annual precipitation is less than 260 mm, whereas the area immediately upstream has a mean annual precipitation in excess of 600 mm). Despite this, the relative contribution of this section to the discharge at Tangnaihai is almost directly commensurate with the drainage area (29.1 and 29.5 %, respectively; Table 4.5).

As noted for the section immediately upstream (Jimai–Maqu), the 1980s had notably higher discharge than other decades over the last 50 years. The significant drop-off in discharge that took place in subsequent decades is yet to be replenished.

4.5 Future Prospects for Water Supply

Stream discharge is a major component of the water cycle and understanding its origins and magnitude provides a basis for planning, distributing, developing and managing the use of regional water resources. Studies on the responses of run-off and stream flow to climate change have important significance in assessing the trend of water resources, alleviating the shortage supply of water resources and working out effective plans for sustainable development and utilisation of regional water resources.

Some scholars are pessimistic about the trend of future surface run-off in the source area of the Yellow River. They think that continuing increases in temperature will increase evaporation, resulting in a further reduction in discharge (Sun et al. 2010; Jin et al. 2013; Liu and Chang 2005; Liu et al. 2012). However, new data on precipitation and run-off in the source area of the Yellow River have shown that the average annual precipitation since 2004 has exceeded the long-time average value, and run-off through all hydrological sections on the main stream of the Yellow River has increased since 2008, exceeding the long-term average (Lan et al. 2013). This may at least partly be due to the establishment of the Sanjiangyuan National Nature Reserve and the various soil and vegetation recovery programmes undertaken since 2000 (see Ran et al. 2016, Chap. 14).

4.6 Closing Remarks

Water is the main driving force and the carrier of material and energy in the soil–vegetation–atmosphere transfer system. It forms an important linkage between atmospheric, hydrological, ecological processes and human activities in the earth system. Effective approaches to resource and environmental management view water as a mirror of the land. Under the impact of climate change and human activities, water resources in the source area of the Yellow River have decreased since the 1990s. At the same time, environmental deterioration, soil erosion, land desertification, shrinkage of wetlands and lakes, glacier ablation, deterioration of grasslands, rodent infestation, degradation of biological diversity and other environmental and ecological problems have arisen (see Qiao and Duan 2016, Chap. 6; Li et al. 2016a, Chap. 7; Gao 2016, Chap. 9; Li et al. 2016a, b, Chap. 10). As a result, the regional hydro-ecological system has become more and more vulnerable (see Tane et al. 2016, Chap. 13). Future variability in surface run-off in the source area of the Yellow River may exacerbate these problems.

Improving land surface conditions by increasing grassland coverage, recovering biological diversity and effectively controlling rodents can help to increase water and nutrient retention ability of soil, thereby improving the regional ecological–hydrological environment. Establishment of natural reserves in the region has helped by enhancing the management of water resources and water quality actively and efficiently. In addition, water-saving technologies and improving water-delivery infrastructure can be used to support efficient allocating and protection of water resources. It is also necessary to strengthen scientific research on the driving factors and mechanisms affecting the water resources and the hydrological environment.

References

Brierley, G. J., Cullum, C., Li, X. L., et al. (2016a). Conclusion: environmental futures of the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 353–369). Berlin: Springer.

Brierley, G. J., Li, X., Cullum, C., et al. (2016b). Introduction: landscape and ecosystem diversity in the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 1–34). Berlin: Springer.

Brierley, G. J., Yu, G. A., & Li, Z. W. (2016c). Geomorphic diversity of rivers in the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 59–77). Berlin: Springer.

Chen, G., Li, P., Zhang, X., et al. (1997). Impact Assessment of Climate change on Snow: Glacier and Permafrost. Lanzhou, Gansu cultural Press, 22–56 (in Chinese).

Che, Q., Wang, G., & Gou, W. (2004). Analysis on temporal and spatial characteristics and correlation of precipitation and runoff in the source region of the Yellow River. *Gansu Water Conservancy and Hydropower Technology, 40*, 337–339 (in Chinese).

Che, Q., Wang, G., & Sun, S. L. (2005). Analysis on temporal and spatial characteristics and correlation factors of runoff in source region of the Yellow River. *Yellow River, 27*, 9–10 (in Chinese).

Chen, L. Q., & Liu, C. M. (2007). Influence of climate and land-cover change on runoff of the source regions of Yellow River. *China Environmental Science—Chinese Edition, 27*, 559.

Chen, L., Zheng, H., Chen, D., et al. (2008). Base-flow separation in the source region of the Yellow River. *Journal of Hydrologic Engineering, 13*, 541–548.

Dam, J. C. (1999). *Impacts of climate change and variability on hydrological regimes*. Cambridge: Cambridge University Press.

Dong, X. H., Yao, Z. J., & Chen, C. Y. (2007). Runoff variation and responses to precipitation in the source regions of the Yellow River. *Resources Science, 29*, 68–73 (in Chinese).

Du, W. H. (1999). Stem and tributaries in the source region of the Yellow River. *Historical Data of the Yellow River, 2*, 17–19 (in Chinese).

Du, W. H. (2000). Lakes in the source region of the Yellow River. *Historical Data of the Yellow River, 3*, 14–17 (in Chinese).

Gao, J. G. (2016). Wetland and its degradation in the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 209–232). Berlin: Springer.

Gao, Z. X., & Song, Z. S. (1984). Geographic hydrology in the upper reach of the Yellow River. *Hydrology, 24*, 55–58 (in Chinese).

Guo, S., Ma, Y. F., Zhang, Z. M., et al. (2009). The ecology response to climate changes and human disturbance in the source regions of the Yellow River. *Journal of Arid Land Resources and Environment, 23*, 78–84 (in Chinese).

Han, Y. R. (Ed.). (2004). *The evaluation of hydro-resource in Qinghai*. Xining: Qinghai People's Press (in Chinese).

Han, M. Q., Brierley, G. J., Cullum, C., et al. (2016). Climate, vegetation and human land use interactions on the Qinghai-Tibet Plateau through the Holocene. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 253–274). Berlin: Springer.

Huang, R. H. (1987). Physical basis of short-term climate change. *Advances in Earth Sciences, 6*, 23–29 (in Chinese).

Huang, R. H., & Zhou, D. H. (2012). The impact of Climate change on the runoff of the Yellow River and Ecosystem and Frozen Soil in its source area. *Chinese Journal of Nature, 34*, 1–9 (in Chinese).

Jia, Y. W., Gao, H., Niu, C. W., et al. (2008). Impact of climate change on runoff process in headwater area of the Yellow River. *Journal of Hydraulic Engineering, 39*, 52–58 (in Chinese).

Jiang, Y. C., & Li, D. L. (2011). Variations of Tangnaihai runoff and precipitation and temperature in the upper reach of the Yellow River. *Meteorology and Disaster Reduction Research, 34*, 51–57 (in Chinese).

Jin, H. J., Chang, X. L., & Wang, S.L. (2007). Evolution of permafrost on the Qinghai-Xizang (Tibet) Plateau since the end of the late Pleistocene. *Journal of Geophysical Research: Earth Surface,* 112(F2).

Jin, J. L., Wang, G. Q., Liu, C. S., et al. (2013). Responses of hydrology and water resources to the climate change in the Yellow River source region. *Journal of Arid Land Resources and Environment, 27*, 137–144 (in Chinese).

Kang, L. L., Yu, H., Wang, J. H., et al. (2005). Effect of climate variation on natural runoff in Tangnaihai and its upstream of the Yellow River. *Water Power, 31*(22–34), 31 (in Chinese).
Lai, Z. M. (1996). Impact of climate variation on the runoff of large river in the Tibetan plateau. *Journal of Glaciology and Geocryology, 18*, 314–320 (in Chinese).
Lan, Y. C., Ding, Y. J., Shen, Y. P., et al. (2005). Review on impact of climate change on water resources system in the upper reaches of Yellow River. *Advances in Climate Change Research, 1*, 122–125 (in Chinese).
Lan, Y. C., Shen, Y. P., Lin, S., et al. (2006). Changes in high and low flow cycles of the upper reaches of Yellow River and their circumfluence backdrop. *Journal of Glaciology and Geocryology, 28*, 950–955 (in Chinese).
Lan, Y. C., Wen, J., Zhao, G. H., et al. (2010a). Sensibility analysis of the runoff in the headwater regions of the Yellow River to climate change. *Journal of Glaciology and Geocryology, 32*, 175–182 (in Chinese).
Lan, Y. C., Zhao, G. H., Zhang, Y. N., et al. (2010b). Response of runoff in the source region of the Yellow River to climate warming. *Quaternary International, 226*, 60–65.
Lan, Y. C., Lu, C. Y., La, C. F., et al. (2013). The fact of climate shift to warm-humid in the source regions of the Yellow River and its hydrologic response. *Journal of Glaciology and Geocrylogy, 35*, 920–928 (in Chinese).
Li, W. S. (2005). Preliminary analysis on the sediment source in the Yellow River source area. *Journal of Sediment Research, 2*, 67–72 (in Chinese).
Li, L. Q. (2007). Runoff simulation and analysis in the source area of Yellow river. Thesis for Master of Engineering. Hehai University, Nanjing, China (in Chinese).
Li, Y. F., & Wang, Z. Y. (2016). Modeling vegetation-erosion dynamics in the Mugetan Desert, Yellow River Source Zone. In: G.J. Brierley, X. Li, C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 167–182). Berlin: Springer.
Li, W. S., Feng, L., & Sun, S. L. (2001). Influence of Zaling and Eling Lake on the annual discharge of the Huanghe River source area. *Acta Geographica Sinica, 56*, 75–82 (in Chinese).
Li, X. L., Perry, G., & Brierley, G. J. (2016a). Grassland ecosystems of the Yellow River Source Zone: degradation and restoration. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 137–165). Berlin: Springer.
Li, Z. W., Wang, Z. Y., & Pan, B. Z. (2016b). Wetland ecosystems of the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 183–207). Berlin: Springer.
Liang, S. H., Wan, L., Hu, Fu S, et al. (2007). Periodic regularity of the runoff in the source region of the Yellow River based on wavelet analysis. *Journal of Nanjing University (Natural Sciences), 43*, 300–308 (in Chinese).
Liu, X. Y., & Chang, X. H. (2005). A summary of study on runoff variations in source region of the Yellow River. *Yellow River, 27*(6–8), 14 (in Chinese).
Liu, G. H., Zhang, Z. H., & La, C. F. (2009). Trend analysis of the runoff change at Tangnaihai Hydrologic Station on the upper Yellow River. *Gansu Water conservancy and Hydropower Technology, 45*, 4–6 (in Chinese).
Liu, C. H., Yang, Y. H., & Wang, Z. Y. (2012). Impacts of climate change on the summer flow and estimates of the future trends in the upper reaches of the Yellow River. *Progress in Geography, 31*, 845–852 (in Chinese).
Lv, J. Q., Shen, B., Mo, S. H., et al. (2011). The impacts of river water resources on regional climate over the upper Yellow River high cold region. *Journal of Natural Resources, 26*, 2131–2140 (in Chinese).
Ma, Y., Jin, L., Duan, L., et al. (2011). Impact of the wetland degeneracy in three-river source on regional climate model. *Plateau and Mountain Meteorology Research, 31*, 42–45 (in Chinese).

McGregor, G. R. (2016). Climate variability and change in the Sanjiangyuan region. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 35–57). Berlin: Springer.

Miao, C., Ni, J., Borthwick, A. G., et al. (2011). A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. *Global and Planetary Change, 76*, 196–205.

Niu, L., Ye, B. S., Li, J., et al. (2011). Effect of permafrost degradation on hydrological processes in typical basins with various permafrost coverage in Western China. *Science China Earth Sciences, 54*, 615–624.

Qi, D. (2016). Fish of the Upper Yellow River. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 233–252). Berlin: Springer.

Qiao, Y. M., & Duan, Z. H. (2016). Understanding alpine meadow ecosystems. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 117–135). Berlin: Springer.

Qiu, X. F., Liu, C. M., & Zeng, Y. (2003). Changes of pan evaporation in the recent 40 years over the Yellow River Basin. *Journal of Natural Resources, 18*, 437–442 (in Chinese).

Ran, Y. C., Xie, J. X., & Li, X. L. (2016). Socio-economic development and its effects on the ecological environment of the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 331–351). Berlin: Springer.

Ren, J. Z., & Lin, H. L. (2005). Assumed plan on glassland ecological reconstruction in the source region of Yangtze River, Yellow River and Lantsang River. *Acta Prataculturae Sinica, 14*, 1–8 (in Chinese).

Shi, Y. F., & Zhang, X. S. (1995). Influences of climate change on surface runoff in arid regions of northwest of China and the variation trend. *Science in China (Series B), 25*, 968–977 (in Chinese).

Shi, X. H., Qin, N. S., Wang, Q. C., et al. (2007). Research on runoff change and forecasting model in upper reach of the Yellow River. *Qinghai Technology, 5*, 14–19 (in Chinese).

Sun, G. S. (2008). Preliminary analysis on characteristics of precipitation and runoff changes in the source region of the Yellow River. *Journal of Water Resources Research, 29*, 22–25 (in Chinese).

Sun, W. G., Cheng, B. Y., & Li, R. (2009). Multitime scale correlations between runoff and regional climate variations in the source region of the Yellow River. *Acta Geographica Sinica, 64*, 117–127 (in Chinese).

Sun, W. G., Cheng, B. Y., & Li, R. (2010). Seasonal variations of runoff and its wavelet correlations with regional climate in source region of the Yellow River. *Journal of Desert Research, 30*, 712–721 (in Chinese).

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) Headwaters. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 275–330) Berlin: Springer.

Wang, Z., & Chen, D. H. (2001). Analysis on factors of runoff change in the source region of the Yellow River. *Hydrogeology and Engineering Geology, 3*, 35–37 (in Chinese).

Wang, H., & Li, D. L. (2013). Research progress on variations and effectors of the runoff in the source region of the Yellow River. *Plateau and Mountain Meteorology Research, 33*, 93–99 (in Chinese).

Wang, J., Wang, Y. H., & Sun, H. B. (2004). Analysis of regional runoff variation upstream Tangnaihai Hydrological Station. *Journal of Water Resource and Water Engineering, 15*, 68–70 (in Chinese).

Xie, C. W., Ding, Y. J., Liu, S. Y., et al. (2003). Comparison analysis of runoff change in the source Regions of the Yangtze and Yellow Rivers. *Journal of Glaciology and Geocryology, 25*, 422–429 (in Chinese).

Xie, C. W., Ding, Y. J., Han, H. D., et al. (2006). Analysis on the runoff change and its response to the climate factors at the source regions of Yellow River. *Journal of Arid Land Resources and Environment, 20*, 7–11 (in Chinese).

Yang, J. P., Ding, Y. J., Liu, S. Y., et al. (2003). Glacier change and its effect on surface runoff in the source regions of the Yangtze and Yellow Rivers. *Journal of Natural Resources, 18*, 595–602 (in Chinese).

Yang, J. P., Ding, Y. J., & Chen, R. S. (2005). Analysis on periodic variations of annual hydrologic and meteorological series in source regions of Yangtze and Yellow Rivers. *Journal of Desert Research, 25*, 351–355 (in Chinese).

Yu, G., Brierley, G. J., Huang, H. Q., et al. (2014). An environmental gradient of vegetative controls upon channel planform in the source region of the Yangtze and Yellow Rivers. *Catena, 119*, 143–153.

Yuan, F., Berndtsson, R., Zhang, L. et al. (2015a). Hydro climatic trend and periodicity for the Source Region of the Yellow River. *Journal of Hydrologic Engineering*. doi:10.1061/(ASCE)HE.1943-5584.0001182, 05015003.

Yuan, F., Yasuda, H., Berndtsson, R., et al. (2015). Regional sea surface temperatures explain spatial and temporal variation of summer precipitation in the source region of the Yellow River. *Hydrological Sciences Journal*. doi:10.1080/02626667.2015.1035658.

Zhang, J. F. (2006). An analysis of periodic rules of the elements of hydrology and weather of the Yellow River Source. Thesis for Doctor of Engineering. China University of Geosciences, Beijing, China (in Chinese).

Zhang, J. Y., & Wang, G. Q. (2014). *Runoff changes and quantitative recognition*. Beijing: Science Press (in Chinese).

Zhang, O., & Xu, J. X. (2002). Decoupling of the Yellow River basin system. *Geographical Research, 21*, 54–60 (in Chinese).

Zhang, G. S., Li, L., Shi, X. H., et al. (2000). Climate change over the upper Yellow River and its effect on water resources. *Advances in Water Science, 11*, 277–283 (in Chinese).

Zhang, S. F., Jia, S. F., Liu, C. M., et al. (2004). Variation and its influence of water cycle in the source region of the Yellow River. *Science in China Series E Technological Sciences, 34*, 117–125 (in Chinese).

Zhang, S. F., Hua, D., Meng, X. J., et al. (2011). Climate change and its driving effect on the runoff in the "Three-River Headwaters" region. *Acta Geographica Sinica, 66*, 13–24 (in Chinese).

Zhang, Y., Fu, Y. F., & Hou, B. X. (2013). Analysis of the causes for runoff evolution in the Yellow River Source Region. *Yellow River, 35*, 22–24 (in Chinese).

Zhao, X. Q., & Zhou, H. K. (2005). Eco-environmental Degradation, vegetation regeneration and sustainable development in the Headwaters of three rivers on Tibetan plateau. *Bulletin of Chinese Academy of Sciences, 20*, 471–476 (in Chinese).

Zhao, X. F., Wang, S. L., Guo, D. X. et al. (1996). *Research on Permafrost Change in Qinghai-Tibetan plateau*. Comprehensive Observation Report in Qinghai-Tibetan Plateau, Lanzhou University Press, Lanzhou, pp. 1–9 (in Chinese).

Zhao, G. H., Zhang, Y. N., & Lan, Y. C. (2010). Annual runoff in the source regions of Yellow River: long-term variation features and trend forecast. *Journal of Glaciology and Geocryology, 32*, 189–195 (in Chinese).

Zheng, H. X., & Liu, C. M. (2003). Changes of annual runoff distribution in the headwater of the Yellow River basin. *Progress in Geography, 22*, 585–590 (in Chinese).

Zheng, H., Zhang, L., Liu, C., et al. (2007). Changes in stream flow regime in headwater catchments of the Yellow River basin since the 1950s. *Hydrological Processes, 21*, 886–893.

Zheng, H., Zhang, L., Zhu, R., et al. (2009). Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. *Water Resources Research, 45*, 7, W00A19. doi:10.1029/2007WR006665.

Zhou, H. K., Zhou, L., Liu, W., et al. (2003). Study on grassland degradation and strategies for the sustainable development of the livestock raising industry in Guoluo Prefecture of Qinghai. *Pratacultural Science, 20*, 19–25 (in Chinese).

Chapter 5
Hillslope Stability in the Yellow River Source Zone

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Abstract Tectonic uplift is the primary control upon the low relief yet moderately undulating plateau landscapes that make up much of the source zone of the Yellow River. Steep ravines and gullies are restricted to mountain ranges at the northern and southern margins. This contrasts starkly with the deeply dissected landscapes at the eastern margin of the Qinghai–Tibet Plateau. Although the high elevation induces low mean annual temperatures, diurnal temperature ranges are high. Precipitation is sparse but concentrated, and gales are frequent. Hillslope processes such as landslides, debris flows, solifluction and soil erosion are extensively developed in the region. This chapter presents an overview of hillslope stability in the Yellow River Source Zone. First, the landscapes and topography of the Yellow River Source Zone are introduced. Landslide, debris flow, soil erosion (aeolian and rill/gully) and freeze-thaw processes are shown to be key drivers of patterns and rates of grassland degradation. Human activities and climate change are key agents

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of landscape change. The influence of vegetation management upon hillslope stability and in reducing geological disasters is demonstrated. Vegetation plantation and increased vegetation cover enhance the mechanical and hydrologic effects of hillslope protection, increasing soil shear strength and interception of rainfall.

Keywords Hillslope stability · Hillslope process · Landslide · Debris flow · Solifluction · Soil erosion · Hillslope protection by vegetation · Soil and water conservation · Land use

5.1 Introduction

The source zone region of the Yellow River is characterized by a wide range of landscapes with considerable variability in hillslope form and process (Nicoll et al. 2013). The diverse geologic settings generate stark contrasts between mountainous regions, vast plateaus and dissected landscapes at the margins of the Qinghai–Tibet Plateau. Endogenic processes have created profound variability in relief—both absolute and relative. Tectonic uplift of the plateau has induced a sharp altitudinal decline at the eastern margin, demarcating the transition between the first two terrain (topographic) steps in China (Brierley et al. 2016a, Chap. 1). Atop this geologically defined template, climatic factors induce marked within-regional variability in exogenic processes, both horizontally and altitudinally. There is also a significant imprint of former environmental conditions upon the contemporary landscape, such as extensive glacial and periglacial features. Human activities and climate change have altered the distribution and effectiveness of geomorphic processes, greatly accelerating soil erosion, and modifying the depth and extent of permafrost. Collectively, these factors have brought about significant spatial and temporal variability in hillslope processes. In turn, hillslope processes facilitate and impact upon many other relationships, such as vegetation distribution and land use potential, and resulting patterns of human activities. Human relationships are quite different, for example, on the bare hillslopes and dissected landscapes at the plateau margin relative to the grassland and wetland areas that are found across many depositional basins and valley floors (which themselves have a marked altitudinally induced gradient in land use potential).

This chapter presents an overview of hillslope forms and processes in the source zone of the Yellow River. The term ‘plateau landscape’ suggests hillslope processes that are relatively benign and innocuous. However, the plateau is far from flat, with an intriguing complex of plains and undulating hills inset within an array of mountain ranges (see Brierley et al. 2016b, Chap. 3). Hillslope gradients across most areas of the upper Yellow River reflect long-term weathering, surface erosion and the history of fluvial incision processes. This chapter starts by summarizing regional terrains and their associated hillslope characteristics. Hillslope evolution is then framed in relation to the broad (long-term) geological setting. Human interactions with hillslope processes are then discussed, initially assessing factors that have accentuated the distribution and rate of soil erosion, before considering management actions to address concerns for hillslope instability, focusing particularly on vegetation planting.

5.2 Topographic Setting and Primary Hillslope Patterns in the Yellow River Source Zone

The Yellow River Source Zone lies in the eastern part of the Qinghai–Tibet Plateau. The altitude of the region ranges from 2500 to 5500 m (Fig. 5.1). The Kunlun Mountains and Bayan Har Mountains lie to the west and south-west. The Buqing Mountains are aligned along the northern boundary, whilst the north-west–south-east-aligned Anyemaqen Range lies to the east. Among these mountains, Maqinggangri is the highest peak. More than ten peaks are higher than 5000 m. Contemporary glaciers sit at the crest of extreme high mountains at elevations above 6000 m. Elevation differences between peaks and valley floors often extend beyond 2000 m. Above 4800 m plant cover is sparse, dominated by lichens (Cheng et al. 2006; Zheng and Wang 1996). Areas between 4400 and 4800 m are characterized by grassland meadows with alpine *Kobresia humilis* and sedge dominant. Alpine swamp with grassland meadows dominated by *Kobresia tibetica* and *Carex alrofusca* are distributed from 4200 to 4400 m (Zheng and Wang 1996).

The Yellow River Source Zone is part of the Naqu-Maduo plateau within the Qinghai–Tibet Plateau (Brierley et al. 2016a, b, Chaps. 1 and 3). It has an average

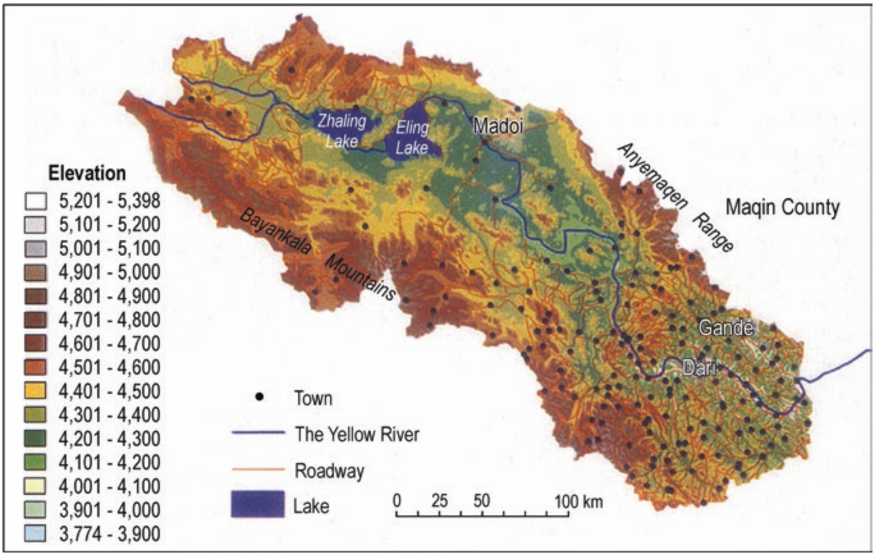


Fig. 5.1 Topography of the Yellow River Source Zone (modified from Zhang et al. 2006a)

altitude of about 4500 m (Zhang et al. 2006a). The interior area comprises an upland plain and lake basin with broad valleys. There are some undulating (rounded) mountains and high-altitude hills with a gentle gradient, but only limited areas of steep mountains and gullies. The whole terrain is inclined from the north-west to the south-east, with river and lake systems aligned along the strike of grabens within this fault-block terrain (Zhang et al. 2006a). Many rivers are ephemeral, characterized by markedly seasonal flows and sandy valley floors. Both freshwater and saltwater lakes are evident. Terraces, piedmont platforms and alluvial fans are found along the margins of the graben basins. Mountains and hills are gently undulating in the east and south of the source zone. Broad valleys and lake basins are found in the west and middle part. Extensive flat plains are evident in the northern part.

Interactions between topography (relief, hillslope angle/length, etc.), climate (hydrology and vegetation cover), geology (weathered materials and soils) and human impacts generate quite different catenas in differing areas of the upper Yellow River. Two examples are presented in Figs. 5.2 and 5.3. Adjacent to Zhaling Lake in Maduo County, the contemporary Yellow River is inset alongside various floodplain, terrace, piedmont and fan features (Fig. 5.2; Cheng et al. 2006). The flat-topped nature of valley floor units reflects the imprint of history—extended phases of valley evolution associated with ancestral versions of the Yellow River, and subsequent patterns of valley infilling and incision associated with climate history. Adjacent mountains make up just a small proportion of this landscape. Ironically, the source zone has little exposed bedrock, and reworked sediments drape much of the landscape (alluvial, colluvial and aeolian stores).

Quite different hillslope relationships are evident in Guide County, but the key driver of hillslope form remains the same, as hillslope morphologies are largely determined by the imprint of valley evolution processes. Here, the dominant influence has been the long-term history of valley infilling of the Guide Basin, followed by relatively rapid incision by the Yellow River and associated tributaries (Pan 1994; Zhao and Liu 2003; Fig. 5.3). Basin fills that separate the gorges along

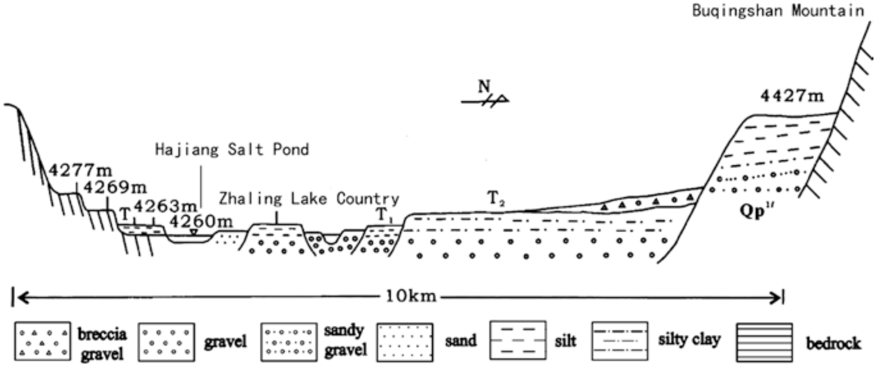


Fig. 5.2 Transverse sections of the valley of the Yellow River near Zhaling Lake, Maduo County (modified from Cheng et al. 2006)

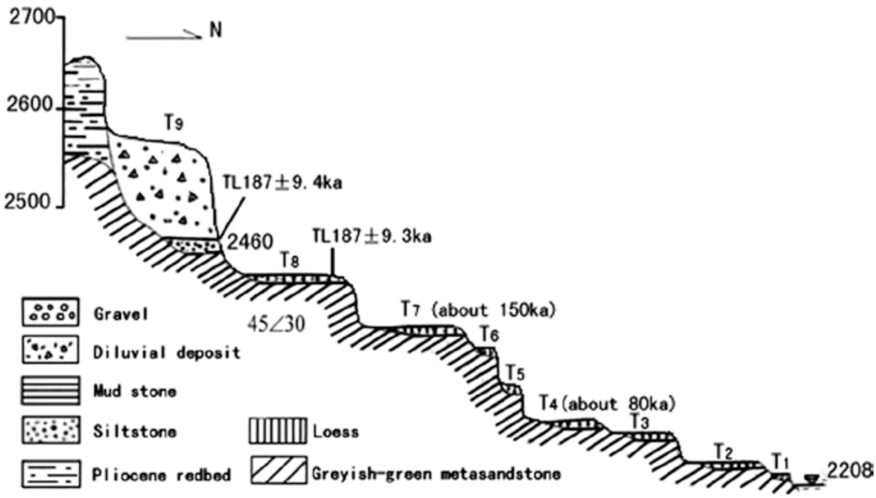


Fig. 5.3 Synthetic cross section of the valley fill of the upper Yellow River at Nina, Guide Basin (modified from Zhao and Liu 2003)

the upper Yellow River result in near-vertical cliffs of Tertiary and Pleistocene aged valley fill deposits (lacustrine, fluvial and aeolian deposits) that line the margin of the incised trunk stream and its tributaries (Brierley et al. 2016a, Chap. 1). Gravel and sand deposits are often hundreds of metres deep.

Unfortunately, systematic appraisals of hillslope process relationships across differing landscape settings of the Yellow River Source Zone are unavailable, hindering our capacity to assess linkages to flow pathways, soil types, vegetation patterns and other abiotic and biotic associations. As shown in Tane et al. (2016, Chap. 13), these are vital considerations in establishing process-based understandings to inform management applications. For now, it is important to simply consider the stark contrasts in landscape settings evident in Figs. 5.2 and 5.3. In the area around Maduo, characteristic of many of the basin fills of the upper Yellow River, landscapes have very subdued relief, the imprint of the long-term sedimentation history lingers and hillslope processes are slow and subtle. In contrast, incised and dissected landscapes at the margin of the Qinghai–Tibet Plateau are characterized by many near-vertical cliffs, whether comprised of bedrock in gorge settings, or cemented alluvial and lacustrine materials in the terraces of incised basin fill deposits. The latter landscapes are prone to dramatic collapse via landslide activity, especially in response to earthquakes or major storms (e.g. Guo et al. 2014; Ouimet et al. 2007).

Permafrost melt and the role of the 'active layer' exert a critical influence upon hillslope processes and forms at higher altitudes of the plateau (especially above 4100 m). Changes to the depth and extent of the active layer that is subjected to repeated freeze-thaw processes impact upon hillslope instability via solifluction and gelifluction processes.

5.3 Hillslope Processes: Landslides, Debris Flows and Solifluction

In general terms, the level of geologic hazard associated with hillslope failure in the source zone of the Yellow River is low, with process activity accentuated locally in high mountain areas and along the trunk stream of the Yellow River itself (Zhang et al. 2003; Fig. 5.4). Contemporary uplift of the plateau and enhanced rates of

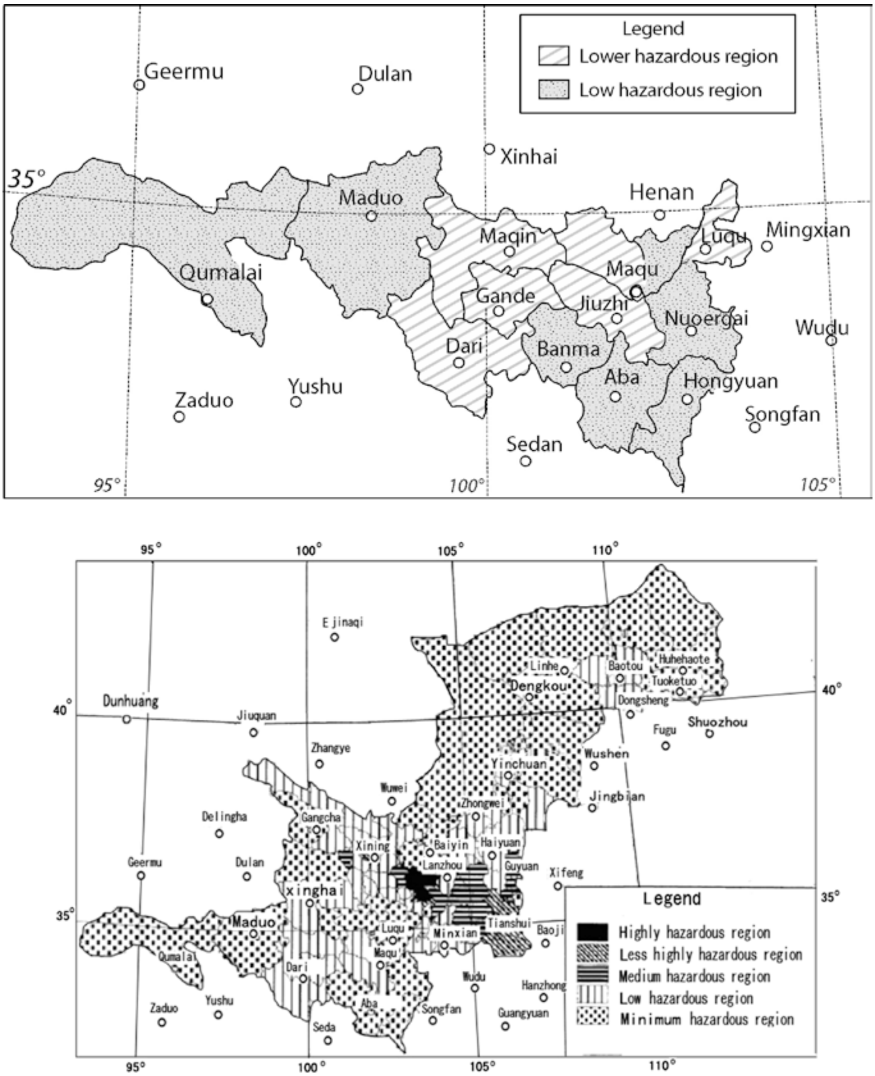


Fig. 5.4 Risk of geological hazards of hillslope failure by collapse, landslide and debris flow activity in the upper reaches of the Yellow River (modified from Zhang et al. 2003)

weathering create extensive areas of talus hillslopes which provide materials for debris flows (Zhang et al. 2006b). Landslides are linked closely with contemporary tectonic movements (Li et al. 2007, 2008a, b; Zhang et al. 2006b). Heavy rainstorms trigger many landslides in the rapidly saturated silty soils, especially in areas where soluble salts are prominent (Li et al. 2008a, b). Elsewhere, high rainfall events and summer snow melts that concentrate water and debris in colluvial depressions or along steep valley floors induce debris flows among Quaternary deposits (You and Jing 1980; Zhang et al. 2000).

Widespread permafrost generates fragmented substrates within the active layer of hillslope soils. Freeze-thaw and frost heave generate many mass hillslope slips by solifluction and gelifluction processes (Fig. 5.5; Yang and Tong 2010). Solifluction processes are prominent in high-altitude areas, whereas shallow landslides and landslips are prominent on the loess hillslopes in the north-eastern part of the plateau (see Hu et al. 2013). Many areas of talus slope are subjected to severe frost weathering and wind erosion. The large number of talus slopes reflects the action of wind erosion and frost weathering, especially at high altitudes (Cheng et al. 2006). Large quantities of bare rock on steep hillslopes are prone to collapse via landslide and debris flow activity. These geological disasters are widespread and frequent (Chen et al. 2007; Xu and Huang 1997).

Fig. 5.5 Solifluction lobes on the hillslope at Huashixia in Qinghai Province

5.4 Soil Erosion

Soils of the upper Yellow River are generally infertile, thin, coarse grained and loose. Soil formation processes occur very slowly and resistance to soil erosion is limited in these mountainous environments with dry climates and fragile ecosystems. As such, they have limited integrity, low water-retention and are very prone/vulnerable to erosion (Han et al. 2011; Zeng et al. 2004; Zhang et al. 2006a). The main soil types in the region are alpine cold desert soil, alpine meadow soil, alpine steppe soil, mountain meadow soil, grey cinnamonic soil, chestnut soil, boggy soil and aeolian sandy soil (Zeng et al. 2004; Zhang et al. 2006a).

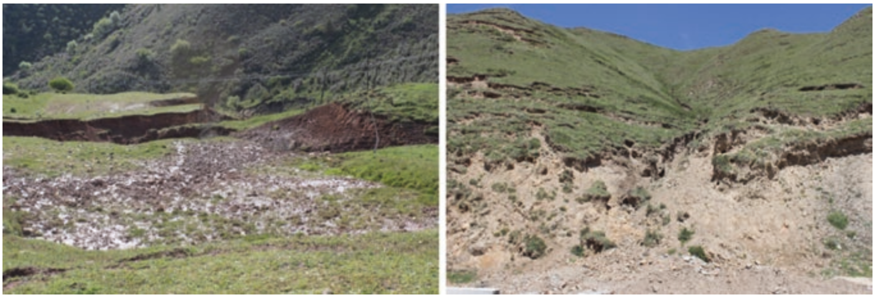
Freeze-thaw erosion, water erosion, wind erosion and gravitational erosion are the primary agents of soil erosion in the region (Yan et al. 2004). Freeze-thaw processes operate over most of the Yellow River Source Zone, especially in higher-altitudinal areas to the west. Freeze-thaw cycles reduce the strength and integrity of the ground, loosening soil particles, so they are more readily moved by wind and water erosion processes (Fan and Cai 2003). Strong frost weathering has led to extensive exposure of bare rocks and gravels on hillslopes (Fig. 5.6). In contrast, erosion in the lower areas to the east is dominated primarily by water and wind processes.

Wind speeds increase from the south-east to the north-east and with altitude. Westerly winds are most prominent. Gale conditions are experienced on 75–128 days per year, with wind speeds up to 30 m s^{-1} (Zeng and Feng 2009). Wind erosion is less pronounced in areas with high underground water level and with better soil and water conditions where ground cover is maintained. Desertified pastures and drying swamps/lakes are subject to localized wind erosion (see Li and Wang 2016, Chap. 8). Wind erosion is especially pronounced in Gonghe, Guinan and Maduo counties (Yan et al. 2004). In areas with little ground cover and abundant medium–fine-grained sands, even lower wind speeds can trigger significant soil erosion.

Talus slope formed by frost weathering in the Yellow River source zone

Talus slope formed by frost weathering in the source zone of the Yellow River

Fig. 5.6 Talus slopes in the Yellow River Source Zone generated by freeze-thaw processes



Grassland degradation and gully development impacted by overgrazing

A gully in the source zone of the Yellow River

Fig. 5.7 Examples of grassland degradation and gully development in the Yellow River Source Zone

Rill and gully erosion is distributed across the Yellow River Source Zone, but it is especially prominent in loess deposits that have accumulated atop the north-eastern corner of the Qinghai–Tibet Plateau. The prominence of relatively loose colluvial, aeolian and alluvial deposits presents abundant scope for incision and channel expansion (Li and Pan 2009; Fig. 5.7). As headcut erosion eats back into the hillslope via network extension, it generates large volumes of sediment. However, given the relatively steep and incised channels, sediment delivery ratios are exceptionally high.

Several factors have aggravated soil erosion in recent years (e.g. Feng et al. 2006; Wang et al. 2013; Zhang et al. 2006a). Since the 1980s, human activities and climate change have brought about extensive vegetation degeneration, transforming areas of previously flourishing hygrophilous vegetation which is well adapted to cold environments into sparse drought-enduring vegetation (Dai et al. 2014; Liang et al. 2007; Pan and Liu 2005; Xu et al. 2012; Yang et al. 2005; Wang et al. 2004). Increased areas of bare soil, associated with overgrazing and rodent removal of topsoil have exposed calcisol horizons that do not favour plant establishment (Li et al. 2016, Chap. 7; Tane et al. 2016, Chap. 13). Decreased herbaceous cover reduces soil moisture, water retention and soil cohesion, leaving soil particles exposed to erosion. This increases the area of bare patches that are prone to further run-off and wind erosion (Fan and Cai 2003; Wang et al. 2008).

Infrastructure development, especially road construction, has locally increased the prevalence of steep and bare hillslopes, increasing susceptibility to landslides following intense rainfall events (Fig. 5.8). These processes inhibit prospects for vegetation establishment and recovery, decreasing prospects for water conservation whilst enhancing conditions for soil erosion (Yan et al. 2004). Proactive management of vegetation cover is required to address erosion problems before they become too severe.

Bare slope caused by road construction *Hillslope failures associated with road construction*

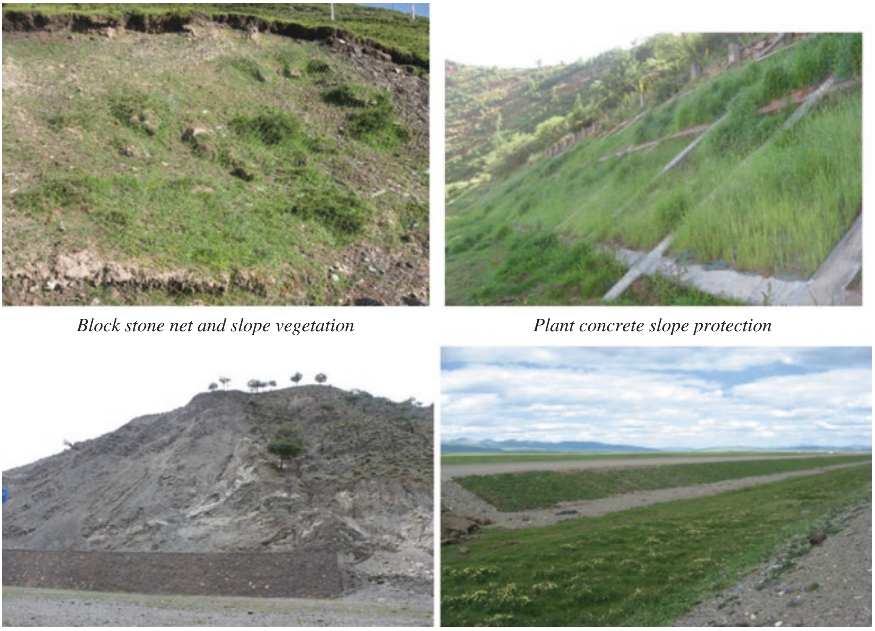
Fig. 5.8 Hillslope instability associated with road construction in the Yellow River Source Zone

5.5 Approaches to Hazard Reduction on Hillslopes of the Yellow River Source Zone

Hillslope processes such as landslides, debris flows and solifluction are key agents of grassland degradation, desertification and soil erosion in the Yellow River Source Zone. Hillslope instability damages infrastructure and property, decreases agricultural productivity and threatens human safety. Protection of grasslands and associated ecosystems is a high-priority issue in this largely undeveloped region.

In many areas, artificial measures need to be taken to mitigate the effects of landslides (Fig. 5.9). Commonly used engineering measures include grouting, anchoring, soil nailing walls, retaining walls and load reduction. Increasingly, these hard engineering measures have been supplemented by a range of soft (environmentally friendly) measures such as hillslope protection by vegetation. Hillslope protection by vegetation is beneficial for both prevention/reduction of geological hazards and the protection and restoration of ecosystems. Often hard and soft measures are used in combination, with deep layer reinforcement using soil nails and rock bolt, and shallow layer reinforcement using vegetation (Hu et al. 2013; Li et al. 2014; Wang and Chen 2003; Zhou and Zhang 2003). Compared with traditional hillslope protection measures, vegetation has the advantages of being cheap, fast and long-lasting, whilst also increasing biodiversity and providing carbon credits (Yang et al. 2007). However, plants struggle to establish and survive on steep, rocky hillslopes, so protective planting is only effective on shallow hillslopes.

Figure 5.10 presents an overview of the influence of vegetation cover upon hillslope stability. Shrubs and herbs that are well adapted to the cold and dry environment of the north-eastern part of Qinghai–Tibet Plateau can significantly enhance soil strength on hillslopes, reducing soil erosion and shallow landslides (Hu et al. 2009, 2013; Li et al. 2006, 2008a, b; Zhang et al. 2006a; Zhu et al. 2008). Hillslope stability is enhanced by vegetation through soil reinforcement by shallow root, anchorage by taproots, lowering of pore water pressure, interception of rainfall, and reduced rain splash erosion. Roots enhance hillslope stability (e.g. Operstein and Frydman 2002; Wu et al. 1988). Plant



Block stone net and slope vegetation *Plant concrete slope protection*

Road protection at the base of a talus slope *Roadbed hillslope protection by vegetation*

Fig. 5.9 Measures to address concerns for hillslope instability associated with road construction in the Yellow River Source Zone

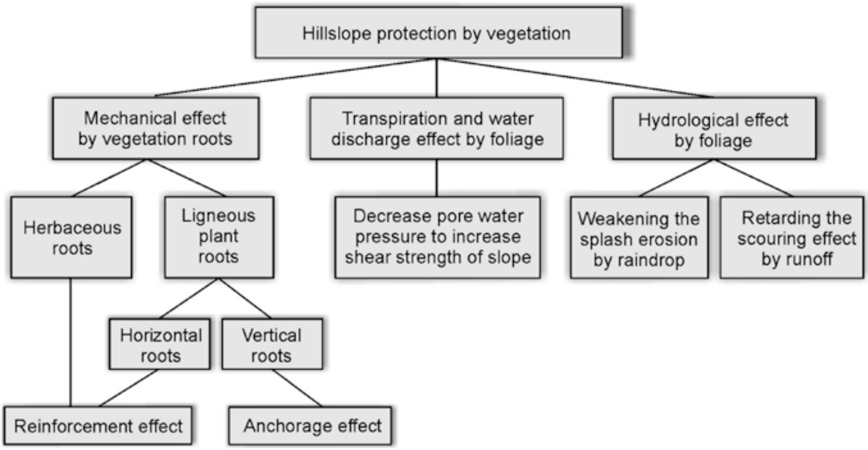


Fig. 5.10 Influence of vegetation in strengthening hillslope stability (modified from Fu 2011; Wang et al. 2005; Zhou and Zhang 2003)

root structure influences the reinforcement effect. Deep tap roots have an anchoring role, whilst horizontal roots have a traction role (Li et al. 2003). Shallow herbaceous roots significantly reinforce and strengthen surface soil layers (Li et al. 2003; Xiao 2004; Zhou et al. 2012). Greater vegetation cover also reduces run-off erosion and the generation of rills and gullies, regulates local climates and increases biodiversity (Gong 2011; Lv et al. 2010; Zhu and Li 2006). Vegetation cover intercepts rainfall and reduces rainsplash, reducing flow and sediment concentration and the effectiveness of sheet flows (Zhu and Li 2006). Increases in effective surface roughness enhance the infiltration rate along roots and improve the water storage capacity of soils by enhancing soil structure (Xiao et al. 2006). Dissipation of flow energy and greater retention of run-off not only decreases surface erosion on hillslopes, but also reduces prospects for incision and the initiation and expansion of rill and gully networks, and their extension into hillslopes. Leaf area index and other indicators of plant coverage have a positive correlation with the amount of rainfall interception and absorption (Hu and Shao 2002; Wen et al. 2005; Fang and Dai 2001). Herbaceous cover also increases the roughness of hillslope surfaces, reducing run-off velocity, changing run-off patterns and reducing soil erosion (Li et al. 1992; Wu et al. 1988).

5.6 Concluding Remarks

Land use change and infrastructure development are key influences upon, and in turn are greatly affected by, geological hazards in the Yellow River Source Zone. Efforts to prevent disasters and protect society on the one hand must be accompanied by ecologically sensitive measures that protect or enhance environmental conditions on the other. These concerns are all the more pressing in areas that have accentuated sensitivity to climate change, such as permafrost zones.

To date, research on hillslope forms, processes and patterns across the Qinghai–Tibet Plateau remains in its infancy, limiting prospects to develop and implement effective and comprehensive management plans and practices.

Vegetation can play a key role in hillslope management in the region. Locally adapted plants can effectively protect and control disasters associated with surface water loss and soil erosion, reducing impacts of shallow landslide and debris flow activity. At the same time, these practical, adaptable and relatively cheap (low cost) measures have environmental benefits and create no pollution. Importantly, these measures must be adapted in locally sensitive ways, harmoniously supporting community livelihoods and well-being across the region.

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References

Brierley, G. J, Li, X., Cullum, C., et al. (2016a). Introduction: Landscape and ecosystem diversity in the Yellow River Source Zone. In: G. J Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 1–34). Berlin: Springer.

Brierley G. J., Yu, G. A., & Li, Z. W. (2016b). Geomorphic diversity of rivers in the Upper Yellow River basin. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 59–78). Berlin: Springer.

Chen, L., Guo, K., Xu, Q., et al. (2007). Wavelet analysis of slope evolvement auspice abnormality identification. *Progress in Geophysics, 22*, 1966–1969.

Cheng, J., Zhang, X. J., Tian, M. Z., et al. (2006). *Quaternary geology and ecological environment in the source area of the Yellow River*. Beijing: Geological Publishing House.

Dai, J. G., Guo, W. G., & Ren, D. F. (2014). The land cover change and the process of climate change in the source region of the Yellow River in late 20th century. *Chinese Journal of Soil Science, 45*, 519–523.

Fan, H. M., & Cai, G. Q. (2003). Review of research progress in freeze-thaw erosion. *Science of Soil and Water Conservation, 1*, 50–55.

Fang, S. Q., & Dai, Q. H. (2001). Soil and water conservation and vegetation. *Jilin Water Resource, 7*, 24–26.

Feng, J. M., Wang, T., & Xie, C. W. (2006). Eco-environmental degradation in the source region of the Yellow River, Northeast Qinghai-Xizang Plateau. *Environmental Monitoring and Assessment, 122*, 125–143.

Fu, Y. Q. (2011). Research the slope vegetation mechanism and engineering. *Hunan Communication Science and Technology, 37*, 49–52.

Gong, B. (2011). The use of slope protection with vegetation and the analysis of its hydrological effect. *Science and Technology Innovation Herald, 26*, 135.

Guo, X., Lai, Z., Sun, Z., et al. (2014). Luminescence dating of Suozi landslide in the Upper Yellow River of the Qinghai-Tibetan Plateau China. *Quaternary International, 349*, 159–166.

Han, J. E., Yu, J., Zhu, D., et al. (2011). The palaeoenvironmental evolution of the Yellow River headwater basin in Qinghai Province since early Pleistocene. *Geological Bulletin of China, 30*, 1941–1949.

Hu, L. J., & Shao, M. A. (2002). Review on water eco-environment in vegetation restoration in Loess Plateau. *Chinese Journal of Applied Ecology, 13*, 1045–1048.

Hu, X. S., Brierley, G. J., Zhu, H. L., et al. (2013). An exploratory analysis of vegetation strategies to reduce shallow landslide activity on loess hillslopes, northeast Qinghai-Tibet Plateau China. *Journal of Mountain Science, 10*, 668–686.

Hu, X. S., Li, G. R., Zhu, H. L., et al. (2009). Research on interaction between vegetation root and soil for slope protection and its mechanical effect in cold and arid environments. *Chinese Journal of Rock Mechanics and Engineering, 28*, 613–620.

Li, G. R., Hu, X. S., Mao, X. Q., et al. (2008a). A study of mechanical effects of shrub roots for slope protection in frigid and arid-semiarid loess area. *Hydrogeology and Engineering Geology, 1*, 94–97.

Li, G. Y., Hu, X. T., Li, X. L., et al. (2014). Mechanical effects of alpine grassland plants in slope protection in Maqin County of the source area of the Yellow River. *Mountain Research, 32*, 550–560.

Li, H. Y., & Pan, D. C. (2009). Research progresses in gully erosion of water and soil erosion region in China. *Journal of Liaoning Technical University (Natural Science), 28*, 214–216.

Li, P., Li, Z. B., Hao, M. D., et al. (2003). Root distribution characteristics of natural grassland on loess plateau. *Research of Soil and Water Conservation, 10*, 144–145.

Li, X. L., Ma, J. Q., & Hu, G. S. (2007). Genetic analysis on huge landslides along the section from Longyang Gorge to Liujia Gorge of the Yellow River. *The Chinese Journal of Geological Hazard and Control, 18*, 28–32.

Li, X. L., Ma, J. Q., Zhang, T. T., et al. (2008b). Analysis of the distribution features of large landslides in Qinghai and the influencing factors. *Urban Geology, 3*, 26–30.

Li, X. L., Perry, G., & Brierley, G. J. (2016). Grassland ecosystems of the Yellow River Source Zone: degradation and restoration. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 137–166). Berlin: Springer.

Li, Y. F., & Wang, Z. Y. (2016). Modeling vegetation-erosion dynamics in the Mugetan Desert, Yellow River Source Zone. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 167–182). Berlin: Springer.

Li, Y. S., Wang, G. X., Wang, Y. B., et al. (2006). Impacts of land cover change on runoff and sediment yields in the head water areas of the Yangtze River and the Yellow River. *China Advances in Water Science, 17*, 617–622.

Li, Y., Xu, X. Q., Zhu, X. M., et al. (1992). Intensifying effect of herb roots on soil anti-scouribility. *Acta Pedologica Sinica, 29*, 302–309.

Liang, S. H., Wan, L., Li, Z. M., et al. (2007). The effect of permafrost on alpine vegetation in the source regions of the Yellow River. *Journal of Glaciology and Geocryology, 29*, 45–52.

Lv, L., Wen, S. Z., Hu, K. F., et al. (2010). The hydro-ecological effects study of the *Liquidambar formosana* plantation in suburban area of Changsha. *Journal of Central South University of Forestry and Technology, 30*, 21–25.

Nicoll, T., Brierley, G. J., & Yu, G. A. (2013). A broad overview of landscape diversity of the Yellow River Source Zone. *Journal of Geographical Sciences, 23*, 793–816.

Operstein, V., & Frydman, S. (2002). The stability of soil slopes stabilised with vegetation. *Proceedings of the ICE-Ground Improvement, 6*, 163–168.

Ouimet, W. B., Whipple, K. X., Royden, L. H., et al. (2007). The influence of large landslides on river incision in a transient landscape: Eastern margin of the Tibetan Plateau (Sichuan, China). *Geological Society of America Bulletin, 119*, 1462–1476.

Pan, B. T. (1994). A study on the geomorphic evolution and development of the upper reaches of the Yellow River in guide basin. *Arid Land Geography, 17*, 43–50.

Pan, J. H., & Liu, J. L. (2005). Land use and landscape pattern change in source region of the Yellow River. *Bulletin of Soil and Water Conservation, 25*, 29–32.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) headwaters. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 275–330). Berlin: Springer.

Wang, G. X., Ding, Y. J., Wang, J., et al. (2004). Land ecological changes and evolutional pattern in the source regions of Yangtze and the Yellow River in recent 15 years. *Acta Geographica Sinica, 59*, 163–173.

Wang, J. T., Yun, X. J., Su, H. T., et al. (2008). Technologies to monitor the rodent in the degraded grassland in “Three-River Headwaters” region. *Pratacultural Science, 25*, 110–112.

Wang, L. Q., & Chen, S. H. (2003). Study on the principle of dividing root system type of lawn plant. *Journal of Inner Mongolia Agricultural University, 24*, 11–14.

Wang, W. S., Yang, X. H., & Xie, Y. L. (2005). Mechanism of biotechnical protection for highway slope. *Journal of Chang’an University (Natural Science Edition), 4*, 26–30.

Wang, Y., Li, Y. H., & Sun, X. Y. (2013). Eco-environment changes and countermeasures in the Yellow River source region. *Journal of Arid Meteorology, 31*, 550–557.

Wen, Z. M., Jiao, F., Liu, B. Y., et al. (2005). Natural vegetation restoration and soil nutrient dynamics of abandoned farmlands in forest-steppe zone on Loess Plateau. *Chinese Journal of Applied Ecology, 16*, 2025–2029.

Wu, T. H., Beal, P. E., & Lan, C. (1988). In-situ shear test of soil-root systems. *Journal of Geotechnical Engineering, 114*, 1376–1394.

Xiao, D. S. (2004). Quantify the theoretical slope vegetation increases the shear strength. *Sichuan Architectural, 24*, 63–64.

Xiao, J. Q., Zhang, Z. Q., & Wu, J. (2006). Preliminary study of the influence of vegetation in natural forested land runoff plots slope on ground runoff. *Research of Soil and Water Conservation, 13*, 227–231.

Xu, J. B., Song, L. S., Zhao, Z. Z., et al. (2012). Monitoring grassland degradation dynamically at Maduo County in source region of Yellow River in past 15 years based on remote sensing. *Arid Land Geography, 35*, 615–622.

Xu, Q., & Huang, R. Q. (1997). Discussion on self-organized characters in the course of slope development. *The Chinese Journal of Geological Hazard and Control, 8*, 8–12.

Yan, M. S., Xu, F., Zhang, W., et al. (2004). Soil erosion analysis in headstream basin of Yellow River. *Bulletin of Soil and Water Conservation, 24*, 75–78.

Yang, J. P., Ding, Y. J., & Chen, R. S. (2005). NDVI reflection alpine vegetation change in the source regions of the Yangtze and Yellow River. *Acta Geographica Sinica, 60*, 467–478.

Yang, K. Y., & Tong, H. K. (2010). Geological characteristics of freeze-thaw process and eco-environmental geology of the Yellow River source region. *Gansu Geology, 19*, 64–66.

Yang, Y. H., Wang, C. H., Liu, S. Z., et al. (2007). Experimental research on improving shear strength of soil in surface landslide by root system of different vegetation type. *Research of Soil and Water Conservation, 14*, 233–235.

You, L. Y., & Jing, K. (1980). A preliminary study of the landforms in Yellow River source area. *Yellow River, 5*, 59–63.

Zeng, Y. N., & Feng, Z. D. (2009). Analysis of cause mechanism of desertification in head water area of Yellow River. *Journal of Natural Disasters, 18*, 45–52.

Zeng, Y. N., Feng, Z. D., Cao, G. C., et al. (2004). The soil organic carbon storage and its spatial distribution of alpine grassland in the source region of the Yellow River. *Acta Geographica Sinica, 59*, 497–504.

Zhang, C. S., Zhang, Y. C., & Ma, Y. S. (2003). Regional dangerous on the geological hazards of collapse, landslide and debris flow in the upper reaches of the Yellow River. *Journal of Geomechanics, 9*, 211–218.

Zhang, Y. L., Liu, L. S., Bai, W. Q., et al. (2006a). Grassland degradation in the source region of the Yellow River. *Acta Geographica Sinica, 61*, 3–14.

Zhang, X. G., Wang, S. J., & Zhang, Z. Y. (2000). *Chinese engineering geology* (pp. 125–131). Beijing: Science Press.

Zhang, S. Q., Li, Y. G., Shang, X. G., et al. (2006b). Effects of neotectonic movement in the source area of the Yellow River, China on eco-environmental deterioration. *Geological Bulletin of China, 25*, 213–220.

Zhao, Z. M., & Liu, B. C. (2003). Relation between the formation of the Yellow River valley landforms from Gonghe, Qinghai to Lanzhou, Gansu and the uplifting in northeast part of Qinghai-Xizang plateau. *Northwestern Geology, 36*, 1–11.

Zheng, B. X., & Wang, S. M. (1996). A study on the paleo-glaciation and paleoenvironment in the source area of the Yellow River. *Journal of Glaciology and Geocryology, 18*, 210–218.

Zhou, D. P., & Zhang, J. Y. (2003). *The engineering technique for slope protection by vegetation*. Beijing: China Communications Press.

Zhou, Y. Y., Chen, J. P., & Wang, X. M. (2012). Progress of study on soil reinforcement mechanisms by root and its expectation. *Ecology and Environmental Sciences, 21*, 1171–1177.

Zhu, H. L., Hu, X. S., Mao, X. Q., et al. (2008). Study on mechanical characteristics of shrub roots for slope protection in loess area of Tibetan plateau. *Chinese Journal of Rock Mechanics and Engineering, 27*, 3445–3452.

Zhu, J. X., & Li, X. F. (2006). Discussion on the hydrology effect of the slope protection by vegetation. *West-China Exploration Engineering, 124*, 274–276.

Chapter 6
Understanding Alpine Meadow Ecosystems

Youming Qiao and Zhonghua Duan

Abstract This chapter introduces the alpine meadow and its distribution in the headwater region of the Yellow River, including subtypes of alpine meadow, species composition and productivity, soil types and their properties. Various views on causes of grassland degradation are summarized. The shortcomings of current criteria for evaluating alpine meadow ecosystem health are outlined. Underlying causes, processes and mechanism of alpine meadow degradation are examined. Protection or restoration strategies of degraded grassland are discussed. Many factors influence alpine meadow degradation in the Yellow River Source Zone. Vegetation degradation caused by overgrazing may result in soil degradation and soil erosion, impacting upon hydrological processes and carbon sequestration. Fencing and resting pastures are key management strategies in preventing overgrazing. Reseeding degraded meadows may increase productivity and boost a higher above- and below-ground biomass input, prospectively enhancing long-term soil carbon storage. However, such measures may cause severe soil organic carbon and nitrogen loss.

Keywords *Kobresia* meadow · Degradation · Sheet erosion · Permafrost · Overgrazing · Anthropogenic activity · Rodents · Government policy · Microbial activity · Sediments · Run-off · Carbon pool · Carbon sequestration · Restoration · Rehabilitation · Reseeding

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6.1 Alpine Meadow and its Distribution

Alpine meadow is a major vegetation component of the Qinghai–Tibet Plateau (Zhou et al. 1987). It occupies about 3.05 million ha, accounting for 35 % of total vegetation cover in the headwater region of the Yellow River (Li et al. 2013; Wang et al. 1999). Alpine meadow vegetation communities are dominated by cold-tolerant plant species with sedges of *Kobresia* family, and the dominant plants are *Kobresia pygmaea*, *K. humilis*, *K. capillifolia*, *K. tibetica*, *K.prattii* and *K. kansuensis*. Alpine plants such as *Polygonum viviparum*, *P. sphaerostachyum* and Gentiana, Saxifrage and Anemone are common companion species (Zhou et al. 2001). Alpine meadow has a short growing period, a simple plant community structure and low biomass production. It is distributed over a wide range of altitudes and locations, with quite distinct characteristics relative to intrazonal meadows in low-lying areas of China (Zhou et al. 1987). Alpine meadow is used exclusively for livestock grazing chiefly by domestic animals such as yak (*Bos grunniens*) and Tibetan sheep (*Ovis aries*). This natural resource supports many Tibetan herders who have a long tradition of semi-nomadic pastoralism. Together with alpine shrubland, alpine meadow is the favoured habitat for white-lipped deer (*Cervus albirostris*), Tibetan wild ass (*Equus kiang*), Tibetan gazelle (*Procapra picticaudata*) and blue sheep (*Pseudois nayaur*) (Li and Li 2002).

Uplift of the Qinghai–Tibet Plateau and headward erosion of rivers are the primary determinants of landscape form and process relationships in the source region of the Yellow River (Brierley et al. 2016, Chap. 1). Plant communities are subjected to a severe plateau climate, with strong solar radiation and cold and dry conditions (McGregor 2016, Chap. 2). The development and distribution of alpine meadow, as with other zonal vegetation types, is subject to geographical constraints. It is commonly associated with large mountain ranges of steep valleys and gorges interspersed with relatively level and wide intermontane grassland areas in the Yellow River Source Zone. Bioclimatic conditions are influenced largely by the south-western warm and humid air of the East Asia summer monsoon (also known as the Indian monsoon; Zhou et al. 1987, 2001). Here, westerly winds reinforce the continental climate, with the South Asian monsoon being a source of summer precipitation (Fig. 6.1; Yao et al. 2013). The annual average temperature is below 0 ℃, with the coldest month (January) being lower than −10 ℃. Annual rainfall varies from 400 to 600 mm, occurring mostly in the growing period from June to September, with a decreasing trend from south-east to north-west. Winter and spring are characteristically cold, dry and windy (Zhao et al. 2009).

Alpine meadow soils are thin (20–50 cm), have a coarse texture and high organic content and are rich in nitrogen, phosphorus and potassium (though much of the mineral content is not available in a readily accessible state). Topographically induced variability atop hills, ridges and hillsides at elevations around 4000 m creates several subtypes of alpine meadow soil, including mountain meadow soil, grey cinnamon soil, chestnut soil, marsh soil, peat soil and aeolian sandy soil (ZOQAR 1997). Nutrient levels are much lower in aeolian sandy soils. Mountain meadow

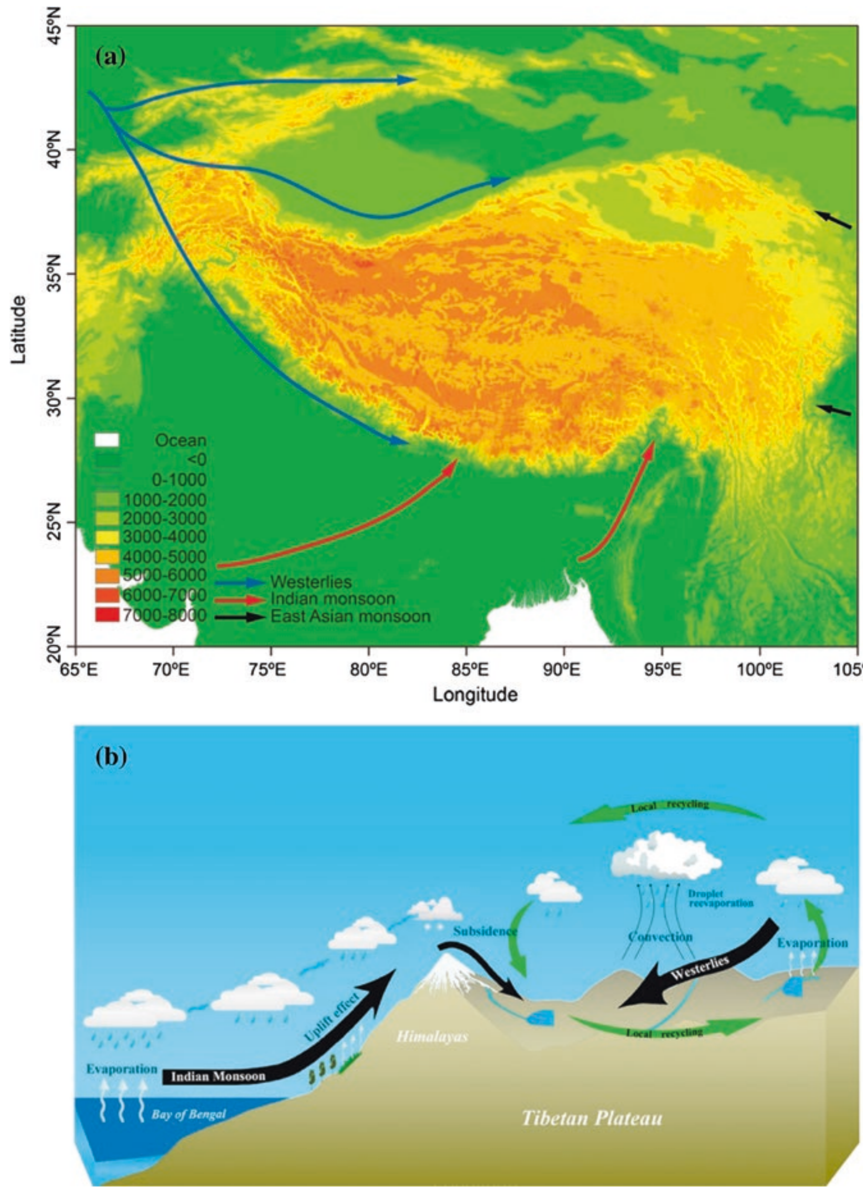


Fig. 6.1 Influence of topography upon the climate of the Qinghai–Tibet Plateau (modified from Yao et al. 2013)

soil is distributed in the shrubland zone. Grey cinnamon soil is distributed on valley hillslopes below 4300 m. Chestnut soil is located mainly on the south-facing hillslopes of valleys, terraces and alluvial fans. Marsh soil can be found on riversides, floodplains, low-lying areas of river junctions and flat areas of foothills.

Aeolian sandy soil is found only in some areas such as Maduo and Maqin counties. Peat soil is locally distributed and dispersed. Because of poor drainage, both marsh soil and peat soil in low-lying land have a sporadic distribution. The general characteristics of these soils are still in an early developmental stage, with little microbial activity, weak chemical reactions and a light bulk density (Qin 2014).

The intertwined grass roots form a densely compacted, flexible matlike turf layer that has a light or sandy loam texture. Gravel content in the soil profile varies from 5 to 30 %, increasing with depth. The soil pH is 6–7.5, increasing with depth. About 80–90 % of roots are concentrated in the upper 20 cm of alpine meadow soils. Due to the cold climate conditions, microbial decomposition rate is rather low, and a large number of partially decomposed plant litter and dead roots remain in the soil (ZOQAR 1997). This, together with moderate soil moisture and temperature in the growing season, creates favourable conditions for micro-organisms in the turf layer to thrive (Zhou et al. 1987). Bacteria are the dominant micro-organisms in alpine meadow soil (Jiang 2001). Soil bacteria, fungi and actinomycetes in alpine meadow ecosystem change with seasons. Bacteria and fungi peak in August, but actinomycetes peak in July.

The development and formation of alpine meadow soil is a complex physical, chemical, biological and geological process, affected by climate, topography and geomorphology, soil parent material, altitude, hydrology, biology and the influence of human activities. Topography does not affect soil evolution directly, but it indirectly affects soil development and evolution. Physical, chemical and biological processes are affected by climate factors such as precipitation, temperature, sunshine, wind and biological factors. All of these factors influence the redistribution of hydrothermal conditions, which in turn affects soil materials and energy migration and transformation, generating vertical and horizontal differentiations of soil types. Because the Qinghai–Tibet Plateau is gently inclined from north-west to south-east, latitude and elevation jointly define a gradient of cooling temperature from south-east to north-west in the south of the Yellow River headwater zone. Latitude affects temperature by controlling the angle and intensity of solar radiation. Elevation affects temperature by controlling air pressure and hence the heat capacity of the air.

As is typical throughout much of the Eastern Himalayan alpine region, aspect determines the physiognomy of vegetation. As south-facing hillslopes are often snow-free and exposed to cold wind during winter, they are able to support sedge meadow vegetation. Species richness and plant height gradually become low, and physiognomy tends to become more monotonic towards the north-west (Zhao et al. 2009).

There are three major subtypes of alpine meadows in the Yellow River headwater zone, namely steppe *Kobresia* meadow, typical *Kobresia* meadow and marsh *Kobresia* meadow (Table 6.1). Typical formations are *K. pygmaea*, *K. humilis* and *K. schoenoides*, respectively. Each has its own community characteristics, species composition and height, species mixture and richness, soil property, yield and vegetation cover. The distribution of different formations is governed by geographical location, elevation, precipitation, temperature, soil moisture and hillslope aspect.

With respect to the general biogeography of the region, alpine meadows exhibit local zonation of plant communities on mountain hillslopes (see Tane et al. 2016,

Table 6.1 Distribution and community characteristics of *Kobresia* meadow

Formation	Distribution	Community
Kobresia pygmaea	Elevation 3200–4700 m	Cover 75–95 %
		Species number 25–40 m^{-2}
	Sunny slope, rounded hill, upper part of piedmont, broad valley terraces, less soil moisture	Sward height *Kobresia* 3–5 cm, graminoids and forbs 15–25 cm
		Above-ground biomass 221–368 g m^{-2}
Kobresia humilis	Elevation 3200–4500 m	Cover 70–85 %
	Semi-shady slope, open flat terrace of river, piedmont, well drained	Species number 20–30 m^{-2}
		Sward height *Kobresia* 5–8 cm, graminoids and forbs: 15–25 cm
		Above-ground biomass 294–418 g m^{-2}
Kobresia schoenoides	Elevation 3200–4800 m	Cover 60–90 %
	Riverside, lake shore, poorly drained, intermontane basin, dishlike depressions, saddle part of a mountain, overflow area of piedmont	Species number 10–20 m^{-2}
		Sward height *Kobresia* 20–30 cm
		Above-ground biomass 365–518 g m^{-2}

Chap. 13). Shrubs dominate the lower hillslopes, especially north-facing ones. *Kobresia* meadows occur at higher and drier locations, along with certain cushion plants (*Arenaria musciformis* and *Androsace tapete*). *Kobresia humilis* and various grasses and forbs (depending on grazing density) are widely distributed along valley floors. The shrub *Potentilla fruticosa*, along with shrubby *Salix* species, are located on northern hillslopes. The marsh vegetation consists primarily of *Kobresia schoenoides* and *Pedicularis longiflora*. *Kobresia pygmaea* meadows are mainly distributed on upper hillslopes. Soil types correspond to different formations of alpine meadow, transitioning down-profile from alpine meadow soil through mountain meadow soil to chestnut soil and finally marsh soils on the valley floor (Fig. 6.2).

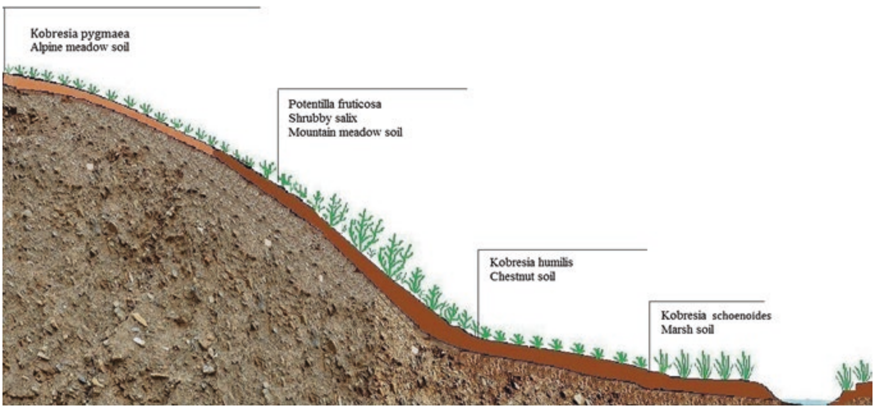


Fig. 6.2 Altitudinal and horizontal distribution of *Kobresia* meadow on a north-facing slope

6.2 Degradation of Alpine Meadows

Degradation of alpine meadows in the headwater region of the Yellow River has been reported since the early 1980s (Peng et al. 1980). Although evidence for the severity of degradation and its underlying causes remains contentious (Harris 2010), it is widely believed that overgrazing since the 1970s has triggered significant degradation of alpine meadows (Li and Li 2002; Liu et al. 1999; Shang and Long 2005). Most researchers have reported that overgrazing has triggered alpine meadow degradation and destruction by rodents, while wind and water erosion has accelerated the degradation process. However, the underlying causes of degradation vary across the vast area of the plateau, with no consensus on the exact causes and ecological processes of alpine meadow degradation (Li et al. 2013, 2014). Some scholars emphasize the importance of human activities in the environment (Jing et al. 2005, 2006; Shang and Long 2005; Wang 2003); some stress the impact of climatic factors on the environment (Wu 2003; Yan et al. 2004; Rowntree et al. 2004), while others focus on the biophysical (geomorphic and pedogenic) influences of alpine meadow degradation (see Li et al. 2016, Chap. 7; Tane et al. 2016, Chap. 13).

The various views on degradation causes can be summarized as follows:

(1) Freeze–thaw weathering and soil removal by sheet erosion, landsliding or solifluction (Huo 1985). This promotes the emergence of bare ground on the upper slope under the action of gravity or other external forces (Fig. 6.3). Permafrost melt and erosion are especially prominent on steep hillslopes in the south of the headwater region. In this instance, ‘degradation’ is characteristic of the system, independent of human activity.
(2) Overgrazing. The formation of degraded alpine meadow is due mainly to overgrazing, which leads to decreased plant height, reduced coverage and limited opportunity for plant regeneration. Such changes cause forages to be replaced by unpalatable forbs and the emergence of bare patches over an

Fig. 6.3 Sheet erosion on the Qinghai–Tibet Plateau

Fig. 6.4 Degradation of alpine meadow caused by overgrazing. Denuded patches are evident. Some areas of forage have been replaced by unpalatable forbs

extended period (Fig. 6.4). Overgrazing also indirectly creates conditions for some small mammals to invade (Liu et al. 1999; Wang and Wang 2001).

(3) Climate warming and aridity. Drought causes soil degradation, worsens hydrological conditions, and triggers degradation of vegetation. Climate-induced changes to the hydrological regime, including snowmelt and retreating glaciers, have altered the permafrost boundary and groundwater supply to the aquifer system. The lowered regional water table causes vegetation degradation, which in turn decreases water conservation, resulting in a vicious cycle of worsening conditions (Zhang et al. 2003). Lower permafrost layers also promote favourable conditions for small mammals to burrow. Destruction of vegetation is further intensified by wind and water erosion driving vegetation recession towards completely bare ground.

(4) Joint drivers. Alpine meadow degradation results from multiple ecological factors. Global warming, cryoturbation, water and wind erosion, small mammal attack and long-term overgrazing have all contributed to alpine meadow degradation (Li et al. 2013; Wang and Wang 2001).

Attempts to quantify the extent of alpine meadow degradation have yielded conflicting results. Satellite imagery in southern Qinghai failed to support range degradation during the 1980s and 1990s (Perryman 2001). However, after studying variations in several typical alpine rangeland ecosystems in the source regions of the Yangtze and Yellow rivers based on 1986 and 2000 Landsat TM data, Qian et al. (2006) concluded that vegetation cover of alpine meadow decreased by 5.15 %. Through analysis of spatial and temporal calibrated NDVI data derived from NOAA/AVHRR images, Yang et al. (2005) noted no significant trend in alpine vegetation cover between 1982 and 2001 in the source regions of the Yangtze and Yellow rivers, although severe degradation continued in certain locations around Zhaling and Eling lakes, at the northern foot of the Bayan Har Mountains. A comparative analysis of satellite images in 1985 and 2000 and field investigation in the Yellow River source region by Zhang et al. (2006) found that the degradation rate on south-facing hillslopes is higher than that on north-facing slopes. Affected by population density, alpine meadow degradation rate is inversely proportional to altitude and distance to settled areas. The closer the distance to settlements, the higher the degradation rate, especially when the distance is less than 12 km.

Ecosystem degradation is a response to external interferences through internal attributes and their interactions. Hence, system attributes and their ability to withstand disturbance are key influences upon sensitivity/resilience. Intrinsic factors often result in progressive succession, inducing changes from simple to more complex communities. In contrast, external forces may induce retrogressive succession towards a less mature community. For example, if alpine meadow is severely overgrazed by yak or sheep, the most palatable species will disappear first. As overgrazing continues, the grass cover is reduced to create bare ground where weeds may become established, forming the initial stage of succession. The alpine meadow ecosystem has a special and unique structure and function. Its resilience defines its capacity to tolerate disturbance. However, its inherent vulnerability means that it is difficult to be restored to its original state naturally once it evolves to another state. The special geographical environment of the Yellow River source region determines the vulnerability of the region's ecosystems, and prospects for ecosystem recovery are minimal once innate attributes and values are destroyed (Shang and Long 2005; Wang and Wang 2001).

6.3 Criteria to Evaluate Alpine Meadow Ecosystem Health

The best way to assess whether a meadow is degraded or not is to compare the range land conditions experienced in the same area at different periods. Unfortunately, lack of long-term monitoring data makes this kind of assessment impossible. As noted by Harris (2010), some researchers have concluded that alpine meadow has degraded based on their subjective reference without carrying out any long-term comparative research. Others have proposed criteria for evaluating degradation severity of alpine meadows, differentiating between non-degraded, lightly, moderately or heavily degraded conditions (Table 6.2). This grading system may yield subjective and non-informative results as it presents only a single quantitative measure (cf., Li et al. 2014).

Soil degradation may impair the function of soil organisms and thus result in further problems. During degradation, changes occur to soil moisture distribution and content, and the bulk density of topsoil. Microbial activity provides an indicator of the status of alpine meadow. Since the soil microbial community is essential to cycling of nutrients and decomposition of materials, hindrance of microbial activities may have serious ecological implications. Bacterial groups

Table 6.2 Criteria for the evaluation of alpine meadow health (*Source*: Ma et al. 2008)

Degradation level	Cover (%)	Palatable forage (%)	Indicative degraded cover (%)	Soil organic matter of top 10 cm (%)	Ratio of roots to soil of top 10 cm
I Virgin vegetation	>90	>75	<10	>15	<20
II Light	75–90	55–75	10–30	10–15	20–35
III Fair	55–75	35–55	30–50	7–10	35–50
IV Heavy	45–55	20–35	50–75	5–7	50–75
V Extreme	<45	<20	>75	<5	>75

are influenced by soil environmental factors. The total number of soil bacteria, fungi and actinomycetes of non-degraded alpine meadows is greater than that of degraded meadows. The number of nitrifying bacteria, aerobic nitrogen-fixing bacteria, anaerobic nitrogen-fixing bacteria and aerobic cellulolytic bacteria decreases with degradation, while the quantity of denitrifying bacteria and anaerobic cellulolytic bacteria increases with degradation (Shang et al. 2005, 2006). Degradative forces such as erosion that result in loss of organic matter may also cause long-term loss of microbial activities (Qiao and Wang 2010).

Soil physicochemical properties are also indicative of ecosystem health. Vegetation degradation increases soil bulk density in alpine meadow, especially in the upper 10 cm. For example, Wang et al. (2007) showed that degraded soils were coarser-grained, with a reduction in soil organic matter in the surface layer of meadow soil from 179.58 to 49.48 g kg^{-1} and a 30 % loss in the hydrolysable nitrogen content. Soil properties of alpine meadow change with soil depth. While soil moisture decreases gradually with depth, soil bulk density increases. Soil organic carbon and total nitrogen content decrease markedly, with profound accumulation in upper horizons. Soil moisture and bulk density are associated with the level of degradation. The soil nitrogen stock of alpine meadows shows patterns of soil organic content.

Others have found that total coverage and above-ground phytomass of alpine meadow decreased with the degree of degradation. Compared with moderately and lightly degraded meadow, the vegetation cover of heavily degraded meadow decreased by 2.05 and 6.3 %, respectively, and the above-ground phytomass decreased by 55.33 and 73.38 %, respectively (Zhao et al. 2011; Qiao et al. 2013). Impacts of grazing on plant functionality vary markedly. Species richness, diversity and evenness are important quantitative indices that reflect community structure and physioecological characteristics of rangelands (West 1993). Species diversity can be used as an indicator of ecological gradients and environmental quality of an ecosystem (Wang and Wang 2001). Species richness, diversity and evenness indices tend to be greater in moderately degraded meadows than in heavily or lightly degraded meadows or original *Kobresia* meadows (Wang et al. 2006; Zhou et al. 2004b). Standing biomass declines with increasing grazing intensity (Wang et al. 1995). Trends in species composition are also associated with stocking rates, with overgrazing resulting in a notable reduction in the relative abundance of palatable grasses and a corresponding increase in forbs and poisonous plants (Han et al. 1991; Zhao et al. 1988; Zhou et al. 1995, 2001). Species diversity tends to rise rapidly at first as successive invasions occur, but declines again with the elimination of pioneer species by the climax community. Studies have shown that short-rhizome *Kobresia* and dense bunch grasses such as *K. pygmea*, *K. humilis*, *Stipa aliena* and *Festuca ovina* are dominant species on lightly degraded alpine meadows, associated partly with forbs such as *Gentiana straminea*, *Saussurea superb* and *Potentilla bifurca*. On moderately degraded meadow, sparse clump grasses and short-rhizome sedges are dominant species, such as *Elymus nutans*, *Poa alpigena* and *Kobresia pygmea*, and forbs, such as the *Saussurea superb*, *Gentiana Lanrencei Var.farveri* and *Potentilla nivea*, are main companion species. Stolon plants such as *Potentilla anserine* and *Lagotis brachystachys* are the dominant species of plants in heavily degraded meadows, associated with *Lancea tibetica*, *Leontopodium nanum*, *Glaux maritima*, *Ajania tenuifolia*, *Polygonum sibiricum* and *Oxytropis sp*., etc., while grasses and sedges occur occasionally (Ma 2006; Qiao et al. 2009). However, over a longer period, grazing intensity exerts little effect on overall vegetation cover or species richness, even though palatable grasses are progressively replaced by forbs under heavy grazing (Zhou et al. 2004a, b, 2005).

6.4 Process and Mechanism of Alpine Meadow Degradation

Interconnected biological, physical and chemical processes fashion the complex structure and function of ecosystems. Biological processes begin with ecosystem photosynthesis of green plants. The normal biological processes of ecosystems include primary production, organic matter decomposition and accumulation. Physical processes mainly refer to hydrological processes which regulate the interactions between vegetation, nutrient and carbon fluxes, affecting the development and evolution of the meadow and determining the nature and specific ecological system response (Hollis and Thompson 1998). Chemical processes refer to the element cycle involved in ecosystem behaviour and evolution. Integrated processes within the system include carbon, nitrogen, minerals and trace element cycles. Degradation of meadow ecosystem reflects deviations in biological, physical and chemical processes and their interactions (Qiao and Wang 2010).

Many factors influence alpine meadow degradation in the Yellow River Source Zone. The intensity, frequency and duration of each factor, as well as their different combinations, determine the extent of degradation. Vegetation degradation is closely tied to soil degradation (Wang et al. 2005).

During the past 40 years, enhanced global warming has brought about marked increases in temperature in the Yellow River source region, but precipitation trends have experienced different changes with significant spatial variability (Qiao and

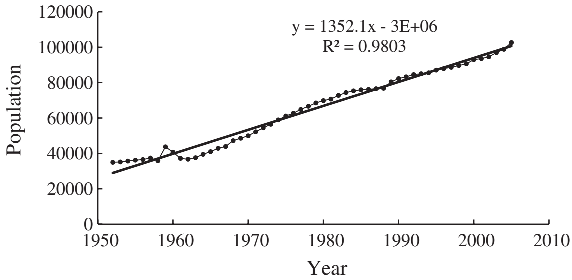
Wang 2010). Degradation of permafrost reflects increases in ground temperature, increasing the thickness of the active layer. Overall, alpine ecosystems showed continued degradation, with reduced vegetation coverage. The relative proportion of alpine meadows, steppes, and marshes of a dense coverage (>70 %) and high biological productivity has decreased, while areas of low coverage grassland have expanded significantly (Qin 2014). Alpine meadow degradation has altered the habitat of rodents, triggering zokor and pika outbreaks in some areas. Environmental degradation and expansion of human activities have led to deterioration of wildlife habitat and resulted in an increase in endangered species and loss of biodiversity (Qiao and Wang 2010).

Climate change does not have a fixed impact on meadow vegetation. Only when elevated temperature and increased precipitation occur simultaneously, is climate change conducive to plant growth. The overall impact of climate change on alpine meadow vegetation is long-lasting, gradual and geographically extensive. In the absence of excessive grazing, grassland degradation does not occur over a massive scale in the short term.

Xu et al. (2009) found that the degree of human effect on run-off volume has been increasing since 1983, with change in run-off volume primarily affected by natural factors in the east of the Sanjiangyuan, but by anthropogenic ones to the west of the source area of three rivers. Although climate change is the main cause of grassland ecological degradation in the headwater area of the Sanjiangyuan, local, seasonal and high-intensity grazing activities are important human factors of degradation. Overall, grazing intensity exerts a more profound impact in the Yellow River source region than in the Yangtze River headwater region, and the influence of climate change on grassland degradation in the source region of the Yellow River is less significant than that of the Yangtze River (Qin 2014). In the headwater region of the Yellow River, roughly one-third of degraded meadows occur in areas of winter pasture near lakes, rivers, floodplains, foothills and settlements. On the contrary, alpine meadow used as summer pastures remains in a relatively good state because of lower utilization. As degradation of alpine meadow on summer pasture is limited to only communal grazing land, its degradation is isolated and localized.

Population pressure is another important influence upon the degradation of alpine meadows. Population growth not only exacerbates demand for food but also deepens the conflict between resources and the environment. A larger population requires more land resources and energy to sustain. From 1952 to 2005, the population in four counties (Maqin, Maduo, Gande and Dari) in the Yellow River source region increased by 70,000 (Qiao and Wang 2010). A similar trend of population growth can be observed over the entire source region of the Yellow River (Fig. 6.5; see Ran et al. 2016, Chap. 14). The impact of population growth upon grassland degradation has been exacerbated by expansion and improvement of transport facilities. In addition, illegal mining, firewood harvesting and medicinal herb collection have all been identified as drivers of land degradation. For example, illegal mining devastated 213,300 ha of rangeland in Maduo during the 1980s (Dong et al. 2002; Feng et al. 2004). Strong wind aggravated land degradation and

Fig. 6.5 Trend of population in the source region of the Yellow River

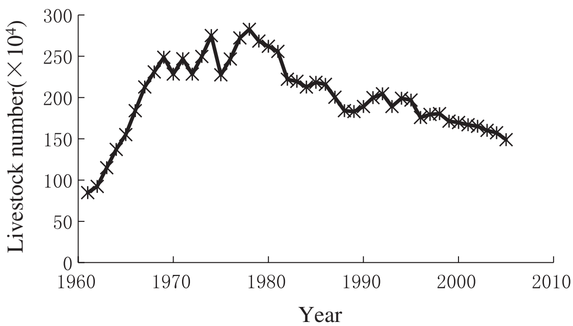


was blamed for the expansion of desertified areas (Wu 2003). Collection of medicinal herbs and chopping of shrubs for firewood by a growing population brought about additional pressures on the environment and the natural resources (Jing and Xu 2005). These activities have broadened the spatial range of degradation and accelerated the rate of water and wind erosion.

The trend in livestock size is characterized by periods of sharp increase, followed by wide fluctuations and slow decrease (Fig. 6.6). Because the stocking rate in the 1960s was historically low, the surplus carrying capacity sustained continuous growth for a period of 10 years. The subsequent period of fluctuation lasted for another decade, as livestock numbers reached the carrying capacity of the alpine meadow (Qiao and Wang 2010). The fluctuation over the last decade or so was caused either by forage shortage or by natural disasters (Fu 2004).

Encouraged or influenced by governmental policies and traditional ideas, the livestock number increased significantly from the 1960s to the 1970s in the Yellow River source region. Both government and herders were insufficiently aware of the potential problems of overgrazing and paid little attention to protect the ecological environment. This led to irrational use of pasture. In the early 1980s, government implemented pasture tenure policies in south Qinghai and enacted settlement and pasture fencing policies in the 1990s. To some extent, these policies and measures improved the living standard of herders and their ability to withstand natural disasters. However, they also forced livestock production to shift to smaller and scattered grazing areas within a shorter range. Alpine meadows in the vicinity of

Fig. 6.6 Variation of total livestock number in the source region of the Yellow River 1960–2010



settlements and water sources were grazed more frequently and intensively. Within fenced areas, pastures were well protected, while communal pasture and passages between fences suffered overgrazing and trampling, forming gateways of winter pasture degradation (Qiao and Wang 2010).

Many factors influence the degradation of alpine meadows at a local scale. These factors are interlinked in a complex manner. As natural factors such as landform and soil change slowly, their effects on alpine meadow degradation are not significant in the short term. In contrast, climate and hydrological factors fluctuate more frequently over a short time frame, exerting a more profound impact on degradation of alpine meadow. The influence of anthropogenic factors such as social systems, policies and traditional ideas is difficult to quantify. Besides, there is a delay in response to changed anthropogenic variables. For instance, the higher livestock number (i.e. overstocking) during the late 1960s and 1970s is still partly responsible for present-day degradation (possibly related to soil erosion factors). Degradation of alpine meadows can be viewed as two stages, with the first stage being passive and the second stage active. The first-stage degradation is caused mainly by human activities, while the second stage of degradation is accelerated by natural factors (Cao et al. 2004; Qiao and Wang 2010).

External disturbances to alpine meadows can disrupt the spatial distribution of vegetation and cause a substantial loss of water by increasing hydrological connectivity, impacting upon ecosystem functions. Small reductions in the fractional cover of vegetation near a particular threshold can cause abrupt changes in ecosystem function, driven by large nonlinear increases in the length of the connected flow paths.

These nonlinear changes are especially sensitive to the type of disturbance, suggesting that the amount of alterations that an ecosystem can absorb and still remain functional depends largely on disturbance type. In fact, selective thinning of the vegetation patches from their edges can cause a higher impact on hydrological connectivity than spatially random disturbances. Surface connectivity patterns are practical indicators of landscape health.

Sediment production is closely related to run-off (Blackburn et al. 1986). The amount of river sediment increases with increasing stocking rates on continuous grazing pastures (Hanson et al. 1970). Vegetation degradation caused by overgrazing may result in soil degradation and soil erosion, impacting upon hydrological processes. Process–form linkages in channels and floodplains are influenced by flow conditions and their relations to riparian vegetation cover (Dunford 1949; Johnston 1962). Indeed, riparian vegetation slows down run-off, reduces erosion and buffers/filters sediment and nutrient fluxes. Vegetation coverage and run-off duration are positively correlated with alpine meadow, with the run-off duration extended with increasing vegetation cover. Overgrazing accelerates grassland degradation and soil erosion, prompting channels to adjust because of excess sediment load. Hence, increasing the near-surface vegetation coverage is an important measure to reduce soil erosion and run-off (Cheng 2007; Hu et al. 2016, Chap. 5).

6.5 Conclusion: Protection/Restoration Strategies of Degraded Grassland

Healthy and robust rangeland plants are essential for producing forage for grazing animals. Enclosure of rangeland from grazing is a key management strategy in preventing overgrazing. As well, this practice is also conducive to the sustainable use of rangeland. Plants are always affected by grazing. Removing leaves and other herbage reduces not only plant vigour but also root growth. With less roots, plants are not able to fully access soil moisture and nutrients as non-grazed plants do. This reduces their ability to compete with other non-forage plants. Resting pastures before grazing can guarantee that forage plants will be vigorous, high yielding and stable in their food production.

Degradation of alpine meadow is especially pronounced in the vicinity of settlements, particularly on winter pasture. Since overgrazing and trampling are the leading causes of degeneration, reducing livestock number, stocking rate and intensity may be an effective way to protect alpine meadow pasture from degradation. It is well known that overgrazing is a major source of stress to plants. If not given the opportunity to regenerate sufficiently as a result of overgrazing, desirable forage plants will be gradually weakened and eventually die if the external disturbance persists over an extended period.

Currently, different measures have been undertaken to rehabilitate degraded meadows. Fencing, controlling small mammal population and lowering grazing intensity have been adopted to recover lightly degraded meadows. For moderately degraded meadows, fencing plus reseeding and fertilizing improves pasture of intact or slightly damaged vegetation. This strategy is suitable for alpine meadows located on flat and gentle slopes of piedmont areas. Planting mix-seeded perennial grasses to rehabilitate severely degraded alpine meadow has become acceptable to local government officials and some researchers as a means of ensuring the sustainable use of rangelands for livestock production (Zhao et al. 2011). A few demonstration projects have been implemented to rehabilitate degraded alpine meadows through reseeding. However, ploughing the ground and introducing foreign species disrupts the soil equilibrium, reducing soil health in the long term (Fig. 6.7).

Finally, it is interesting to highlight implications of the management of alpine meadows for carbon sequestration. Soil carbon stored in the alpine *Kobresia* meadow ecosystem is a very important carbon pool. It represents a significant proportion of the total carbon system because of its high root mass and the low rate of decomposition owing to the low-temperature regime (Cao et al. 2004). These ecosystems have been stabilized for hundreds to thousands of years. At present, they are considered as an active carbon sink (Kato et al. 2006; Yang et al. 2008). However, they may also act as an important carbon source if land degradation occurs or land use changes. Soil degradation and land use change are therefore one of the critical factors controlling the carbon and nitrogen budgets for these ecosystems. Carbon and nitrogen concentrations and soil carbon stocks of

Ploughed ground is vulnerable to wind and water erosion and nutrient leaching

The introduction of foreign species of grasses may tip the delicate ecosystem equilibrium

Fig. 6.7 Rehabilitation of degraded alpine meadow through planting

Kobresia meadows change at different stages of degradation (Wang et al. 2005). Soil organic matter and carbon storage in alpine meadow significantly declined when vegetation cover was reduced from 90 to 30 % (Wang et al. 2005; Zhou et al. 2005), while nitrogen content in soil was higher in severely degraded land than in lightly degraded land (Wang et al. 2008). Reseeding degraded meadows may increase productivity and boost a higher above- and below-ground biomass input, prospectively enhancing long-term soil carbon storage. As noted for soil erosion concerns, ploughing is not advisable as a component of restoration efforts, as it may cause severe soil organic carbon and nitrogen loss. Schleuss et al. (2015) highlighted complex relationships between nitrogen uptake and carbon cycling in *Kobresia* grasslands, indicating that these systems react extremely sensitively towards changes in climate and management. As noted by Chen et al. (2013), many challenges are faced in integrating field observations with process-based ecosystem models to predict the impacts of future climate change and human activities at various temporal and spatial scales. Additional research is required to integrate data from field observation studies within improved models in efforts to develop enhanced insights into coupling among carbon, nitrogen and phosphorus biogeochemical cycles as well as about the role of microbes in these cycles.

Past and present land cover changes atop the Qinghai–Tibet Plateau may have profound implications not only for carbon storage but also for climate patterns themselves. For example, Babel et al. (2014) showed that increasing degradation of *Kobresia* turf affects carbon allocation and strongly reduces the carbon uptake, compromising the function of *Kobresia* pastures as a carbon sink. Pasture degradation leads to a shift from transpiration to evaporation, while the total sum of evapotranspiration remains unaffected. These results may have significant implications for climate variability across the plateau, as they may promote earlier onset of convection and cloud generation, likely triggered by enhanced evaporation, and hence earlier precipitation, while clouds may decrease the incoming solar radiation. This highlights the enormous importance of research endeavours to realistically appraise eco-environmental futures of the region. More work is required to assess implications of changing ground cover and associated appraisals of environmental responses to management programmes (e.g. Piao et al. 2015).

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References

Babel, W., Biermann, T., Coners, H., et al. (2014). Pasture degradation modifies the water and carbon cycles of the Tibetan highlands. *Biogeosciences Discussions, 11*, 8861–8923.

Blackburn, W. H., Thurow, T. L., & Taylor, C. A. (1986). Soil erosion on rangeland. In: *Symposium Proceedings, Use of Cover, Soils and Weather Data in Range Monitoring* (pp. 31–39). Denver, Colorado: Society for Rangeland Management.

Brierley, G. J., Li, X., Cullum, C., et al. (2016). Introduction: landscape and ecosystem diversity in the Yellow River Source Zone. In: Brierley, G. J., Li, X., Cullum, C., (Eds.), *Landscape and Ecosystem Diversity, Dynamics and Management in the Yellow River Source Zone*. (pp.1–34). Springer.

Cao, G., Tang, Y., Mo, W., et al. (2004). Grazing intensity alters soil respiration in an alpine meadow on the Tibetan Plateau. *Soil Biology and Biochemistry, 36*, 237–243.

Chen, H., Zhu, Q., Peng, C., et al. (2013). The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau. *Global Change Biology, 19*, 2940–2955.

Cheng, H. (2007). *The hydrology process and ecological functions response under the vegetation coverage change of alpine cold meadow in the head water region of the Yellow River* (Doctoral dissertation, Lanzhou University).

Dong, S. C., Zhou, C. J., & Wang, H. Y. (2002). Ecological crisis and countermeasures of the three rivers headstream regions. *Journal of Natural Resources, 17*, 713–720. (in Chinese with English abstract).

Dunford, E. (1949). *Relation of grazing to runoff and erosion on bunchgrass ranges*. USDA Forest Service: Rocky Mountain Forest and Range Experiment Station (Research Note 7).

Feng, J. M., Wang, T., & Xie, C. W. (2004). Land desertification in the source region of the Yellow River: Northeast Qinghai-Xizang Plateau. *Ecology and Environmental Sciences, 13*, 601–604. (in Chinese with English abstract).

Fu, Y. (2004). Natural disasters in Qinghai province and characteristics analysis. *Earthquake Research in Plateau, 16*, 59–67. (in Chinese with English abstract).

Han, F., Ben, G. Y., Shi, S. B., et al. (1991). Effects of stocking rate on plant growth and productivity of alpine meadow. *Alpine Meadow Ecosystem, 3*, 81–88. (in Chinese).

Hanson, C. L., Kuhlman, A. R., Erickson, C. J., et al. (1970). Grazing effects on runoff and vegetation on western south Dakota rangeland. *Journal of Range Management, 23*, 418–420.

Harris, R. (2010). Rangeland degradation on the Qinghai-Tibetan Plateau: A review of the evidence of its magnitude and causes. *Journal of Arid Environments, 74*, 1–12.

Hollis, G. E., & Thompson, J. R. (1998). Hydrological data for wetland management. *Water and Environment Journal, 12*, 9–17.

Hu, X. S., Brierley, G. J., Cullum, C., et al. (2016). Hillslope stability in the Yellow River source region. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 101–116). Springer.

Huo, Y. (1985). Discussion on restoration measures of degraded alpine meadow grassland in Guoluo area. *Farming Resources and Zoning Research, 11*, 9–12. (in Chinese with English abstract).

Jiang, W. (2001). Structure and decomposition of microorganism in *Kobresia* meadow. In X. Zhou, et al. (Eds.), *Kobresia meadow in china* (p. 168). Beijing, China: Science Press.

Jing, H., & Xu, J. (2005). The affect of human economic activity, from on mid-Qing dynasty, on the eco-environment of three rivers source regions. *Journal of Qinghai Environment, 3*, 87–92. (in Chinese with English abstract).

Jing, H., Xu, J., & Gu, Y. (2006). A new solution to degeneration of the grassland ecosystem in Sanjiangyuan district induced by human activities. *Ecology and Environment, 15*, 1042–1045. (in Chinese with English abstract).

Johnston, A. (1962). Effects of grazing intensity and cover on water intake rate of fescue rangeland. *Journal of Range Management, 15*, 79–83.

Kato, T., Tang, Y., Gu, S., et al. (2006). Temperature and biomass influences on interannual changes in CO_2 exchange in an alpine meadow on the Qinghai-Tibetan Plateau. *Global Change Biology, 12*, 1285–1298.

Li, X. L., Gao, J., & Brierley, G. J. (2013). Rangeland degradation on the Qinghai-Tibet Plateau: Implications for rehabilitation. *Land Degradation and Development, 24*, 72–80.

Li, D., & Li, J. (2002). *Biodiversity of Sanjiangyuan—scientific investigation report of Sanjiangyuan Nature Reserve*. Beijing, China, 4: Science Press (in Chinese).

Li, X. L., Perry, G., & Brierley, G. J. (2016). Grassland ecosystems of the Yellow River Source Zone: Degradation and restoration. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 137–166). Springer.

Li, X. L., Perry, G. L. W., Brierley, G. J., et al. (2014). Quantitative assessment of degradation classifications in degraded alpine meadows (Heitutan), Sanjiangyuan, western China. *Land Degradation and Development., 25*, 417–427.

Liu, W., Wang, Q. J., Wang, X., et al. (1999). Ecological process of forming 'Black-Soil-Type' degraded grassland. *Acta Agrestia Sinica, 7*, 300–307. (in Chinese with English abstract).

Ma, Y., Dong, Q., Shi, J., et al. (2008). Classification gradation and control measure of "Black-soil-beach" degraded grassland in Three River Headwater Region, *Chinese Qinghai Journal of Animal and Veterinary Medicine, 3*, 1–3. (in Chinese with English abstract).

Ma, Y., Shang, Z., Shi, J., et al. (2006). Studies on communities diversity and their structure of "black-soil-land" degraded grassland in the headwater of Yellow River. *Prataculture Science, 12*, 6–11. (in Chinese with English abstract).

McGregor, G. R. (2016). Climate variability and change in the Sanjiangyuan region. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 35–58). Springer.

Peng, L., Yan, X., Zhou, J., et al. (1980). Bare land restoration of Qinghai Qumalai. *Grassland of China, 4*, 7–17. (in Chinese).

Perryman, A. (2001). Changes in a vegetation index, 1982–1999. In: van Wageningen, N., Sa, W. J. (Eds.), *The living plateau; changing lives of herders in Qinghai. Concluding seminar of the Eu-China Qinghai livestock development project* (pp. 11–24). Kathmandu, Nepal: ICIMOD.

Piao, S., Yin, G., Tan, J., et al. (2015). Detection and attribution of vegetation greening trend in China over the last 30 years. *Global Change Biology, 21*, 1601–1609.

Qian, J., Wang, G., Ding, Y., et al. (2006). The land ecological evolutional patterns in the source areas of the Yangtze and Yellow Rivers in the past 15 years. *Environmental Monitoring and Assessment, 116*, 137–156.

Qiao, Y., Li, X., Schwendenmann, L., et al. (2013). Plant community structure and soil carbon and nitrogen status of degraded alpine meadows. In: *Proceedings of 2013 IAHR Congress*, S10070.

Qiao, Y., & Wang, Q. (2010). Driving forces of alpine meadow degradation in the Yellow River headwaters. In G. J. Brierley, X. Li, & G. Chen (Eds.), *Landscape and environment science and management in the Sanjiangyuan region* (pp. 149–165). Xining: Qinghai People's Publishing House.

Qiao, Y. M., Wang, Q. J., & Wang, W. Y. (2009). Yak (*Bos grunniens L.*) grazing effects on vegetation of alpine meadow with Rosaceae (*Potentilla fruticosa L.*) shrub in Qinghai-Tibet Plateau. *Polish Journal of Ecology, 57*, 769–777.

Qin, D. (Ed.), (2014). *Eco-protection and sustainable development of the Sanjiangyuan area.* Beijing, China, 5–6: Science Press (in Chinese).

Ran, Y. C., Xie, J. X., & Li, X. L. (2016). Socio-economic development and its effects on the ecological environment of the Yellow River Source Zone. In: Brierley, G. J., Li, X., Cullum, C. et al. (Eds.) *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 331–352). Springer.

Rowntree, K., Duma, M., Kakembo, V., et al. (2004). Debunking the myth of overgrazing and soil erosion. *Land Degradation and Development, 15*, 203–214.

Schleuss, P. M., Heitkamp, F., Sun, Y., et al. (2015). Nitrogen uptake in an alpine *Kobresia* pasture on the Tibetan Plateau: Localization by 15 N labeling and implications for a vulnerable ecosystem. *Ecosystems, 18*, 946–957.

Shang, Z., Ding, L. L., Long, R., et al. (2006). Numerical characteristics of soil microorganism of alpine meadows in the headwater region of Yangtze and Yellow River. *Grassland and Turf, 3*, 3–7. (in Chinese with English abstract).

Shang, Z., Long, R. (2005). Formation causes and recovery of the "Black Soil Type" degraded alpine grassland in Qinghai-Tibetan Plateau. *Frontiers of Agriculture in China, 1*, 197–202.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) headwaters. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.) *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 275–330). Springer.

Wang, Q., Shixiong, L., Zengchun, J., et al. (2008). Response of carbon and nitrogen content in plants and soils to vegetation cover change in alpine *Kobresia* meadow of the source region of Lantsang, Yellow and Yangtze Rivers. *Acta Ecologica Sinica, 28*, 885–894. (in Chinese with English abstract).

Wang, S. (2003). Causes of vegetation degradation and protection strategy for Sanjiangyuan in Qinghai Province. *Acta Prataculture Sinica, 6*, 1–9. (in Chinese with English abstract).

Wang, W., & Wang, Q. (2001). The structure and plant species diversity of the degraded ecosystems in alpine *Kobresia* meadow. *Acta Prataculture Sinica, 10*, 8–14. (in Chinese with English abstract).

Wang, W. Y., Wang, Q. J., Jing, Z. C., et al. (2006). Effects of vegetation cover change of alpine *Kobresia* meadow on plant community structure and diversity in source region of the Yangtze and Yellow Rivers. *Resources Science, 28*, 118–124. (in Chinese with English abstract).

Wang, W. Y., Wang, Q. J., Wang, C. Y., et al. (2005). The effect of land management on carbon and nitrogen status in plants and soils of alpine meadows on the Tibetan Plateau. *Land Degradation and Development, 16*, 405–415.

Wang, Y. B., Wang, G. X., Zhang, C. M., et al. (2007). Response of soil physicochemical properties to the changes of the vegetation ecosystem on the Tibetan Plateau. *Journal of Glaciology and Geocryology, 29*, 921–927.

Wang, Q., Zhou, L., & Wang, F. (1995). Effects of grazing intensity on community structure and function of winter-spring pasture. In: *Alpine meadow ecosystem* (vol. 4, pp. 353–364). Beijing: Science Press (in Chinese).

Wang, Q., Zhou, X., & Wang, W. (1999). Species diversity of main plant communities in alpine meadow. *Collected Papers of Plateau Biology, 14*, 77–87. (in Chinese with English abstract).

West, N. E. (1993). Biodiversity of rangelands. *Journal of Range Management, 46*, 2–13.

Wu, Y. (2003). Eco-environmental protection and construction of The Yellow River Headwaters. *Qinghai Environment, 2*, 60–64. (in Chinese).

Xu, X., Yan, J., & Liang, X. (2009). Evaluation of changes in runoff and the effect of human activities in the source area of three rivers. *Arid Zone Research, 26*, 88–93.

Yan, P., Dong, G. R., Su, Z. Z., et al. (2004). Desertification problems in the Yangtze River source area. *Land Degradation and Development, 15*, 177–182.

Yang, J., Ding, Y., & Chen, R. (2005). NDVI reflection of alpine vegetation changes in the source regions of the Yangtze and Yellow Rivers. *Acta Geographica Sinica, 60*, 467–478. (in Chinese with English abstract).

Yang, Y., Fang, J., Tang, Y., et al. (2008). Storage, patterns, and controls of soil organic carbon in the Tibetan grasslands. *Global Change Biology, 14*, 1592–1599.

Yao, T., Masson-Delmotte, V., Gao, J., et al. (2013). A review of climatic controls on δ18O in precipitation over the Tibetan Plateau: observations and simulations. *Reviews of Geophysics, 51*, 525–548.

Zhang, Y. L., Ding, M. J., Zhang, W., et al. (2006). Spatial characteristic of vegetation change in the source regions of the Yangtze River, Yellow River and Lancang River in China. *Geographical Research, 3*, 500–507.

Zhang, S., Wang, Y., Zhu, H., et al. (2003). Water environment changes in the source region of the Yellow River and its geological effects. *Hydrogeology and Engineering Geology, 3*, 11–14. (in Chinese with English abstract).

Zhao, X., Cao, G., & Li, Y. (2009). *Alpine meadow ecosystem and global change*. Beijing, China, 2: Science Press (in Chinese).

Zhao, X., Ma, Y., Wang, Q., et al. (Eds.) (2011). *Restoration and sustainable management of degraded alpine meadow grassland ecosystem in Sanjiangyuan region* (pp. 67–68). Beijing 137–144: Science Press (in Chinese).

Zhao, X., Wang, Q. J., & Pi, N. L. (1988). Principal components analysis of herbage resources utilized by Tibetan sheep under different stocking rates on alpine meadow. *Acta Biologica Plateau Sinica, 8*, 89–95.

Zhou, X. (2001). Ecological feature and life history types of plants composing *Kobresia* meadow. In X. Zhou, et al. (Eds.), *Kobresia meadow in China* (pp. 49–50). Beijing, China: Science Press. (in Chinese).

Zhou, X., Wang, Z., & Du, Q. (1987). *Vegetation of Qinghai*. Xining, Qinghai, China: People's Publishing House (in Chinese).

Zhou, L., Wang, Q. J., Zhao, J., et al. (1995). Studies on optimum stocking intensity in pasturelands of alpine meadow IV. The measuring of vegetation change and the maximum stocking intensity of non-degenerated grasslands. *Alpine Meadow Ecosystem, 4*, 403–418. (in Chinese).

Zhou, H., Xhao, X., Tang, Y., et al. (2005). Alpine grassland degradation and its control in the source region of the Yangtze and Yellow Rivers China. *Grassland Science, 51*, 191–203. (in Chinese with English abstract).

Zhou, H., Zhao, X. Q., Tang, Y. H., et al. (2004a). Effect of long-term grazing on alpine shrub vegetation in the Qinghai-Tibet Plateau. *Grasslands of China, 26*, 1–11. (in Chinese).

Zhou, H., Zhao, X. Q., Zhou, L., et al. (2004b). A study on correlations between vegetation degradation and soil degradation in the 'alpine meadow'of the Qinghai-Tibetan Plateau. *Acta Prataculture Sinica, 14*, 31–40. (in Chinese with English abstract).

Zhou, H., Zhou, L., Zhao, X., et al. (2001). Influence of grazing disturbance on alpine grassland. *Grasslands of China, 24*, 53–60. (in Chinese).

Zoning Office of Qinghai Agricultural Resource (ZOQAR) (1997) *Soils of Qinghai*. Beijing, China, 94: China Agriculture Press (in Chinese).

Chapter 7
Grassland Ecosystems of the Yellow River Source Zone: Degradation and Restoration

Xilai Li, George Perry and Gary John Brierley

Abstract Why are the grassland resources in the Yellow River Source Zone in the Sanjiangyuan region on the Qinghai–Tibet Plateau important for eco-environmental protection in China? What are the key ecological issues in this area? This chapter provides a summary of the biological resources and protection measures in the Yellow River Source Zone. Desertification of Alpine-steppe and Heitutan formation of alpine meadows across the Yellow River Source Zone are assessed to identify the processes of grassland degradation. Impacts of grazing on grassland are related to the effects of climate change. Particular emphasis is placed on the potential role of small mammals in grassland degradation. Building on field analyses, findings from modelling work and key implications from the international literature, alternative stable states in the processes of grassland degradation and restoration are developed to frame management interventions. Management programmes that can be applied to restore Heitutan in the Yellow River Source Zone on the Qinghai–Tibet Plateau are outlined, highlighting implications for sustainable development strategies in the management of grassland resources.

Keywords Grassland resources · Alpine-steppe · Alpine meadow · Alpine ecosystems · Desertification · Heitutan grassland · Soil erosion · Grassland degradation · Climate change · Overgrazing · Small mammals · Outbreak · Alternative stable states · Restoration · Management strategies · Sustainable development · Qinghai–Tibet plateau

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7.1 Introduction

Across the world, livestock grazing is the dominant land use in arid and semi-arid regions. Pastoralists in these areas rely on healthy rangelands. The impacts of rangeland degradation, such as biodiversity loss, depletion of soil and water resources, desertification and concerns for food security affect both socio-economic and cultural conditions, threatening livelihoods and wellbeing. In severe instances rangelands may completely lose their productive value and people may even be forced to leave their traditional (historically-used) lands.

Grassland, rangeland and pasture are terms used in different parts of the world to refer to a similar set of environmental conditions in which ecosystems produce biomass, in the form of palatable plants, which can be grazed (Ren 2000; Li et al. 2013a). Grassland ecosystems provide many ecological services, including animal habitat, soil maintenance, grazing resources for livestock (White et al. 2000; Lund 2007) and carbon storage (Ingrisch et al. 2015). The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines grassland as land covered with herbaceous plants with less than 10 % tree and shrub cover, while wooded grassland has 10–40 % tree and shrub cover (White 1983). In essence, grassland refers to ground covered by grass-dominated vegetation, with minimal, if any, cover (Suttie et al. 2005). Grassland is, therefore, a type of land cover, rather than a type of land use (Squires and Zhang 2009). Rangeland is not a synonym for grassland; rather, rangelands encompass a number of vegetation types including savannah, woodlands and steppe (Heady and Child 1994). Rangeland refers to broad swathes of mostly unimproved land supporting grasses or grass-like plants that is often used for livestock grazing.

Estimates of the extent of the world's grassland area(s) range from approximately 41–56 million km^2; that is 31–43 % of the Earth's surface (Whittaker and Likens 1973; Atjay et al. 1979; World Resources Institute 2000). Grasslands are distributed across multiple climate zones, but are concentrated in Sub-Saharan Africa and Asia (14.5 and 8.9 million km^2, respectively) (White et al. 2000). Rangelands in China cover nearly 4 million km^2, or about 40 % of the total land area.

The Qinghai–Tibet Plateau is one of the world's major pastoral areas, covering an area of 300 million ha, of which 257 million ha is in China. Only around 0.4 % of this land is cultivated. Wherever practicable, the remainder is used for grazing. Rangeland on the Plateau is comprised mostly of alpine meadow (44.6 %) and Alpine-steppe (28.8 %). Typical alpine meadows are found on the slopes of mountains and fluvial fans, and on river terraces with an elevation range of 3200–4800 m asl. Alpine-steppe is a variant of the temperate steppe that is found under colder conditions where the soils lack the sod layer found in gravel and coarse sandy loam (Li et al. 2013a).

Given its biophysical attributes and its sparsely populated area, the Qinghai–Tibet Plateau contributes little to China's overall economy (Ran et al. 2016, Chap. 14; Wen et al. 2013a). However, its rangelands have rich cultural and geographic diversity and harbour high biodiversity. This area provides numerous ecosystem services, including plant diversity conservation, carbon sequestration, soil and water protection, as well as the maintenance of Tibetan culture and traditions. The Qinghai–Tibet Plateau supported around 30 million sheep and goats and 12 million yaks in 2005, making it one of China's major pastoral centres (Wen et al. 2013a). However, almost 30 % of the alpine grasslands on the Qinghai–Tibet Plateau have been severely degraded due to the combined and interactive effects of climate change, shifts in human population density, inappropriate resource usage and damage caused by rodents (plateau pika, *Ochotona curzoniae*) (Wen et al. 2013a). While the drivers of these changes are multifarious and not easy to disentangle, they undoubtedly have serious impacts on local pastoralists as productivity declines and soil and water resources become degraded.

Grassland degradation also threatens a suite of environmental and socio-cultural values, meaning that isolating the underlying cause(s) of degradation, and developing appropriate measures to address them, are critical concerns atop the Qinghai–Tibet Plateau. This is a very sensitive political issue. As Harris (2010: 2) notes: "Because most pastoralists are Tibetan, Mongolian, or other non-Han ethnic minorities whereas political authority rests largely in the hands of Han Chinese, and because discussion of ethnic tension remains a sensitive issue in China, dispassionate analysis of rangeland degradation has been constrained by its close association with politically charged issues." Sound scientific guidance is required to inform the management of grassland resources on the plateau.

We start this chapter by providing a summary of the biological resources in this vast region, followed by an assessment of variability in underlying causes and controls upon rangeland degradation across it. A concerted effort has been made to address concerns for overgrazing on the Alpine-steppe and alpine meadow landscapes in the source zone of the Yellow River. An assessment of the impacts of overgrazing includes consideration of the role of small mammals (on the one hand they are considered as a critical ecosystem engineer, on the other they are perceived as a major threatening pest). A conceptual model grounded in alternative stable state theory (Scheffer et al. 2001) is then developed to evaluate stages of grassland degradation and prospects for restoration. Finally, management options in the restoration of degraded grasslands are analysed, providing a critique of sustainable management strategies for grassland resources in the area.

7.2 Grassland Resources and Protection in the Yellow River Source Zone

The Yellow River Source Zone makes up the eastern half of the Sanjiangyuan region in the southern part of Qinghai Province (Fig. 7.1). It covers a total area of 137,700 km^2, accounting for 19.03 % of the total area of Qinghai Province. Prior to 2013, it only covered a total area of 106,400 km^2, as Guinan, Guide, Gonghe, Jianza and Tongren Counties were formally added to the Yellow River Source Zone at this time (Fig. 7.2). Grasslands are the primary ecosystem type in the Yellow River Source Zone.

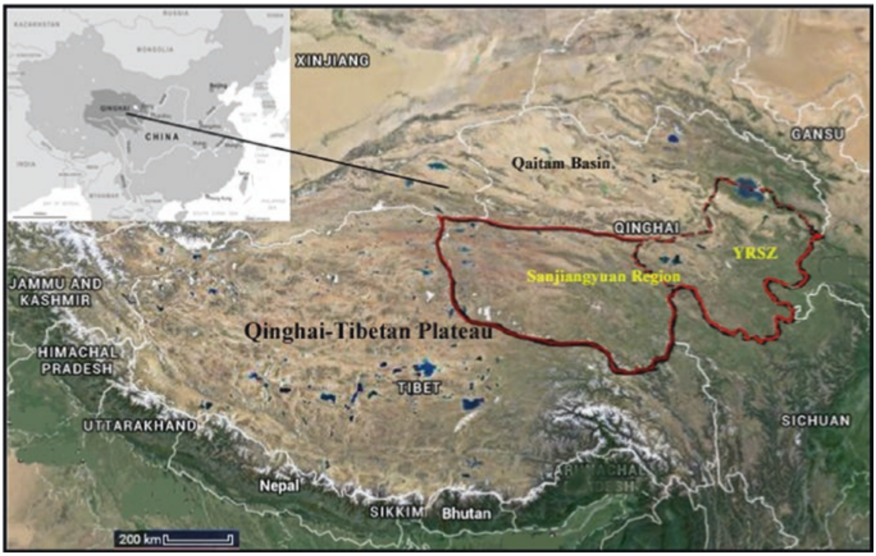


Fig. 7.1 The Sanjiangyuan region (*red line*) is located in southern Qinghai atop the Qinghai-Tibet Plateau. It lies between 31°39′–37°10′N and 89°24′–102°27′E. The Yellow River Source Zone (YRSZ) lies within the eastern part of the Sanjiangyuan

Fig. 7.2 The Sanjiangyuan region makes up the southern half of Qinghai Province. The region is divided into 22 administrative districts. The Yellow River Source Zone (YRSZ) is made up of 15 counties in southeastern Qinghai Province (demarcated by the *black line*). Counties in Sichuan and Gansu are not included in this definition of the YRSZ. Figure modified from Li et al. (2012)

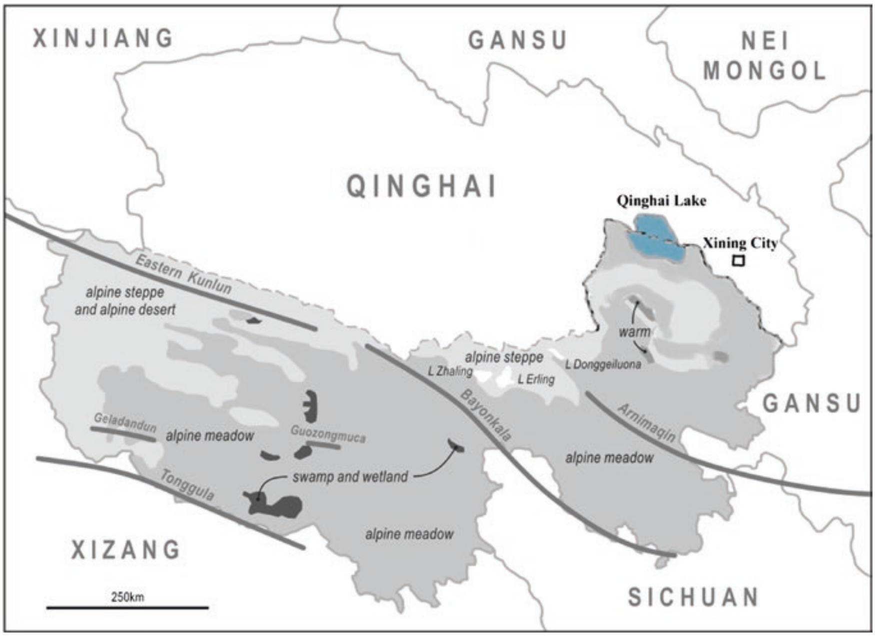


Fig. 7.3 Vegetation map of the southern half of Qinghai Province. Alpine meadow (*middle tone*, large areas), alpine steppe (*light tone*, small areas) and wetlands (*dark tone*) are noted for the Sanjiangyuan region (modified from Li et al. 2012). *Thick lines* show the broad trend of mountain ranges. The Bayan Har Mountains divide the Sanjiangyuan, separating the headwaters of the Yellow River from the headwaters of the Yangtze and Lancang (Mekong) Rivers

Major mountain ranges in the Sanjiangyuan region, such as Anyemaqen and Bayankala, lie at 3335–6564 m asl (Fig. 7.3). Headwater areas of the Yellow River are separated from the Yangtze and Lancang (Mekong) Rivers by the Bayankala Mountains. The alpine continental climate is characterized by a clear separation of dry and wet seasons but a small annual temperature range, large diurnal range, long sunshine hours and strong radiation (Zhang et al. 1999; Li et al. 2012). The cold season, which lasts for seven months, is controlled by high pressure systems (McGregor 2016, Chap. 2).

Primary vegetation classes in the region are comprised of a range of cold-tolerant perennial plants, including coniferous forest, broadleaf forest, needleleaf and broadleaf mixed forest, shrub, meadow, steppe, swamp and aquatic vegetation, cushion plants, and zones of sparse vegetation (Li et al. 2012). Forests cover 1.57 million ha of the Yellow River Source Zone (11.4 % of the total land area), while grasslands account for 11.25 million ha (81.2 %) of the total land area (Table 7.1).

The modern-day pasture assemblages of Northeast Tibet originate largely from the conversion of forests to grasslands at least 8000 years ago (Miehe et al. 2008), with a grazing history extending back over 9000 years (Miehe et al. 2009). Grassland falls into two broad types in the Yellow River Source Zone

Table 7.1 Land utilization in the Yellow River Source Zone (NDRC 2014)

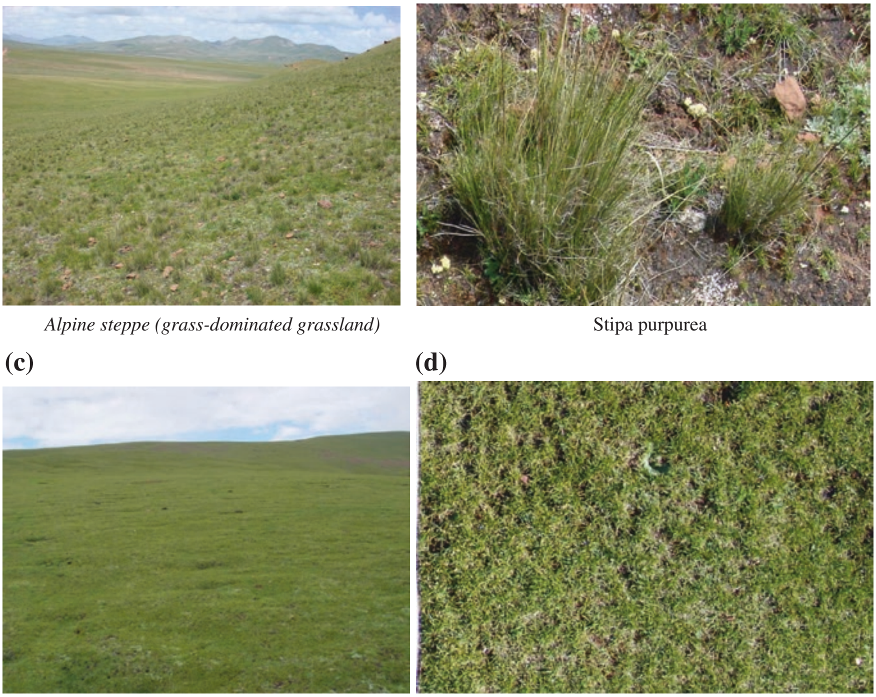
Prefecture	Total land area (10^4 km^2)	Grassland area (10^4 ha)	Woodland area (10^4 ha)	Tilled and ploughed land (10^4 ha)	Water area (10^4 ha)	Others (10^4 ha)
Total	13.77	1124.74	156.90	5.65	17.49	72.23
Guoluo (six counties)	7.64	627.49	85.81	3.13	9.70	37.87
Hainan (five counties)	4.34	344.16	48.20	1.78	5.51	34.35
Huangnan (four counties)	1.79	153.09	22.89	0.73	2.27	0.01

(NDRC 2014), alpine-steppe (21 %) and alpine meadow (72 %). The main grassland species (across both steppe and meadow) include *kobresia* (*Kobresia* spp.), needlegrass (*Stipa* spp.), sedge (*Carex* spp.), saussur (*Saussurea* spp.), roegneria (*Roegneria*, spp.), bluegrass (*Poa* spp.), wild ryegrass (*Elymus* spp.) and speargrass (*Achnatherum* spp.). All of these species have low productivity. Their forage height is low, ranging between 10 and 30 cm. *Stipa purpurea* is the dominant species on the Plateau in alpine-steppe (see Fig. 7.4a, b; Tang et al. 2015), while *Kobresia pygmaea* is the dominant species in the alpine meadow (see Fig. 7.4c, d; Tang et al. 2015).

The alpine meadows of the Yellow River Source Zone represent a distinctive natural landscape and provide a suite of important ecological resources (Li et al. 2012; NDRC 2014). Typical alpine meadows are found on the slopes of mountains and fluvial fans, and on river terraces in an elevation range of 3200–4800 m asl (e.g. Fig. 7.5). Alpine meadow is the emergent outcome of long-term grazing of the dominant *Kobresia* species on the Plateau (Fig. 7.4c, d; Zhou et al. 2005; Li 2012; Li et al. 2012; Tang et al. 2015). Such meadows have an enriched root biomass (Kaiser et al. 2008), forming what Miehe et al. (2008) refer to as a golf course-like "carpet" dominated by *Kobresia* species cropped very close to the ground (<5 cm height; see Tane et al. 2016, Chap. 13).

Alpine meadow ecosystems play a central role in carbon cycling and storage in these landscapes (Ingrisch et al. 2015), with the soil carbon pool accounting for more than 90 % of the ecosystem's vegetation-soil storage (Wen et al. 2013b). Meadow grasslands provide important resources for animal husbandry. When subjected to heavy grazing (more than c. 60 % the maximal stocking rate), and in the absence of damage by small mammals, alpine meadow is grazed down to uniformly short plants (<2 cm high). Under 'traditional' grazing regimes (less than c. 60 % stocking rate), alpine meadows contain a diversity of palatable annual species that grow during summer, supporting a reasonable density of grazing animals (Zhou 2001; Pech et al. 2007; Miehe et al. 2008, 2009; Li 2012; Li et al. 2012).

A typical catenal arrangement of hillslope and vegetation associations in the Yellow River Source Zone is shown in Fig. 7.5. The catena in Nanqi Village, Henan County (34°51′N, 101°28′E) of Qinghai Province has an altitude of



(a) *Alpine steppe (grass-dominated grassland)*

(b) Stipa purpurea

(c) *Alpine meadow (sedge-dominated grassland)*

(d) Kobresia pygmaea *of a uniform height*

Fig. 7.4 Alpine steppe (**a**) is dominated by grass, mainly *Stipa purpurea* (**b**). Plant height of alpine steppe is higher than alpine meadow. The ‘carpet’ grassland (**c**) of alpine meadows is comprised mainly of *Kobresia* species (*Kobresia pygmaea* and K. *humilis*) with a very low plant height (<5 cm; (**d**)). Alpine meadows are rich in plant species, with up to 30 species per m^2 (Chen et al. 2007). Severe grazing of alpine meadow results in a uniformly short plant community comprised primarily of *Kobresia*. In summer this takes on the appearance of a large green grassland carpet (*Photos* Li Xilai)

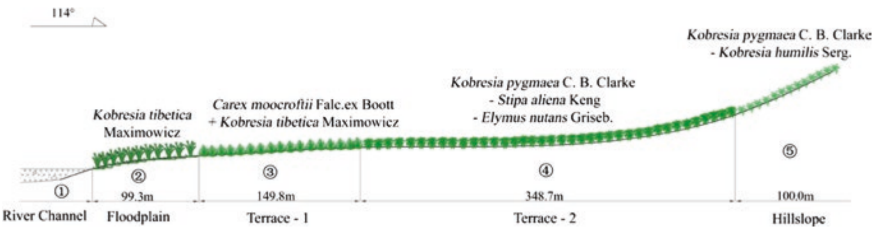


Fig. 7.5 A typical catenal section in the Yellow River Source Zone, taken at Nanqi Village, Henan County (we thank Hu Xiasong and his research group for this figure)

3580 m. The river channel is comprised of angular-subangular gravels, reflecting a colluvial rather than an alluvial origin. Flow is generated both from runoff and groundwater stores. The adjacent floodplain surface is comprised of swampy meadow (wetland). It is dominated by cold-tolerant species such as *Kobresia tibetica*. Rising onto the terrace surface, *Carex moocroftii* and *K. tibetica* start to appear with distance and elevation from the river channel (slope angle of 7°). This area of the terrace −1 is drier than the floodplain, but it is still swampy meadow (wetland). Because of their proximity to the river, these areas of floodplain and terrace-1 have high soil moisture. As a result, plants grow well, with the intertwining root network supporting significant resistance to soil erosion. Slope angle increases to 5° on the terrace surface (terrace-2), the margins of which are characterized by bare ground that reflects severe degradation. Given the relatively low soil moisture and the influence of water erosion and rodent activity, surface soils of some parts of the terrace-2 are relatively loose, with small patches of bare earth. The dominant species in this area include *K. pygmaea* and *Stipa aliena*, associated with *Elymus nutans*. On the steeper hill slope itself (slope of 24°), the dominant species include *K. pygmaea* and *Kobresia humulis*.

The Yellow River Source Zone has long been a key habitat for a range of wild animals and supported herding activity. However, over the last few decades a range of environmental stressors, including human activity, have resulted in deteriorating conditions in both its terrestrial and aquatic ecosystems (Li et al. 2012). To address these concerns, Phase II of the Qinghai Ecological Protection and Construction in the Sanjiangyuan was officially launched in December, 2013 (NDRC 2014). This project includes significant expenditure on ecological (re) construction in the Yellow River Source Zone, extending the vegetation and soil restoration accomplishments of Phase I. Despite these improvements, which also aim to benefit local farmers and communities, the environmental degradation of the area has not been curbed, and further work is required to identify and address the underlying causes of rangeland degradation in the region (NDRC 2014).

7.3 Desertification of Alpine Steppe and Heitutan Formation of Alpine Meadows

Grassland degradation, whether natural or anthropic in origin, is the decline of grassland quality to such a level that surface vegetation has been fragmented (Li 1997). Degradation has a range of undesirable outcomes, both direct and indirect, including a loss of grassland cover (with associated soil impacts) and reduced productivity (including an increase in unpalatable grass species), which ultimately affect the pastoralists dependent on these ecosystems (Li et al. 2013a; Harris 2010; Harris et al. 2015). The degradation process also influences the composition of the plant community itself, with Wang et al. (2015), for example, describing a more than 50 % decline in species richness on a gradient from healthy ($S = 36$) to severely degraded ($S = 15$) grassland.

Grassland degradation arises from a wide range of inter-dependent factors including inappropriate stocking levels and management practices and climate change (Harris 2010). Population irruptions of small mammals such as plateau pika have also been implicated in grassland degradation by some researchers although their exact role in the degradation process is a matter of ongoing debate. Official perspectives in China emphasize overstocking of livestock (Wang et al. 2005; Zhou et al. 2005). Harris (2010) contends that it is unclear to what degree this reflects pastoralist behaviour or policy initiatives (e.g. land tenure arrangements), as limited research has been undertaken to assess current socio-ecological systems in the region. It is widely accepted, however, that traditional pastoral lifestyles have been practiced in this area for several thousand years (see Han et al. 2016, Chap. 12), with recent research pointing to long-term transitions in the emergence and maintenance of grazing-adapted ecosystems across the region (e.g. Miehe et al. 2008, 2009).

In the Yellow River Source Zone both alpine-steppe and alpine meadow ecosystems show signs of degradation (Li et al. 2013a). Of the two, alpine-steppe is considered to be more vulnerable to degradation due to its lower biomass and its location in arid areas. Severe degradation of alpine-steppe ecosystems can ultimately result in deleterious environmental consequences, such as desertification (Fig. 7.6a, b).

The degradation of alpine meadows ranges from minor degradation to desertification and *Heitutan* (black soil beach) degradation. Importantly, however, degraded environments lie along a continuum rather than forming distinct (discrete) states (Li et al. 2014). The initial stages of degradation are characterised by the fragmentation of the previously continuous grass cover. Once degradation has advanced to the *Heitutan* stage, the soil has lost so much of its physico-chemical structure and fertility that no vegetation can survive (Li et al. 2014). The shift

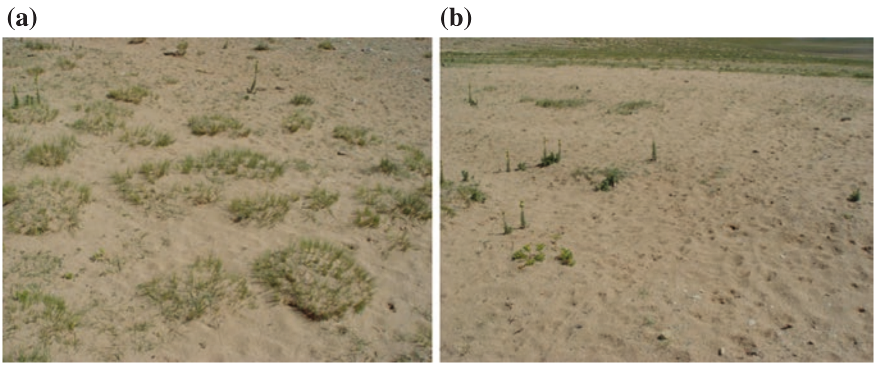
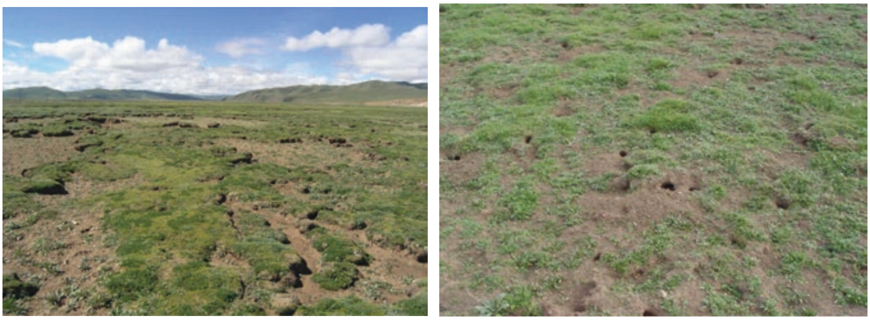


Fig. 7.6 Qualitatively different states of desertification of alpine steppe vegetation (*Photos* Li Xilai 2005). **a** Severe degradation—Less than 50 % of alpine steppe is usable by animals. **b** Extreme degradation—Less than 10 % of alpine steppe is usable by animals

to severe forms of degradation is characterised by changes in the plant community (reduced biomass, reduced richness and cover of palatable species) and soils (increased compaction and decreased moisture and organic content) (Zhou et al. 2005). While grassland areas can remain as meadow despite grazing pressure, over time the loss of vegetation coupled with small mammal activity can negatively

Intact photograph *Carpet-like condition photograph*

(a) Intact alpine meadow – a carpet-like condition (Figure 7.4 c, d)



(b) *Severely degraded Heitutan: small mammal outbreaks and severe soil erosion extend across around 40% of alpine meadow*

(c) *Extremely degraded Heitutan: less than 10% of alpine meadow is usable by grazing livestock*

Fig. 7.7 Various stages of Heitutan formation in the Sanjiangyuan: (**a**) intact; (**b**) severely degraded; (**c**) extremely degraded (*Photos* Li Xilai 2007). Figures on the *right* show a close-up view of grassland conditions in each state impact grasslands and promote a shift towards an extreme form of degradation termed "*Heitutan*" grassland (Figs. 7.4 and 7.6; see Wang et al. 2005; Li et al. 2013a, b, 2014). This type of extreme degradation is characterized by a prevalence of degraded/eroded ground, reduced levels of edible herbage and more inedible plants, and accelerated water and soil erosion (Fig. 7.7).

The formation of *Heitutan* in the Yellow River Source Zone threatens the ecological integrity of the region, and negatively impacts upon local peoples' livelihoods and economic development. In schematic terms, the process of extreme *Heitutan* formation follows a pathway of: increasing grazing disturbance → triggering high frequency of small mammal outbreak → increasing burrows abundance of small mammals → soil erosion → emergence of largely eroded (bare) ground → *Heitutan* (Li et al. 2013b). Unsustainably high grazing levels seem to underlie this vicious cycle, but it is unlikely that reducing grazing intensity alone will be sufficient to reverse them (see Sect. 7.6). The exact role that small mammals play in the degradation cycle remains unclear, but is likely to be context-dependent (beneficial to the grassland ecosystem where there is an appropriate stocking rate but, under overgrazing, it becomes deleterious).

7.4 Disentangling Human/Grazing Impacts on Grassland from the Effects of Climate Change

Globally, the main anthropic influence on grasslands occurs via grazing, and grassland ecosystems across the world which has proven to be vulnerable to changes in grazing pressure (Van de Koppel et al. 1997; Zhang et al. 2015). Grasslands and populations of wild ungulates have coexisted for millions of years (White et al. 2000). Indeed, their emergence and subsequent adaptive radiation have been described as "among the most thoroughly documented evolutionary patterns in the fossil record" (Frank et al. 1998: 519). The impacts of domestic animals in grassland ecosystems may be either positive or negative, depending on stocking densities; in the words of Janzen (2011, p. 783), "livestock can be both stressors and benefactors to land".

When managed effectively, grasslands provide a source of food for grazing animals, they are a source of fertility that helps to recycle nutrients efficiently, they promote sequestration of soil organic carbon and they sustain and enhance biodiversity (Franzluebbers et al. 2012). At high densities, grazing animals can change the floristic composition and structural characteristics of vegetation, reduce species richness and increase soil erosion (Tane 2011). In extreme situations, grazing may eliminate a significant proportion of the vegetation cover (Evans 1998; Zhang et al. 2015). The extent to which these changes occur depends not solely on the number of livestock but also on the pattern in time and space of grazing activity. Thus, the management of the grazing regime in grassland ecosystems is of overriding importance in determining their long-term sustainable use.

Unsustainable exploitation of grassland resources by overgrazing, alongside hunting and mining activities has degraded alpine meadows and alpine-steppes in the Yellow River Source Zone (Wang et al. 2005; Qiao and Wang 2010; Li 2012). There is marked spatial and temporal variability in the character and underlying mechanisms of rangeland degradation across the Qinghai–Tibet Plateau, with degradation in different places including *Heitutan* (black soil beach) degradation of alpine meadow (e.g. south Qinghai and northern Tibet), desertification of alpine-steppe, degradation of temperate mountain meadow due to invasion by unpalatable plant species (e.g. in the Qilian Mountains) and saline-alkaline degradation of temperate desert environments (e.g. in the Qaidam Basin) (Li et al. 2013a). The role of climate change in rangeland degradation in the Yellow River Source Zone may be most pronounced in those areas subjected to reduction in the depth and range of permafrost, such as high elevation sedge meadows (Harris 2010).

Grazing livestock is the foundation of economic development in the Yellow River Source Zone (Ran et al. 2016, Chap. 14). Grassland resources in the region have been grazed for millennia with little trace of degradation until recent years (Li 1997). Degradation is a recent phenomenon, especially over the last five decades—a period coincident with increasing human disturbance (Xiang et al. 2009). From 1980–1995 the extent of degraded land expanded at the alarming rate of 1.9 % per annum (Li 1997). This increase suggests that anthropogenic factors play at least as important a role in driving degradation as exogenous controls such as climate (e.g. Wang and Cheng 2001; Zhou et al. 2003, 2005; Qiao and Wang 2010; Tane 2011). This claim is supported by the fact that grassland degradation continued despite annual temperature and precipitation rises since the late 1980s in Maduo, while notionally creating more favourable conditions for grass growth (Bai et al. 2002). Furthermore, although temperature has risen over the late Holocene in the Zuigo Marsh, in the absence of intensive human disturbances this did not trigger degradation (Li et al. 2013a). These impacts cannot necessarily be separated (disentangled) from responses to climate change, although human impacts are believed to be the main driver of grassland degradation.

The onset of overgrazing can be traced back to the sharp increases in the size of the livestock herd that occurred in 1978 when grassland was contracted to individual pastoralists (Fig. 7.8; Ran et al. 2016, Chap. 14). This increase reflected changes in grassland property-rights, legal regulation and cultural transformations (Ma 2007). Grassland property-rights were transformed from an early tribal and temple-based (or monastic) ownership system, to a mutual cooperation system from 1949–1958, to a community possession system from 1958–1978, and then in 1978 to a family contract management responsibility system (Li et al. 2012). As noted in other parts of the world (e.g. Cingolani et al. 2005), an increase in stock size reflected a response to human population growth. For instance, the pastoral human population in Qinghai doubled from 1949 to 2003, while livestock numbers increased three-fold during the same period. This equates to an increase in livestock per unit grassland area and a decrease in per capita grassland holding

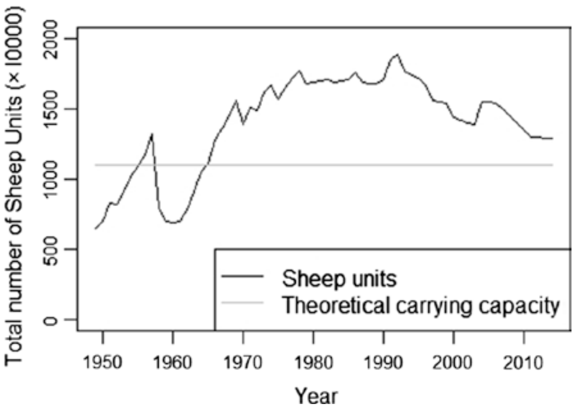


Fig. 7.8 Trend of total number of sheep units ($\times 10^4$) in the Yellow River Source Zone (1949–2014). The theoretical carrying capacity, a weighted average across the Yellow River Source Zone, has been exceeded since the late-1960s (Fu et al. 2007a, b; Li et al. 2012). The total number of sheep units are based on QBS (1949–2006), ARSOQP (1999) and NDRC (2014)

size from 2.1 ha in 1949, 1.0 ha in 2000, to 1.1 ha in 2014 (ARSOQP 1999; NDRC 2014). The theoretical carrying capacity is 1.3 ha grassland per sheep unit (Li et al. 2012). Stocking rates increased notably in the 1990s (Fig. 7.8), coincident with an accelerating rate of grassland degradation (Wang et al. 2006; Fu et al. 2007a, b; Liu et al. 2008a).

Increased stocking levels have resulted in inadequate reserves of fodder and forage, such that some pastoralists have had to graze their livestock at higher elevations, diffusing anthropogenic impact and damage across ever wider areas (Wang and Cheng 2001; Zhou et al. 2003, 2005).

Li (2012) developed a spatial simulation model with which to evaluate the conditions under which the long-term sustainable use of grasslands in the Yellow River Source Zone may occur (see Fig. 7.9). The outcomes of this modelling suggest that sustainable grassland community dynamics are seen at a grazing intensity of 40–60 % with sedges and grasses dominant and fostering local economic development (Fig. 7.9c). Under a simulated grazing intensity of 40–60 % the grassland community becomes dominated by sedges (Fig. 7.9c). Grazing intensities of 60–80 % and over 80 %, however, are detrimental to long-term sustainable use of grasslands with severe degradation emerging at these levels.

Wang et al. (2015) reported that alpine grassland shifted from being dominated by grasses and sedges to a predominance of forbs as the level of degradation increased, with associated shifts in ecosystem function. Thus, the model outcomes suggest that maintaining a grazing intensity between 20–60 % is considered to be suitable for the long-term sustainable use of alpine meadow and alpine-steppe in the Yellow River Source Zone (Fig. 7.9c). A stocking rate of 40–60 % is the sustainable economic development strategy in alpine meadow and alpine-steppe.

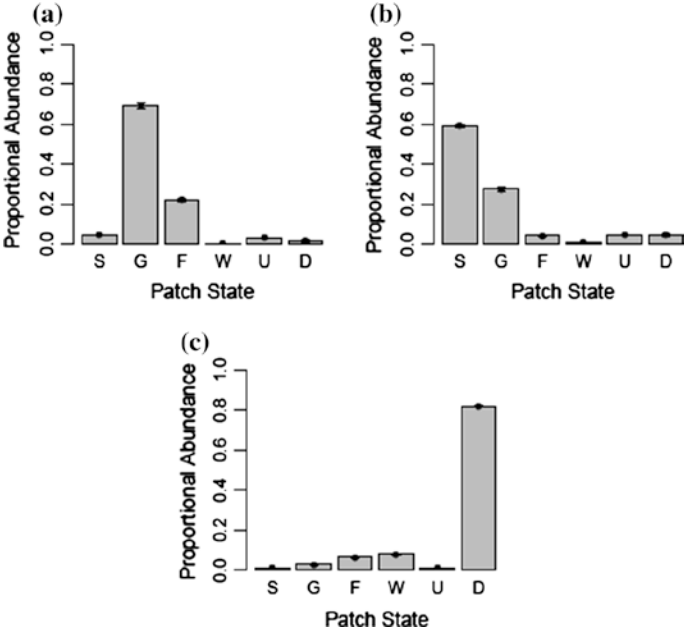


Fig. 7.9 Average proportional abundance of plant functional types (PFTs) (error bars are ±1 SEM) of six states in the landscape under very low (**a**, less than 20 % stocking rate), moderate (**c**, 40–60 % stocking rate) and very high (**e**, more than 80 % stocking rate) grazing levels, across 30 replicates at year 500 of model run. The letters on the x-axes represent four PFTs and two types of ground-sedges (S), grasses (G), forbs (F), weeds (W), unoccupied ground (U) and degraded ground (D)

Reduction of grazing intensity to less than 60 % stocking rate is a key, but not the only, threshold condition for the long-term sustainable use of alpine meadows.

In summary, despite the long history of human activity in the region, large-scale degradation of grassland ecosystems across the Yellow River Source Zone is argued to reflect significant increases in grazing intensity over the past 40–50 years (Liu et al. 2008b, 2013a). It is widely recognized that large mammalian herbivores can change plant community composition and structure (e.g. Augustine and McNaughton 1998). Together with over-trampling, overgrazing leads to local loss of species, reduced vegetative cover, enhanced prospects for soil erosion and loss of soil fertility, and ultimately degradation (Li 1997; Thornes 2007; Papanastasis 2009; Tane 2011; Li et al. 2014). This perspective does not deny the influence of climate change and other stressors upon such process relationships; a combination of factors is surely involved, the relative significance of which varies across the region, but overall, overgrazing is considered to be one of the key drivers of rangeland degradation in the Yellow River Source Zone over the past 50 years or so (Li et al. 2013a).

7.5 The Potential Role of Small Mammals in Grassland Degradation

The rich vertebrate fauna of the Yellow River Source Zone includes plateau pika (*O. curzoniae*, Fig. 7.10), plateau zokor (*Myospalax baileyi*), plateau vole (*Pitymys irene*) and Himalayan marmots (*Marmota himalayana*) (Fig. 1.3). Population irruptions of these small mammals severely affect grasslands via their burrowing and gnawing, which loosen the turf/sod and kill plant roots (Limbach et al. 2000; Zhou et al. 2003, 2005). Outbreaks of these burrowing animals in the Yellow River Source Zone affected an area of 5.03 million ha in 2014 (NDRC 2014); an area equivalent to 36.5 % of the total area of the Yellow River Source Zone. As many as 374 pikas·ha^{-1} have been recorded in some severely damaged areas (Ma et al. 2000). Variability in the population of indigenous small mammals over the past 50 years reflects alterations to the structure of the food chain induced by illegal hunting and inappropriate control measures (e.g. overutilization of poisons). These practices have, in turn, reduced the beneficial role of eagles (*Accipiter* spp.), Tibetan fox (*Vulpes ferrilata*) and weasels in limiting the impacts of small mammals upon grassland (Wang et al. 2000; Zhou et al. 2005; Li et al. 2012). As a result, there have been numerous irruptions of small mammals over the last five or six decades (Li et al. 2013a, b).

The degradation role of these burrowing mammals remains contentious, and degraded *Heitutan* areas have been observed in their absence and where grazing is limited (e.g. Harris 2010). Some researchers argue that some of these species, especially plateau pika, are critical ecosystem engineers (see Smith and Foggin 1999; Lai and Smith 2003; Arthur et al. 2007; Pech et al. 2007; Wilson and Smith 2015), but others consider them harmful and triggers of soil erosion (Zhou et al.

(a) **(b)**

Fig. 7.10 Plateau pika are vital ecosystem engineers atop the Qinghai-Tibet Plateau, benefitting the eco-environment by improving soil conditions and enhancing growth conditions for plants. They feed a large number of carnivores and maintain the balance of ecosystem functions in the Yellow River Source Zone. However, these dynamics are altered at times of irruptions. **a** Alpine meadow with plateau pika activity. **b** Plateau pika (*Ochotona curzoniae*)

2003, 2005; Chen et al. 2007; Li, 2012). Recently, Wilson and Smith (2015) have argued that the ecohydrological engineering effects of pika (enhanced water infiltration due to burrowing reducing overland flow) may have effects across entire catchments. As another example of the engineering role of small mammals on the Qinghai–Tibet Plateau, Liu et al. (2013) shows how higher burrow density decreases the net ecosystem exchange of carbon dioxide, gross ecosystem productivity and ecosystem respiration. There now seems to be a consensus that pikas, as well as burrowing or rodents such as plateau zokors (*M. baileyi*), voles (*Microtus* spp.), and jerboas (*Allactaga* spp.) are naturally occurring features of healthy rangelands on the Qinghai–Tibet Plateau (Smith and Foggin 1999; Lai and Smith 2003; Zhang et al. 2003). When vegetation cover is high, pika occur at moderate densities, but where vegetation cover is lost, they may reach high population densities (Harris 2010). Field investigations have found large differences in the density of small mammal burrows in different degradation classes in the Yellow River Source Zone (cf., Pech et al. 2007). In all but extremely degraded grassland, the magnitude of small mammal irruptions significantly increases with grazing intensity (Liu et al. 2003; Li et al. 2013a, b). On the other hand, populations of small mammals such as plateau zokor can remain stable over decades in the absence of livestock grazing (Zhang et al. 1991). Hence it seems likely that pikas (and other small mammals) exacerbate rather than cause rangeland degradation, and so should be viewed as an indicator rather than a cause of rangeland degradation on the Qinghai–Tibet Plateau.

Despite ongoing debate as to whether high densities of pikas are a result of, rather than a cause of, grassland degradation, programmes to poison small mammals such as the plateau pika have been in place across many areas since the mid-1950s (Fan et al. 1999). The extermination of plateau pika continues to be argued for by researchers who point to the lack of scientific evidence that pika are integral to the ecosystems of the Yellow River Source Zone. In 2014 the control of small mammals was renewed under Phase II of the Qinghai Ecological Protection and Construction in the Sanjiangyuan (NDRC 2014). Extermination, however, has only a localised effect, and populations recover after only a single breeding season as density-dependent controls on the population are relaxed (Pech et al. 2007). Local ecological knowledge supports this assessment; local herders in the Yellow River Source Zone explain that it is not useful to kill pikas, because around six years later, their numbers increase again.

Abandoned and non-active burrows provide opportunities for weeds and forbs to invade and become established (Smith and Foggin 1999). Under low and moderate levels of grazing disturbance, grassland vegetation is more diverse (Wang et al. 2015). Under such conditions, small mammal activity may enhance soil fertility and soil microbial activity (Li et al. 1989), resulting in a wider range of resource conditions for plants (Zhang et al. 2003). Unless intensive physical destruction by small mammals takes place, alpine meadow is little eroded by other natural forces because of its resistant hard sod (i.e. the golf course-like carpet grassland; Miehe et al. 2008). Thus, appropriate levels of grazing may induce a positive influence of small mammals in supporting grassland improvement, but

Fig. 7.11 Small mammal activity at the collapsed edge of healthy grassland (turf/sod meadow). Some degraded ground areas have been excavated by pika at the collapsed edge in the grassland. The difference in surface height between the degraded ground and the turf/sod meadow is less than 10 cm. Photograph from Dari County, 4200 m elevation by Xilai Li in August 2009

these relationships change above some threshold grazing pressure at which point population irruptions of small mammals appear to amplify degradation (Fig. 7.11). Control of small mammals to a fixed, predetermined management target is not a sustainable option because, as noted earlier, small mammal populations rapidly rebound after control measures (Pech et al. 2007).

7.6 Alternative Stable States in the Processes of Grassland Degradation and Restoration

Positive feedbacks (e.g. between topography, soils and vegetation) may hold ecosystems in an apparently stable compositional and structural condition over long periods of time (Groffman et al. 2006; Li 2012; Bowman et al. 2015). However, changes in endogenous and exogenous conditions can result in abrupt changes that bring about abrupt switches in ecosystem condition over broad areas (Williams et al. 2011). Van de Koppel et al. (1997: 355) noted that "a number of empirical studies indicate that plant-soil feedbacks are the dominant cause of catastrophic behaviour in many terrestrial grazing systems". Ecological thresholds arise where small changes in state variables result in large shifts in ecological conditions (Martin et al. 2009). In restoration science, differentiation of alternative stable states and associated threshold conditions can be used to frame management interventions, so long as they identify the underlying mechanisms that drive change (Beisner et al. 2003; Bestelmeyer 2006). For example, ecological thresholds may reflect changes in vegetation and soils that result in shifts to degraded ecosystem states that are expensive or impossible to reverse. Identifying ecological thresholds, and their transgression during ecosystem degradation is vital for the effective rehabilitation of degraded ecosystems (Hobbs and Cramer 2008).

In light of the inherent complexities that must be considered in appraising the underlying controls upon rangeland degradation in the Yellow River Source Zone,

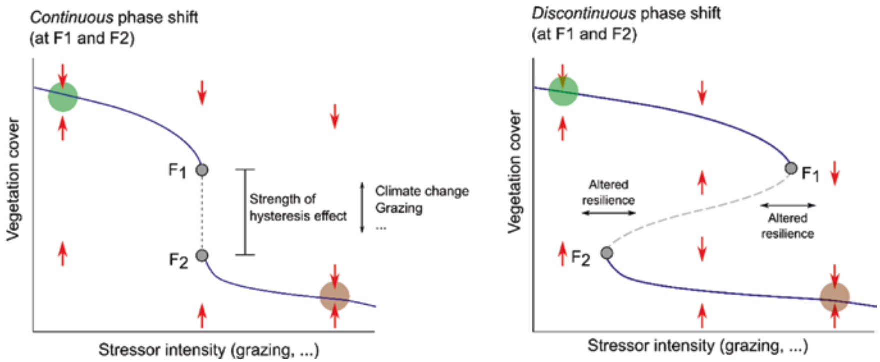


Fig. 7.12 Two possible types of degradation dynamic for grasslands in the Yellow River Source Zone. In both figures the *blue lines* show the environmental state expected under a given set of environment conditions; the *red arrows* represent the direction the system will move in if displaced from the *blue line*; the *green circle* represents relatively intact grassland and the brown circle *Heitutan* grassland. On the *left* is a continuous shift where at point F1 the system 'jumps' to F2. The differences in cover between F1 and F2 represents the strength of the hysteresis effect and may increase with environmental and anthropic stressors. On the *right* is a discontinuous phase shift showing the potential for alternative stable states: that is under the same environmental conditions (stressor intensity) the system can occupy two distinct states. Under such conditions the trajectory of restoration is not symmetrical to that of degradation. The location of thresholds F1 and F2 will be affected by stresses on the system. Figure redrawn from Scheffer et al. (2001) and Filbee-Dexter and Scheilbing (2014)

simple conceptual guidelines may provide useful tools to help frame management responses. Rangeland degradation in this region falls along a continuum of reversibility, both in terms of effort required to address these concerns and the time-frames involved. In the same way that degradation conditions cannot be easily assigned into discrete states, neither can the ease of the recovery process be placed into simple site-level dichotomies such as reversible versus irreversible. At some threshold the capacity of the community to 'self-restore' (i.e. return to some desired state without external intervention) will be lost (e.g. F1 in Fig. 7.12), and at this point restoration will require some form of active intervention. A key biophysical transition occurs when the ground cover becomes bare and soil conditions (physical character and nutrient levels) deteriorate. In these instances, human intervention is likely required to restore the former productivity of these degraded rangelands. This situation is exemplified by the "black soil beach" alpine meadow (Heitutan) and desertification of alpine steppe.

Whether or not degraded grasslands can even be restored to some desired state depends on the extent of alteration. Flips between alternative stable states occur after abiotic and biotic thresholds are transgressed (Suding et al. 2004; Suding and Hobbs 2009; see Figs. 7.9 and 7.12). In the grassland case considered here, intense grazing can trigger rapid biotic and abiotic changes. Biotic change takes many forms, such as reducing plant height and biomass. By contrast, abiotic change refers to physical change, such as soil loss, changes in soil moisture, and so forth.

The extent of biotic and/or abiotic change will determine the difficulty associated with halting grassland degradation at a site (Li et al. 2013a). If abiotic thresholds are transgressed there may be little prospect, at least in the short-term, of self-recovery of dominant native species. In such settings strong hysteresis effects mean that grassland vegetation cannot quickly revert to its former state, even if grazing intensity is reduced or when droughts end.

Frameworks such as those presented in Fig. 7.12 are conceptually appealing. However, considerable work is still required to identify the processes that drive changes, especially determining the biophysical threshold conditions at which switches between alternate states occur, and assessing their geography (i.e. transferability of understanding from one locality to another). Operationalising these conceptual models will require a mixture of carefully targeted field-work and dynamic simulation modelling (see Sect. 7.8).

7.7 Restoration of Degraded Heitutan Grassland

Suding et al. (2004) and Hobbs and Cramer (2008) argue that for restoration programmes to be effective they must: (i) focus on the underlying causes and processes of degradation (rather than the symptoms) and (ii) be grounded in an understanding of the feedbacks and constraints operating in the degraded system. Various approaches, along a gradient of intervention intensity, have been taken to restore degraded grasslands in the source zone of the Yellow River.

Li et al. (2013a) argue, however, that because traditional engineering-based measures can only 'fix' a limited proportion of affected areas, rehabilitation is beyond the capacity of individual farmers, especially given the potential for hysteresis effects in the degradation and recovery processes (see Fig. 7.12). In this context there is clearly a need to better understand the location of 'leverage points' in these systems—conditions where active restoration and/or intervention are most likely to be effective (Brierley et al. 2010; Hobbs et al. 2011). Despite the challenges involved in restoration over these extended spatial scales, Cai et al. (2015) suggests that ecological protection and restoration projects on the plateau have had some success in mitigating grassland degradation and in some areas may even have begun to reverse the degradation process.

Identifying and quantifying ecological thresholds (see Li 2012; Li et al. 2013b, 2014) and the time frames of *Heitutan* degradation processes will aid determination of appropriate land management practices, which will, in turn, help to guide effective ecosystem management. Previous research suggests that restoration of the most extreme classes of *Heitutan* is difficult and slow (Li et al. 2013a, b), especially on steep slopes (Li et al. 2010). Given the challenges in restoring *Heitutan*, management efforts may be better served by targeting areas of moderate degradation, promoting recovery mechanisms that reduce the risk that such areas will be transformed into more degraded *Heitutan*. Commonly suggested rehabilitation and restoration strategies include reducing grazing intensity (Fan et al. 2010), and measures aimed at protecting remaining soil resources from further depletion (Li 2002; Qiao and Duan 2016, Chap. 6; Shang et al. 2006).

Reductions in stock size and enclosure grazing help to lessen the site-specific grazing recurrence interval such that the grassland has sufficient time to recover before the emergence of degradation. As described earlier, *Heitutan* degradation involves multiple constraints and takes multiple trajectories (Li et al. 2013b). Because the abiotic and biotic components of the ecosystem may be altered in extremely degraded grassland, significant human intervention is required to combat the constraints (Li et al. 2013b). In such degraded grasslands, cultivated seeding and introduction of pioneering species are needed to lessen abiotic constraints (Li 1996). In those instances where long-term overgrazing has stripped the protective vegetation cover from the land, leaching nutrients in the exposed soil, and accelerating wind and water erosion, human intervention in the form of artificial seeding of annual and/or pioneering species such as barley and oats is needed to improve soil fertility. Although some more easily germinated plants may not be edible to stock and so have little economic value (e.g., *Pedicularis* spp. and *Ligularia* spp.), they may have a role to play in the process of restoring the degraded ecosystem.

If extremely degraded rangeland is caused by small mammals, two methods are available to control their population: ecological and chemical. Ecological measures are designed to restore the food chain and to increase the population of small mammals' predators, especially eagles. This sustainable control measure has the advantage of no residual environmental impact, but it suffers from a long delay before tangible benefits can be reaped. By comparison, some researchers view chemical control using botulinum toxin baits to be a more effective measure, so long as it does not pollute the environment via secondary poisoning (Jing et al. 2006). These human intervention measures aim to facilitate the self-recovery of degraded ecosystem by promoting the restoration of the wildlife food chain. Different measures are needed to rehabilitate rangelands that have been degraded by different mechanisms. A summary of measures that can be applied in *Heitutan* areas is presented in Table 7.2.

7.7.1 Programmes to Restore Extreme Heitutan on Beach (Low Slope) Areas

The establishment of cultivated grassland may be suitable for the restoration of extremely degraded *Heitutan* on gentle slopes (Ma et al. 2008). In such settings, which typically have poor soil nutrition and relatively flat slopes, ploughing land by machines is feasible due to the relative low risk of water erosion. In areas of extreme *Heitutan*, sedge (*Kobresia*) and grass cover is usually less than 30 % and degraded ground widespread (Fig. 7.7). In such areas, traditional agricultural skills have been applied to enhance the rate of recovery. The fencing-off of areas of extremely degraded grassland and long-term control of grazing (Feng et al. 2003;

Table 7.2 Programmes to restore different grades of degraded Heitutan grassland

Ecological types		Beach		Hillslope	
Degraded grades/classes		Severe	Extreme	Severe	Extreme
Restoration processes		Re-sowing and semi-artificial grassland	Engineering techniques and artificial grassland	Fencing and natural self-restoration	Engineering techniques
Details on method	Suitable native grass species	*Elymus nutans, Elymus breviaristatus*, *Poa crymophila*, *Festuca sinensis*, *etc*.	Same as severe Heitutan with additional annual species and transplanting of native clump species	*Elymus nutans, Elymus breviaristatus*, *Poa crymophila*, *Festuca sinensis*, *etc*.	Same as severe Heitutan with additional annual species and transplanting of native clump species
	Machine management measures	Enclosing grassland → small mammal control → slight raking (5 cm) → re-sowing of big seeds and fertilizing → slightly raking again and earthing up (2–4 cm) → re-sowing of small seeds → compaction of soil to retain soil moisture	Enclosing grassland → small mammals control → deep ploughing deeply (18–22 cm)→ raking → sowing of big-forage seed and fertilizing→ slight raking and earthing up of land (2–4 cm) →sowing of small-forage seed→ compaction of soil to retain soil moisture	Raking of land, alongside procedures for severe Heitutan on beach	Enclosing grassland → small mammal control → slight raking (5 cm) → re-sowing of big seeds and fertilizing → slightly raking again and earthing up (2–4 cm) → re-sowing of small seeds → compaction of soil to retain soil moisture
	Seed sowing density	30–15 kg ha^{-1} for big seeds and 4–7.5 kg ha^{-1} for small seeds	37.5–22.5 kg ha^{-1} for big seeds and 4–7.5 kg ha^{-1} for small seeds	30–15 kg ha^{-1} for big seeds and 4–7.5 kg ha^{-1} for small seeds	37.5–22.5 kg ha^{-1} for big seeds and 4–7.5 kg ha^{-1} for small seeds
	Sowing date	End of May	Early May to middle June	End of May	Early May to middle June
	Field management	150 kg ha^{-1} of urea fertilizer needed for normal seedling growth. No grazing is allowed but utilization in winter is permitted	150 kg ha^{-1} of urea fertilizer needed for normal seedling growth. No grazing is allowed but utilization in winter is permitted	150 kg ha^{-1} of urea fertilizer needed for normal seedling growth. No grazing is allowed but utilization in winter is permitted	150 kg ha^{-1} of urea fertilizer needed for normal seedling growth. No grazing is allowed but utilization in winter is permitted

Kaiser et al. 2008), along with treatment of suitable grass seeds (e.g. pelleting, Liu et al. 2010) and the planting of native species (e.g. *Kobresia* spp.) are required to restore these *Heitutan* grasslands (Zhou et al. 2005; Li et al. 2013b; 2014). Engineering measures may be required to limit soil erosion and improve soil properties. In some instances the use of inedible/weed plants as pioneer plants may also be necessary (Li et al. 2013a, b). Restoration of these areas is likely to take many decades at least; the more severe the degree of degradation, the higher—in both time and money—the cost of repair. Hence, targeted management of less degraded areas may be required to minimize the costs associated with restoration, ensuring that these areas are not transformed into an extremely degraded condition.

7.7.2 Programmes to Restore All Forms of Heitutan on Steeper Slopes

Fencing/enclosure to encourage the self-regeneration of grassland is suitable for restoring all grades/classes of *Heitutan* grasslands on steeper slopes (>7°). This type of degradation accounts for around 5 % of the total land area of the Yellow River Source Zone (Ma et al. 2008; NDRC 2014). Due to its loose surface and soil structure, abandoned and ploughed cropland is highly vulnerable to soil erosion and desertification so ploughing is not suitable.

The restoration of Heitutan has typically involved the control of small mammal outbreaks, and the fencing of degraded areas over extended time-frames (Ma et al. 2007). More interventionist measures such as sowing suitable native grass species may help to restore such degraded areas more quickly (e.g. Shang et al. 2006; Ma et al. 2007). Planting of suitable grass pelleted seeds could be prioritised in *Heitutan* grassland on steeper slopes, and *Kobresia* plants could be transplanted to support the restoration of original vegetation of alpine meadow (Zhao et al. 2006; Li 2012). In other degraded environments, the potential for nurse plants to play an important role for seedling establishment via facilitative effects has been demonstrated (Huber-Sannwald and Pyke 2005), and such methods are worth trialling in the Yellow River Source Zone.

In areas of extreme Heitutan, the following restoration pathway is recommended: rehabilitate largely eroded (bare) ground [→ control small mammal outbreaks] → control soil erosion → reduce overgrazing disturbance → … Field observations indicate that some degraded areas of *Heitutan* have been gradually restored through regeneration of few grasses and sedges, and some of weeds and forbs, following controls to small mammal outbreaks since 1990 (as indicated on Fig. 7.13). Irrespective of the application of such interventions, restoration in such areas is likely to be slow and expensive, and by necessity is initially likely to be highly local. It is also important to note the relative dearth of information regarding the restoration of *Heitutan* grasslands compared to restoration of grassland elsewhere in the world. Further empirical and model-based research is required to evaluate the potential effectiveness of restoration options.

Fig. 7.13 A 20-year naturally recovered area of degraded *Heitutan* with control of small mammals. Prominent patches in the photo are the remnants of the previous alpine meadow. There are many weeds and forbs in the grassland. Photographed in Gande County in the Sanjiangyuan region, 4100 m, August 2009. (*Photo* X.L. Li)

7.8 Concluding Comment: Implications for Sustainable Development Strategies in Grassland Resources

The Qinghai-Tibet Plateau is a vast geographic area and contains a diverse array of landforms, climates and ecosystem types. Given the variability in the inherent sensitivity of rangelands in differing areas, and the differing histories and intensities of human activities in different areas, there are marked differences in the extent of rangeland degradation. In some parts of the region ecosystems remain reasonably intact with little obvious trace of degradation, but many other environments show grave signs of degradation. The evidence available indicates that rangeland degradation started to increase in the 1970s (Liu et al. 2008b), coincident with the intensification of human activities (especially population growth and stocking rates).

Building upon notions outlined by Scheffer et al. (2001) that show how a loss of resilience can trigger a switch to an alternative and persistent ecosystem state, it is suggested that strategies for sustainable management of grassland ecosystems should focus on maintaining resilience. Degradation pathways may take differing forms depending upon the primary agents of change, and may, therefore, engender a suite of alternative stable states. Critically, different recovery starting-points and pathways will require different management practices and will proceed at very different rates. Reduction in grazing intensity is required to rehabilitate reversibly degraded rangelands but is unlikely to be sufficient of itself (see Harris 2010). However, targeted human intervention in the forms of selective planting of grasses and artificial seeding is recommended to rehabilitate 'irreversibly' degraded rangelands.

Ecological protection and restoration are prerequisites for the sustainable development of the region, and these potentially carry with them considerable economic and social benefits (Li et al. 2012; NDRC 2014). Effective approaches to conservation of grassland ecosystems require a strategy that carefully balances protection and construction, with a focus on the livelihoods and wellbeing of local people (Chen et al. 2007; NDRC 2014). Ultimately, grazing management, perhaps supported by modern agricultural approaches and technologies, is fundamental to the successful and sustained restoration of degraded alpine meadows.

Visions for an ecologically sustainable future integrate proactive biodiversity management programmes with coherent strategies that promote regional development and natural resource management (Brierley et al. 2010; Li et al. 2012). Ecological degradation and biodiversity losses in the rangelands of the Yellow River Source Zone will continue unless human developments are managed sensitively and appropriately (Foggin et al. 2006; Shang et al. 2014). Community engagement is required to unite conservation goals with sustainable development initiatives.

Importantly, benefits from environmental conservation and rehabilitation measures extend well beyond the Yellow River Source Zone. Coherent approaches to management of water resources in headwater areas assist prospects for stable and sustained ecological security and economic development downstream (Li et al. 2012; NDRC 2014). Effective conservation programmes do not view ecological reserves as isolated landscape fragments—it should never be forgotten that many species in protected areas depend upon resources outside them (Li et al. 2012; Ran et al. 2016, Chap. 14). Rather, protected areas must be linked to the wider region, providing a basis for the sustainable use of landscapes and natural resources (Brierley et al. 2016, Chap. 15). Precautionary measures should provide sufficient ecological and landscape quality over as wide a range of territory as possible. This enhances the adaptive capacity of the system, enabling appropriate adjustments to be made in response to social and environmental changes.

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References

ARSOQP (Agricultural Resources Section Office of Qinghai Province). (1999). *Agricultural resources data*. China: Qinghai. (in Chinese).

Arthur, A, D., Pech, R. P., Jiebu, Z. Y., et al. (2007). *Grassland degradation on the Tibetan Plateau: The role of small mammals and methods of control*. Canberra: Australian Centre for International Agricultural Research Technical Report 67, p. 35.

Atjay, G. L., Ketner, P., & Duvigneaud, P. (1979). Terrestrial primary production and phytomass. In B. Bolin, E. T. Degens, S. Kempe, et al. (Eds.), *The global carbon cycle* (pp. 129–181). Chichester: Wiley.

Augustine, D. J., & McNaughton, S. J. (1998). Ungulate effects on the functional species composition of plant communities: Herbivore selectivity and plant tolerance. *The Journal of Wildlife Management, 62*, 1165–1183.

Bai, W., Zhag, Y., Xie, G., et al. (2002). Analysis of formation causes of grassland degradation in Maduo County in the source region of Yellow River. *Chinese Journal of Applied Ecology, 13*, 823–826.

Beisner, B. E., Haydon, D. T., & Cuddington, K. (2003). Alternative stable states in ecology. *Frontiers in Ecology and the Environment, 1*, 376–382.

Bestelmeyer, B. T. (2006). Threshold concepts and their use in rangeland management and restoration: The good, the bad, and the insidious. *Restoration Ecology, 14*, 325–329.

Bowman, D. M. J. S., Perry, G. L. W., & Marston, J. B. (2015). Feedbacks and landscape-level vegetation dynamics. *Trends in Ecology & Evolution, 30*, 255–260.

Brierley, G. J., Cullum, C., Li, X. L., et al. (2016). Conclusion: Environmental futures of the Upper Yellow River Basin. In G. J. Brierley, X. Li, & C. Cullum (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 353–370). Berlin: Springer.

Brierley, G. J., Li, X. L., & Chen, G. (Eds.). (2010). *Landscape and environmental science and management in the Sanjiangyuan Region*. Xining: Qinghai People's Publishing House. 176 pp.

Cai, H., Yang, X., & Xu, X. (2015). Human-induced grassland degradation/restoration in the central Tibetan Plateau: The effects of ecological protection and restoration projects. *Ecological Engineering, 83*, 112–119.

Chen, G. C., Chen, X. Q., & Gou, X. J. (Eds.). (2007). *Ecological environment in Sanjiangyuan Natural Reserve*. Xining: Qinghai People's Press. (in Chinese).

Cingolani, A. M., Noy-Meir, I., & Dìaz, S. (2005). Grazing effects on rangeland diversity: A synthesis of contemporary models. *Ecological Applications, 15*, 757–773.

Evans, R. (1998). The erosional impacts of grazing animals. *Progress in Physical Geography, 22*, 251–268.

Fan, J. W., Shao, Q. Q., Liu, J. Y., et al. (2010). Assessment of effects of climate change and grazing activity on grassland yield in the Three Rivers Headwaters Region of Qinghai-Tibet Plateau, China. *Environmental Monitoring and Assessment, 170*, 571–584.

Fan, N. C., Zhou, W. Y., Wei, W. H., et al. (1999). Rodent pest management in Qinghai-Tibet alpine meadow ecosystem. In G. Singleton, L. Hinds, H. Leirs, et al. (Eds.), *Ecologically-based management of rodent pests* (pp. 285–304). Canberra: Australian Centre for International Agricultural Research.

Feng, M., Yang, Z., Deng, Y., et al. (2003). Grassland rehabilitation and social development in the low mountain area of the Jinsha River Valley, China. *Mountain Research and Development, 23*, 124–127.

Filbee-Dexter, K., & Scheibling, R. (2014). Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. *Marine Ecology Progress Series, 495*, 1–25.

Foggin, P. M., Torrance, M. E., Dorje, D., et al. (2006). Assessment of the health status and risk factors of Kham Tibetan pastoralists in the alpine grasslands of the Tibetan plateau. *Social Science and Medicine, 63*, 2512–2532.

Frank, D. A., McNaughton, S. J., & Tracy, B. F. (1998). The ecology of the earth's grazing ecosystems. *Bioscience, 48*, 513–521.

Franzluebbers, A. J., Paine, L. K., Winsten, J. R., et al. (2012). Well-managed grazing systems: A forgotten hero of conservation. *Journal of Soil and Water Conservation, 67*, 100A–104A.

Fu, Y., Li, F. X., & Zhang, G. S. (2007a). Natural rangelands degradation and environmental driving factors in Qinghai Province. *Journal of Glaciology and Geocryology, 29*, 525–535. (in Chinese with English abstract).

Fu, Y., Zhang, G. S., & Li, L. (2007b). The change features and its tendency of ecological environment on Qinghai-Tibetan Plateau. *Journal of Qinghai Meteorology, 2*, 4–10. (in Chinese with English abstract).

Groffman, P., Baron, J., Blett, T., et al. (2006). Ecological thresholds: The key to successful environmental management or an important concept with no practical application? *Ecosystems, 9*, 1–13.

Han, M. Q., Brierley, G. J., Cullum, C., et al. (2016). Climate, vegetation and human land use interactions on the Qinghai-Tibet Plateau through the Holocene. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 253–274). Berlin: Springer.

Harris, R. B. (2010). Rangeland degradation on the Qinghai-Tibetan plateau: A review of the evidence of its magnitude and causes. *Journal of Arid Environments, 74*, 1–12.

Harris, R. B., Wenying, W., Smith, A. T., et al. (2015). Herbivory and competition of Tibetan steppe vegetation in winter pasture: effects of livestock exclosure and plateau pika reduction. *PLoS ONE, 10*(7), e0132897.

Heady, H. F., & Child, R. D. (1994). *Rangeland ecology and management*. Boulder: Westview Press, Inc.

Hobbs, R. J., & Cramer, V. A. (2008). Restoration ecology: Interventionist approaches for restoring and maintaining ecosystem function in the face of rapid environmental change. *Annual Review of Environment and Resources, 33*, 39–61.

Hobbs, R. J., Hallett, L. M., Ehrlich, P. R., et al. (2011). Intervention ecology: Applying ecological science in the twenty-first century. *Bioscience, 61*, 442–450.

Huber-Sannwald, E., & Pyke, D. A. (2005). Establishing native grasses in a big sagebrush-dominated site: An intermediate restoration step. *Restoration Ecology, 13*, 292–301.

Ingrisch, J., Biermann, T., Seeber, E., et al. (2015). Carbon pools and fluxes in a Tibetan alpine Kobresia pygmaea pasture partitioned by coupled eddy-covariance measurements and $^{13}CO_2$ pulse labeling. *Science of the Total Environment, 505*, 1213–1224.

Janzen, H. H. (2011). What place for livestock on a re-greening earth? *Animal Feed Science and Technology, 166*, 783–796.

Jing, Z. C., Wang, Q. J., Shi, H. L., Ma, Y. S., & Shi, J. J. (2006). The poison effect experiment of Botulin model D for plateau pikas (*Ochotona curionial*). *Pratacultural Science, 23*, 89–91. (in Chinese with English abstract).

Kaiser, K., Miehe, G., Barthelmes, A., et al. (2008). Turf-bearing topsoils on the central Tibetan Plateau, China: Pedology, botany, geochronology. *Catena, 73*, 300–311.

Lai, C. H., & Smith, A. T. (2003). Keystone status of plateau pikas (Ochotona curzoniae): effect of control on biodiversity of native birds. *Biodiversity and Conservation, 12*(9), 1901–1912.

Li, X. L. (1996). Effects of resowing grasses on resuming vegetation of 'black soil patch'. *Pratacultural Science, 13*, 17–19. (in Chinese with English abstract).

Li, B. (1997). The rangeland degradation in North China and its preventive strategy. *Scientia Agricultura Sinica, 30*, 1–9. (in Chinese with English abstract).

Li, X. L. (2002). Natural factors and formative mechanism of "black sands" formed on grassland in Qinghai-Tibetan plateau. *Pratacultural Science Sinica, 19*(1), 20–22 (in Chinese with English abstract).

Li, X. L. (2012). *The spatio-temporal dynamics of four plant functional types (PFTs) in alpine meadow as affected by human disturbance*, Sanjiangyuan region, China. Unpublished PhD thesis, The University of Auckland, New Zealand.

Li, X. L., Brierley, G. J., Shi, D. J., et al. (2012). Ecological protection and restoration in Sanjiangyuan National Nature Reserve, Qinghai Province, China. In D. Higgitt (Ed.), *Perspectives on environmental management and technology in Asian River Basins* (pp. 93–120). Berlin: SpringerBriefs in Geography.

Li, X. L., Gao, J., Brierley, G. J., et al. (2013a). Rangeland degradation on the Qinghai-Tibet Plateau: Implications for rehabilitation. *Land Degradation and Development, 24*, 72–80.

Li, X. L., Perry, G. L. W., Brierley, G. J., et al. (2013b). Restoration prospects for Heitutan degraded grassland in the Sanjiangyuan. *Journal of Mountain Science, 10*, 687–698.

Li, X.L., Perry, G.L.W., Brierley, G., & Gao, J. (2010). Grassland degradation of alpine meadow in the Sanjiangyuan region. In G.J. Brierley, X.L. Li, and G. Chen (Eds.). *Landscape and Environmental Science and Management in the Sanjiangyuan Region*, (pp.138–148). Xining: Qinghai People's Publishing House.

Li, X. L., Perry, G. L. W., Brierley, G. J., et al. (2014). Quantitative assessment of degradation classifications for degraded alpine meadows (Heitutan), Sanjiangyuan, Western China. *Land Degradation & Development, 25*, 417–427.

Li, J., Yang, T., & Zhu, G. (1989). Studies on soil microbiology and decomposition of alpine meadow at Haibei Station. In W. Xia (Ed.), *Proceedings of the International Symposium of Alpine Meadow Ecosystem* (pp. 25–28). Beijing: Science Press.

Limbach, W., Davis, J., Bao, T., et al. (2000). The introduction of sustainable development practices of the Qinghai livestock development project. In D. Zheng & L. Zhu (Eds.), *Formation and evolution, environment changes and sustainable development on the Tibetan Plateau* (pp. 509–522). Beijing: Academy Press.

Liu, W., Wang, X., Zhou, L., & Zhou, H. (2003). Studies on destruction, prevention and control of plateau pikas in Kobresia pygmaea meadow. *Acta Theriologica Sinica, 23*, 214–219 (in Chinese with English abstract).

Liu, Y., Fan, J., Harris, W., et al. (2013). Effects of plateau pika (*Ochotona curzoniae*) on net ecosystem carbon exchange of grassland in the Three Rivers Headwaters region, Qinghai-Tibet, China. *Plant and Soil, 366*, 491–504.

Liu, Y., Horisawa, S., & Mukohata, Y. (2010). Effect of seed coating on plant growth and soil conditions: A preliminary study for restoration of degraded rangeland in the Qinghai-Tibetan Plateau, China. *Grassland Science, 56*, 145–152.

Liu, J., Xu, X., & Shao, Q. (2008a). Grassland degradation in the "Three-River Headwaters" region, Qinghai Province. *Journal of Geographical Sciences, 18*, 259–273.

Liu, H. W., Zhou, L., Liu, W., et al. (2008b). Study on dispersal of plateau pika in degraded alpine meadow. *Prataculture and Animal Husbandry, 153*, 8–11. (in Chinese with English abstract).

Lund, H. G. (2007). Accounting for the World's Rangelands. *Rangelands, 29*, 3–10.

Ma, H. (2007). Explanation about the causes of ecological degradation in the Sanjiangyuan District under the perspectives of new institutional economics. *Tibet Studies, 3*, 88–96. (in Chinese with English abstract).

Ma, Y., Dong, Q., Shi, J., et al. (2008). Classification and rehabilitating measurements of "black-soil-beach" degraded grassland in Three River Source Region. *Chinese Qinghai Journal of Animal and Veterinary Sciences, 3*, 1–3. (in Chinese with English abstract).

Ma, Y., Lang, B., Shi, D. (2000). Establishing pratacultural system: a strategy for rehabilitation of 'black soil type' deteriorated grassland on the Qinghai-Tibetan Plateau. In D. Zheng, & L. Zhu (Eds.). *Formation and evolution, environment changes and sustainable development on the Tibetan Plateau*, (pp. 334–339). Beijing: Academy Press (in Chinese with English abstract).

Ma, Y. S., Shang, Z. H., Shi, J. J., et al. (2007). Studies on allocate skills of artificial community of "black soil type" degraded grassland in the Yellow River Source Region. *Acta Agriculturae Boreali-Occidentalis Sinica, 16*, 1–6.

Martin, J., Runge, M. C., Nichols, J. D., et al. (2009). Structured decision making as a conceptual framework to identify thresholds for conservation and management. *Ecological Applications, 19*, 1079–1090.

McGregor, G. R. (2016). Climate variability and change in the Sanjiangyuan region. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 35–58). Berlin: Springer.

Miehe, G., Miehe, S., Kaiser, K., et al. (2008). Status and dynamics of the *Kobresia pygmaea* ecosystem on the Tibetan Plateau. *Ambio, 37*, 272–279.

Miehe, G., Miehe, S., Kaiser, K., et al. (2009). How old is pastoralism in Tibet? An ecological approach to the making of a Tibetan landscape. *Palaeogeography, Palaeoclimatology, Palaeoecology, 276*, 130–147.

NDRC (National Development and Reform Commission, China). (2014). *The second phase for the ecological protection and restoration of Sanjiangyuan*, http://www.sdpc.gov.cn/zcfb/zcfbghwb/201404/W020150203319341893483.pdf. (In Chinese)

Papanastasis, V. P. (2009). Restoration of degraded grazing lands through grazing management: Can it work? *Restoration Ecology, 17*, 441–445.

Pech, R. P., Arthur, A. D., Yanming, Z., et al. (2007). Population dynamics and responses to management of plateau pikas *Ochotona curzoniae*. *Journal of Applied Ecology, 44*, 615–624.

QBS (Qinghai Bureau of Statistics). (1949-2006). *Qinghai Statistical Yearbook* (Vol. 8, pp. 1950–2007). Beijing: China Statistics Press.

Qiao, Y. M., & Duan, Z. H. (2016). Understanding alpine meadow ecosystems. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 117–136). Berlin: Springer.

Qiao, Y. M., & Wang, Q. J. (2010). Driving forces of alpine meadow degradation in the Yellow River headwaters. In G. J. Brierley, X. L. Li, & G. Chen (Eds.), *Landscape and environmental science and management in the Sanjiangyuan Region* (pp. 149–165). Xining: Qinghai People's Publishing House.

Ran, Y. C., Xie, J. X., & Li, X. L. (2016). Socio-economic development and its effects on the ecological environment of the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 331–352). Berlin: Springer.

Ren, J. (2000). Grassland definition. In J. X. Sun (Ed.), *Grassland improvement* (pp. 1–2). Beijing: China Agricultural Press. (in Chinese).

Scheffer, M., Carpenter, S., Foley, J. A., et al. (2001). Catastrophic shifts in ecosystems. *Nature, 413*, 591–596.

Shang, Z. H., Gibb, M. J., Leiber, F., et al. (2014). The sustainable development of grassland-livestock systems on the Tibetan plateau: Problems, strategies and prospects. *Rangeland Journal, 36*, 267–296.

Shang, Z. H., Long, R. J., & Ma, Y. S. (2006). Discussion on restoration and rebuilding of 'Black Soil Patch' degraded meadow in the headwater area of Yangtze and Yellow Rivers. *Chinese Journal of Grassland, 28*, 69–74.

Smith, A. T., & Foggin, J. M. (1999). The plateau pika (*Ochotona curzoniae*) is a keystone species for biodiversity on the Tibetan plateau. *Animal Conservation, 2*, 235–240.

Squires, V. R., & Zhang, K. B. (2009). The context for the study of rangeland degradation and recovery in China's pastoral lands. In V. R. Squires, X. S. Lu, Q. Lu, T. Wang, & Y. L. Yang (Eds.), *Rangeland degradation and recovery in China's pastoral lands* (pp. 3–4). UK: MPG books Group.

Suding, K. N., Gross, K. L., & Houseman, G. R. (2004). Alternative states and positive feedbacks in restoration ecology. *Trends in Ecology & Evolution, 19*, 46–53.

Suding, K. N., & Hobbs, R. J. (2009). Threshold models in restoration and conservation: A developing framework. *Trends in Ecology & Evolution, 24*(5), 271–279.

Suttie, J. M., Reynolds, S. G., & Batello, C. (Eds.). (2005). *Grasslands of the world (Plant Production and Protection Series No. 34)*. Publishing Management Service, Information Division, FAO, Viale delle Terme di Caracalla, 00100 Rome, Italy (www.fao.org/docrep/008/y8344e/y8344e0f.htm)

Tane, H. (2011). The Yellow River watershed in Qinghai's Sanjiangyuan region. In C. Gang, X. L. Li, J. Gao, et al. (Eds.), *Wetland types and evolution and rehabilitation in the Sanjiangyuan Region* (pp. 92–110). Xining: Qinghai People's Publishing House.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) Headwaters. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 275–330). Berlin: Springer.

Tang, L., Dong, S., Sherman, R., et al. (2015). Changes in vegetation composition and plant diversity with rangeland degradation in the alpine region of Qinghai-Tibet Plateau. *The Rangeland Journal, 37*, 107–115.

Thornes, J. B. (2007). Modelling soil erosion by grazing: Recent developments and new approaches. *Geographical Research, 45*, 13–26.

Van de Koppel, J., Rietkerk, M., & Weissing, F. J. (1997). Catastrophic vegetation shifts and soil degradation in terrestrial grazing systems. *Trends in Ecology & Evolution, 12*, 352–356.

Wang, G., & Cheng, G. (2001). Characteristics of grassland and ecological changes of vegetations in the source regions of Yangtze and Yellow Rivers. *Journal of Desert Research, 21*, 101–107. (in Chinese with English abstract).
Wang, G., Shen, Y., & Cheng, G. (2000). Eco-environmental changes and causal analysis in the source regions of the yellow river. *Journal of Glaciology and Geocryology, 22*(3), 200–205. (in Chinese with English abstract).
Wang, X., Dong, S., Sherman, R., et al. (2015). A comparison of biodiversity–ecosystem function relationships in alpine grasslands across a degradation gradient on the Qinghai-Tibetan Plateau. *The Rangeland Journal, 37*, 45–55.
Wang, Q., Lai, D., Jing, Z., et al. (2005). The resources, ecological environment and sustainable development in the source regions of the Yangtze, Yellow and Yalu-Tsangpo Rivers. *Journal of Lanzhou University (Natural Science), 41*, 31–37. (in Chinese with English abstract).
Wang, H., Ren, J. Z., & Yuan, H. B. (2006). Study on the desertification mechanism of natural grassland in the source regions of the Yellow River. *Acta Prataculturae Sinica, 15*, 19–25. (in Chinese with English abstract).
Wen, L., Dong, S., Li, Y., et al. (2013a). Effect of degradation intensity on grassland ecosystem services in the alpine region of Qinghai-Tibetan Plateau, China. *PLoS ONE, 8*, e58432.
Wen, L., Dong, S., Li, Y., et al. (2013b). The impact of land degradation on the C pools in alpine grasslands of the Qinghai-Tibet Plateau. *Plant and Soil, 368*, 329–340.
White, F. (1983). *The vegetation of Africa: A descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa*. Natural Resources Research Series, XX. Paris: UNESCO, 356 p.
White, R., Murray, S., & Rohweder, M. (Eds.). (2000). *Pilot analysis of global ecosystems: Grassland ecosystems*. Washington, D.C: World Resources Institute, http://www.wri.org/wr2000
Whittaker, R., & Likens, G. (1973). The biosphere and man. In H. Lieth & R. H. Whittaker (Eds.), *Primary productivity of the biosphere, ecological studies no. 14* (p. 306). Berlin: Springer.
Williams, J. W., Blois, J. L., & Shuman, B. N. (2011). Extrinsic and intrinsic forcing of abrupt ecological change: Case studies from the late quaternary. *Journal of Ecology, 99*, 664–677.
Wilson, M. C., & Smith, A. T. (2015). The pika and the watershed: The impact of small mammal poisoning on the ecohydrology of the Qinghai-Tibetan Plateau. *Ambio, 44*, 16–22.
World Resources Institute—PAGE. (2000). Downloaded from http://earthtrends.wri.org/text/forests-grasslands-drylands/map-229.htm
Xiang, S., Guo, R., Wu, N., & Sun, S. (2009). Current status and future prospects of Zoige Marsh in Eastern Qinghai-Tibet Plateau. *Ecological Engineering, 35*(4), 553–562.
Zhang, Y., Gao, Q., Dong, S., et al. (2015). Effects of grazing and climate warming on plant diversity, productivity and living state in the alpine rangelands and cultivated grasslands of the Qinghai-Tibetan Plateau. *The Rangeland Journal, 37*, 57–65.
Zhang, G., Li, L., & Wang, Q. (1999). Effects of climatic changes of south Qinghai Plateau on the alpine meadow. *Acta Pratacultural Science, 3*, 1–10. (in Chinese with English abstract).
Zhang, Y., Zhou, W., Fan, N., et al. (1991). Population dynamics and number prediction of plateau zokor. In J. Liu & Z. Wang (Eds.), *From alpine meadow ecosystem fasc. 3* (pp. 175–179). Beijing: Science Press.
Zhang, Y., Zhang, Z., & Liu, J. (2003). Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors Myospalax fontanierii in alpine meadow ecosystems on the Tibetan Plateau. *Mammal Review, 33*(3-4), 284–294.
Zhao, Q.-F., Wang, G., Li, Q.-X., et al. (2006). Genetic diversity of five *Kobresia* species along the eastern Qinghai-Tibet plateau in China. *Hereditas, 143*, 33–40.
Zhou, X. (Ed.). (2001). *Chinese Kobresia Meadow* (p. 297). Beijing: China Science Press. (in Chinese).
Zhou, H., Zhao, X., Tang, Y., et al. (2005). Alpine grassland degradation and its control in the source region of the Yangtze and Yellow Rivers, China. *Grassland Science, 51*, 191–203.
Zhou, H. K., Zhou, L., Zhao, X. Q., et al. (2003). Degradation process and integrated treatment of “black soil bleach” grassland in the source regions of Yangtze and Yellow Rivers. *Chinese Journal of Ecology, 22*, 51–55. (in Chinese with English abstract).

Chapter 8
Modelling Vegetation–Erosion Dynamics in the Mugetan Desert, Yellow River Source Zone

Yanfu Li and Zhaoyin Wang

Abstract Vegetation and aeolian sand erosion are competing and interactive factors in the management of desertification. Outcomes of these interactions affect the geomorphic tendency of desertification areas. This chapter presents a dynamic model of vegetation and aeolian sand erosion and its application in the Mugetan desertification area in the source region of Yellow River. Vegetation–erosion dynamics are assessed to develop a coupling equation of vegetation coverage and aeolian sand erosion. This model takes into account the major influence factors on the dynamics including the climate, landscape, ecological stress and human stresses. This model can be used to simulate and predict the tendencies of vegetation development and aeolian sand erosion in the research area. Results from the application of the model are used to develop the vegetation–aeolian sand erosion chart for the Mugetan desertification area. In this instance, the vegetation–aeolian sand erosion chart has a relatively large Zone C, indicating that once the vegetation coverage reaches a certain value, the capacity for self-improvement is high.

Keywords Aeolian sand erosion · Vegetation development · Ecological stresses · Vegetation–aeolian sand erosion dynamics · Modelling · Yellow River source

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8.1 Introduction

Competition between the movement of sand dunes and the establishment of vegetation is a key influence upon landscape changes in areas prone to desertification (e.g. Bendali et al. 1990; Liu et al. 2002). Mobile sand dunes damage adjacent vegetation, while vegetation cover promotes stabilization of moving sand dunes, thereby aiding the ecological restoration of desertified areas. Wind erosion, sand transport and sand accumulation influence vegetation growth and development. Wind erosion damages soil structure, reduces soil fertility and thus affects the growth of vegetation, in some instances causing plants to wither and die (Liao 1980; Jiang 1983).

Moving sand dunes are products of aeolian sand deposition. In some situations, they bury farmland and grassland, destroying adjacent vegetation. Burial beneath sand affects plant invasion, settlement, growth, distribution and seed dispersal. Aeolian sand transport may alter plant community structure, affecting processes of photosynthesis and water utilization by plants (Schenk 1999). Erosion may expose and break vegetation roots. However, vegetation can prevent or retard water and wind erosion. Primary colonizing vegetation such as moss and associated soil crusts can inhibit wind erosion. Aboveground vegetation retains soil moisture, increases surface roughness, decreases or breaks down the surface wind energy, absorbs the momentum of saltated sand particles and intercepts sand (Van de Ven et al. 1989). Underground root systems can fix the soil and improve soil structure (He and Zhao 2003; Zhang et al. 2009). This helps to stabilize or reduce rates of sand dune migration. Vegetation establishment also encourages biological life, assisting in soil development (Zhang et al. 2009).

Models that assess how vegetation cover impacts upon aeolian sand erosion can be used to assess and predict the movement of sand dunes in desertification areas, informing land management and ecological restoration programmes. Examples include the wind erosion equation (WEQ) (Woodruff and Siddoway 1965), Pasak wind erosion equations, Bocharov model, Texas erosion analysis model (TEAM) (Gregory et al. 1988), wind erosion evaluation model (WEAM), revised wind erosion equation (RWEQ) and wind erosion prediction system (WEPS) (Hagen 1991). WEQ and the Bocharov model are empirical models developed from experiments and field observations. The Texas Erosion Analysis Model (TEAM) combines theoretical model and an empirical model to form a simple process model. The WEPS system incorporates weather, crop growth, decomposition, soil, hydrology and farming subroutines, but is still under development (Yang et al. 2003; Liao et al. 2004). Simulations are commonly performed in wind tunnels to appraise the role of factors such as wind speed, air relative humidity, soil particle size, soil hardness, vegetation coverage, structural breakage of soil structure and surface slope (e.g. Dong 1998).

Some sand transport models consider the impact of vegetation coverage on wind speed and entrainment velocities for sand particle movement (Buckley 1987; Wasson and Nanninga 1986; Shi 2005; Leenders et al. 2011). Iterative coupling of calculations of wind shear stress, sediment rate equations, conservation of mass and vegetation growth models are frequently used to simulate the formation and development processes of sand dunes under the action of vegetation (Luna et al. 2011; Durán et al. 2008).

The growth and distribution of plants are influenced by factors such as temperature, light, moisture and soil nutrients. Plants exchange material, energy and momentum with the surrounding environment. There are many plant growth models (Gates 1980; McMartrie and Wolf 1983; Zhang and Zhang 2000; Guo and Yuan 2000). These models may consider a single variable environmental factor or combinations of factors (Walker et al. 1981; Olson et al. 1985), as well as individual plants or entire vegetation communities (Sharpe et al. 1985; Li et al. 2003; Zhang and Yang 2006). Dynamic vegetation models such as the dynamic global vegetation model (DGVM) can simulate responses to environmental or climate change (Wang 2006b; Wang et al. 2009). Plant succession and ecological stresses (e.g. lethal and/or damage stresses) can also be incorporated within these models (e.g. Pedersen 1998; Wang et al. 2003a, b). Lethal stress leads to plant death and reduced vegetation coverage through factors such as forest fires, deforestation, volcanic eruptions, landslides and debris flow. Damage stress refers to reduction in vegetation vitality but not death (i.e. physiological adaptation) in response to factors such as plant diseases and insect pests, grazing, cyclones, drought and pollution (Wang et al. 2005a).

Li et al. (2009) developed a vegetation and aeolian sand coupling model that incorporated impacts of water, temperature, soil and wind. The study reported here extends this work by including qualitative estimations of ecological stresses and the impacts of human activities. Vegetation development, water erosion and the effects of soil and water conservation measures are simulated, thereby providing theoretical support for watershed management programmes (Wang et al. 2003a, 2005b, 2008; Wang 2006a). This model can be used to evaluate the ecological status and evolution tendency of desertified areas and to provide technical support for desertification control and ecological management.

8.2 Vegetation–Aeolian Sand Erosion Model

Contestations between aeolian sand erosion and vegetation development are played out at the fringes of desert areas. Moving sand dunes damage the vegetation coverage, whereas vegetation promotes stabilization of moving sand dunes and ecological restoration of desertification areas. Dynamic interactions between vegetation development and aeolian sand erosion affect the geomorphic tendency of these areas, determining whether the desert will expand or retreat. This chapter develops a coupling equation of vegetation coverage and aeolian sand erosion dynamics for desertification. In this model, vegetation coverage and the amount of aeolian sand erosion are used to represent vegetation development and aeolian sand erosion, respectively. This model can be used to simulate and predict trends in the establishment of vegetation and aeolian sand dune movement on the fringes of desertification areas. From this, management strategies can be proposed using a vegetation–aeolian sand erosion chart.

In the fringes of desertification areas, the dynamic process between vegetation development and aeolian sand erosion is influenced by natural stresses and human activities including planting trees, felling trees and erosion reduction measures. Natural stresses and human activities play a key role in the evolution process of vegetation and aeolian sand erosion. Based on the vegetation–erosion dynamic model, assuming that the action among the stresses is independent, the coupled differential equations for the vegetation–aeolian sand erosion processes under the action of stresses are obtained as follows:

$$\begin{cases} \frac{\mathrm{d}V}{\mathrm{d}t} - aV + cE = V_R + V_\tau \\ \frac{\mathrm{d}E}{\mathrm{d}t} - bE + fV = E_\tau + E_S \end{cases} \tag{8.1}$$

in which V represents vegetation cover, E represents the rate of aeolian sand erosion (mass area^{-1} time^{-1}), V_R represents positive human stresses (e.g. reforestation; time^{-1}), V_τ represents negative human stresses (e.g. deforestation; time^{-1}), E_τ represents the reduction of aeolian sand erosion by the application of straw checkerboard barriers (mass area^{-1} time^{-2}), and E_S represents the reduction of aeolian sand erosion by the application of sand-fixation measures including sandy gravel cover and sand-protecting barriers(mass area^{-1} time^{-2}). Parameter a represents the increase of vegetation coverage under the action of vegetation (time^{-1}). As vegetation retains moisture and nutrients in soil and promotes the weathering process of fine sand, then the coverage and density of vegetation will be increased. Parameter c represents the reduction of vegetation coverage under the impact of aeolian sand erosion (length^2 mass^{-1}). Aeolian sand erosion damages soil structure and the vegetation roots. Movement of sand dunes destroys vegetation. Parameter b represents the increase of the aeolian sand erosion rate under the influence of aeolian sand erosion (time^{-1}). Aeolian sand erosion destroys the granular structure in the surface soil of a sand dune and exposes the vegetation roots. Then, the rate of aeolian sand erosion will increase. In addition, aeolian sand erosion destroys vegetation and releases the underlying fine sand, which further increases the aeolian sand erosion. Parameter f represents the decrease of the aeolian sand erosion rate under the action of vegetation (mass length^{-2} time^{-2}). Vegetation development promotes the stabilization of sand dunes and the soil-forming process. The development of surface crusts and humus layers protects the sand dunes from aeolian sand erosion.

The theoretical solution for the non-homogeneous linear ordinary differential equations is as follows:

$$\begin{aligned} V &= c_1 e^{m_1 t} + c_2 e^{m_2 t} \\ &\quad + e^{m_1 t} \int \left[e^{-m_1 t} e^{m_2 t} \int e^{-m_2 t} \left(\frac{\mathrm{d}(V_\tau + V_R)}{\mathrm{d}t} - b(V_\tau + V_R) - c(E_\tau + E_S) \right) \mathrm{d}t \right] \mathrm{d}t \end{aligned} \tag{8.2}$$

$$E = c_1 \frac{a - m_1}{c} e^{m_1 t} + c_2 \frac{a - m_2}{c} e^{m_2 t} + e^{m_1 t} \int \left[e^{-m_1 t} e^{m_2 t} \int e^{-m_2 t} \left(\frac{\mathrm{d}(E_\tau + E_S)}{\mathrm{d}t} - a(E_\tau + E_S) - f(V_\tau + V_R) \right) \mathrm{d}t \right] \mathrm{d}t \tag{8.3}$$

in which c_1 and c_2 are the integral constants determined by the boundary and initial conditions, and indices of m_1 and m_2 were given as:

$$m_{1,2} = \frac{1}{2} \left[(a + b) \mp \sqrt{(a + b)^2 - 4(ab - cf)} \right] \tag{8.4}$$

The parameters a, c, b and f are important factors in determining the vegetation–aeolian sand erosion dynamics and the resulting vegetation–aeolian sand erosion chart. They are closely related to climate, soil characteristics and geomorphic conditions and are not related with vegetation and the erosion rate. As such, the parameters of the vegetation–aeolian sand erosion dynamic model and the vegetation–erosion chart are the same in deserts with the same climate and landform conditions. Based on the vegetation–aeolian sand erosion dynamic model, the parameters can be derived using trial-and-error methods and field gathered data. First, the vegetation coverage, V, aeolian sand erosion rate, E, vegetation ecological stress, V_τ and V_R, and reduction of aeolian sand erosion rate, E_τ and E_S, are calculated from measured and related data collected over many years. Second, the coupled differential equations of vegetation–aeolian sand erosion dynamics [Eq. (8.1)] are adapted to difference equations using a differential unit of one year. Third, the parameters a, c, b and f are derived using a trial-and-error method and measured data. Finally, the evolution of vegetation and aeolian sand erosion in the research area is applied to derive the vegetation–aeolian sand erosion chart.

8.3 Application of the Vegetation–Aeolian Sand Erosion Dynamic Model to the Mugetan Desert Area

8.3.1 The Mugetan Desert Area in the Source Area of the Yellow River

The Mugetan Desert area is located in the Gonghe Basin in the source area of the Yellow River with an area of 790 km^2 (see Fig. 8.1). Geophysical explorations indicate that the silt–sand terrane of the Gonghe Basin extends to about 1500 m thick (Xu and Xu 1983). Development of the basin reflects the collapse of the main planation surface of the plateau associated with differential uplift of the Qinghai–Tibet Plateau, with vertical deformation of up to 1700 m (Brierley et al. 2016a, Chap. 1). The Gonghe Movement caused the Yellow River to enter the Gonghe Basin around 0.11 million years ago. Since then, the Yellow River has incised into its basin via

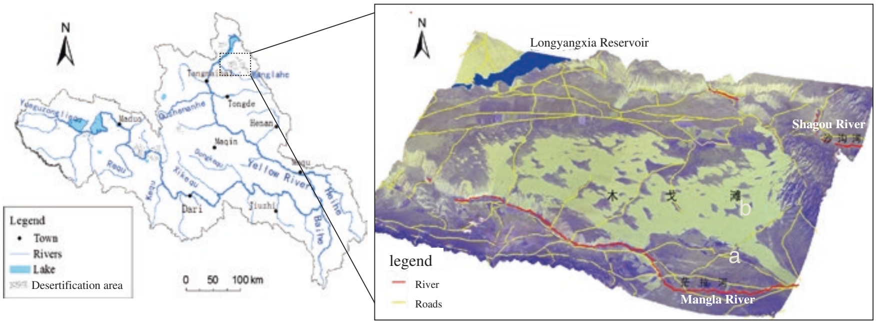

Fig. 8.1 The Mugetan Desert area in the source area of the Yellow River and surrounding streams

knickpoint retreat, at an average rate of 3.5 mm per year. At the same time, ancient alluvial fans at the edge of the basin rose at a similar rate. The resulting layered landform system extends over about 2000 m of elevation difference.

The Yellow River and its tributaries have incised the plateau for a long time, developing multistage terraces at elevations from 3000 to 2200 m asl (Brierley et al. 2016b, Chap. 3). The Mugetan Desert area is located in a high level terrace without any influence of water erosion. The area has a typical plateau continental climate (McGregor 2016 Chap. 2). The average temperature over many years was 2.4 °C, with average annual sunlight exposure of 2720 h, average rainfall of 400 mm and average annual evaporation of 1500 mm. The prevailing wind direction is south-east by south. The maximum wind speed is 14 m per year, with maximum wind speeds $\geq$7 m s^{-1} occurring on an average of 12 days per year (Guo et al. 2009, 2010).

Figure 8.2 shows the number of annual high-wind days and the maximum annual high-wind values from 1961–2009. Aeolian sandstorms are severe and have

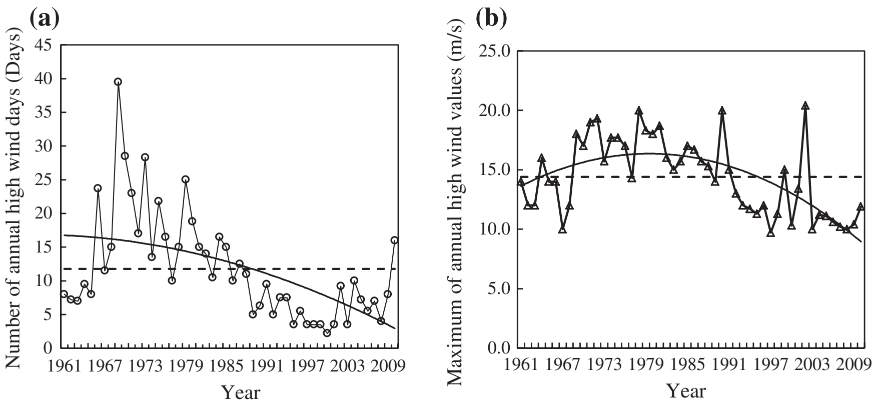

Fig. 8.2 Trend lines of the main characteristics of wind properties from 1961 to 2009. **a** Number of annual high-wind days. **b** Maximum of annual high-wind values

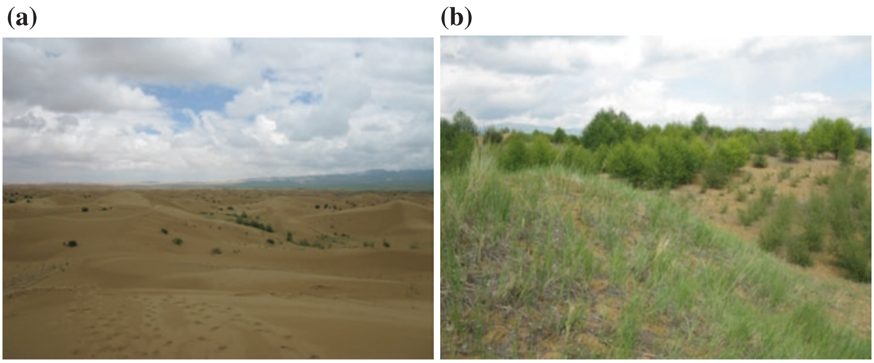

Fig. 8.3 The Mugetan Desert area. **a** Moving sand dunes. **b** Fixed sand deposits

become a serious threat to ecology and pasture land at the margins of the Mugetan Desert area. Vegetation restoration projects have been applied in this area since the 1970s, mainly including afforestation, laying grass squares and gravel and sand fixation. Since then, vegetation growth and aeolian sand erosion have competed with each other in the fringe area of the Mugetan Desert area. The effectiveness of these remedial effects depends on whether vegetation coverage can control wind erosion. Once the movement of sand dunes is controlled by vegetation within a certain region, the desert area will shrink, prompting recovery of the ecological environment.

Moving sand dunes, semi-fixed sand dunes and fixed sand deposits are widely distributed in the fringe area of the Mugetan Desert. The vegetation coverage of moving sand dunes is less than 5 % (Fig. 8.3a). The surface sand of a moving dune is easily moved by wind. The vegetation cover of a fixed sand deposit is over 70~80 % (Fig. 8.3b). The humus layer with a depth of 1–3 cm of a fixed sand deposit effectively retards aeolian sand erosion. The vegetation coverage of semi-fixed sand dunes is 5~60 %. Semi-fixed sand dunes with a vegetation coverage of 5~30 % are mainly covered with trees and shrubs (Fig. 8.4a). The surface sand is easily moved. Semi-fixed sand dunes with a vegetation coverage of 30~60 % are mainly covered with trees, shrubs, straw checkerboard barriers and natural restored vegetation (Fig. 8.4b).

8.3.2 Remote Sensing Analysis of Input Parameters to the Model

Based on remote sensing images, including an MSS image (1977), TM images (1988, 1996, 2003, 2005, 2007, 2008, 2009, 2010), a SPOT 2/4 image (2006) and 43 field ground-object identification spots (widely distributed around the

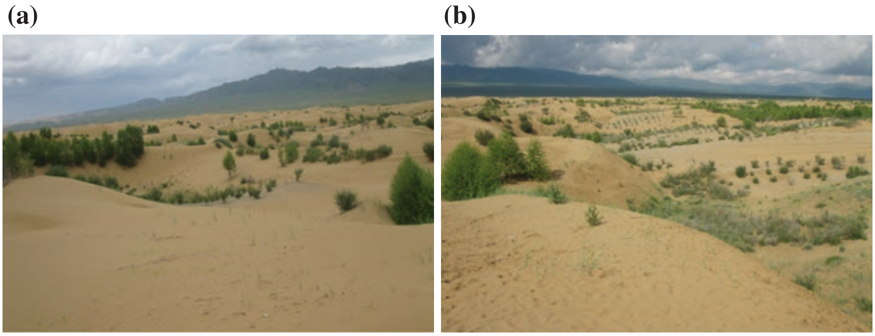

Fig. 8.4 Semi-fixed sand dunes in the Mugetan Desert. **a** Vegetation coverage of 5~30 %. **b** Vegetation coverage of 30~60 %

Mugetan Desert area), the ground features were mapped over a 10-year period. The area values of every ground feature were determined using The Environment for Visualizing Images (ENVI) and an ArcGIS system (Han et al. 2009; Ma et al. 2011). Classes of ground cover were differentiated into areal assessments of moving sand dunes, semi-fixed sand dunes with a vegetation coverage of 5~30 %, semi-fixed sand dunes with a vegetation coverage of 30~60 %, fixed sand deposits with high vegetation cover, meadows, areas of bare soil and open water areas. The regions of fixed sand deposits with high vegetation coverage have a vegetation coverage of 70–80 % without any wind erosion. As the region of bare soil with developed vegetation roots has a much lower aeolian sand erosion rate than the region of aeolian sand dunes, these areas were ignored in the calculation of the aeolian sand erosion rate of the study area. The range of the fringe area of the Mugetan Desert area was identified based on the ground features measured

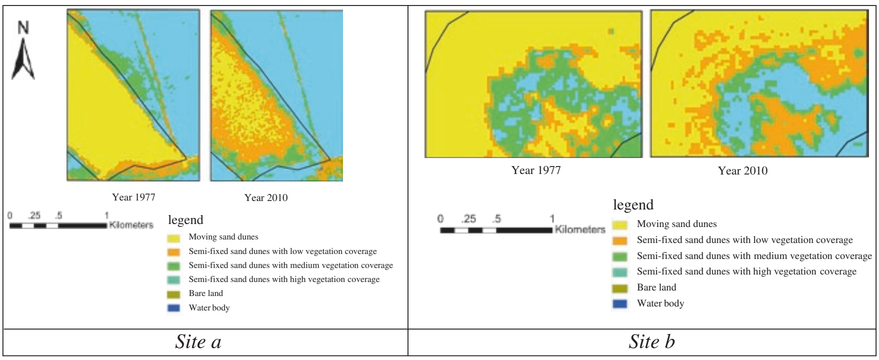

Fig. 8.5 The zoning map of the fringe area of the Mugetan Desert. Sites *a* and *b* are located in Fig. 8.1

Fig. 8.6 Photographs of the fringe area of the Mugetan Desert area. **a** The junction of desert and grassland. **b** The junction of the desert core area and the desert fringe area

between 1977 and 2010 within an area of 423.9 km^2. Figure 8.5a, b shows sketch maps of sites a and site b. Figure 8.6 shows feature photographs on the edges of the study area.

8.3.3 Determination of the Parameters of the Vegetation–Erosion Dynamic Model

In the model of vegetation–aeolian sand erosion dynamics (Eqs. (8.2) and (8.3)), the aeolian sand erosion rate, *E*, is the wind erosion sediment load on a unit area per year, regardless of the sand transport distance and accumulation process. Vegetation coverage, *V*, is the vegetation-covered area on a unit area and can be used to evaluate the development state of the vegetation in the study area. The records of aeolian sand erosion and vegetation in the Mugetan Desert area were rare. Vegetation coverage was estimated using remote sensing images. Aeolian sand erosion rates were approximately calculated using remote sensing images and measured aeolian sand erosion depths (from 1977 to 2010). Planting density was estimated based on engineering documents of sand-fixation projects and field investigation of afforestation areas. Engineering data and documents were used to estimate the wind erosion depth and the reduction of the aeolian sand erosion amount. Forest reservations reduced the outside impact on vegetation by building isolation areas, helping reproduction of vegetation. These vegetation processes are reflected in parameter *a* of the equations of the model of vegetation–aeolian sand erosion dynamics.

Based on the revised remote sensing data of many years, vegetation coverage and the area values of different locations were calculated using ArcGIS and ENVI software (Han et al. 2009; Li et al. 2009; Ma et al. 2011). Aeolian sand erosion depths were obtained by measuring the erosion depth around the vegetation roots. In the region of moving sand dunes, aeolian sand erosion depths at four locations on the surfaces of three moving sand dunes were measured. The annual erosion rate of aeolian sand was roughly 15 cm. In the region of semi-fixed sand dunes with vegetation cover of trees and shrubs, aeolian sand erosion depths at 14 locations on the surfaces of six semi-fixed sand dunes were measured. The aeolian sand erosion depths of 5 years were obtained and used to estimate the aeolian sand erosion depths of the region of semi-fixed sand dunes with a vegetation coverage of 5~30 %. In the region of semi-fixed sand dunes with vegetation cover of trees, shrubs and straw checkerboard barriers, aeolian sand erosion depths of eleven locations on the surfaces of four semi-fixed sand dunes were measured. The aeolian sand erosion depths of 4 years were obtained and used to estimate the aeolian sand erosion depths of the region of semi-fixed sand dunes with a vegetation coverage of 30~60 %. Based on the meteorological and landform data, the annual aeolian sand erosion depths from 1977 to the present were calculated via curve fitting.

As the fringe area of the Mugetan Desert area is far away from agricultural production areas and settlements, inadvertent interference of human activities is negligible. The aeolian sand erosion depths in the fringe areas of the Mugetan desert area are approximately related to climate conditions. Wind tunnel tests and field measurements show that the greater the wind speed and number of high-wind days, the greater the wind erosion depth (Yao et al. 2001). The wind erosion amount has a quadratic relationship with wind speed, a negative quadratic power function relationship with soil particle size and an exponential function relationship with vegetation coverage. Figure 8.7 shows the fitted curves of aeolian sand erosion depth changes as a function of wind strength since 2006. The abscissa is the representative wind strength which is equal to the squared product of the annual maximum wind speed and annual number of high-wind days. Based on the meteorological data at Guinan and the fitting formula given in Fig. 8.7, wind erosion depth values since 1961 were obtained. Based on the wind erosion depth values and area values derived from different locations, the annual aeolian sand erosion rate was calculated (Table 8.1).

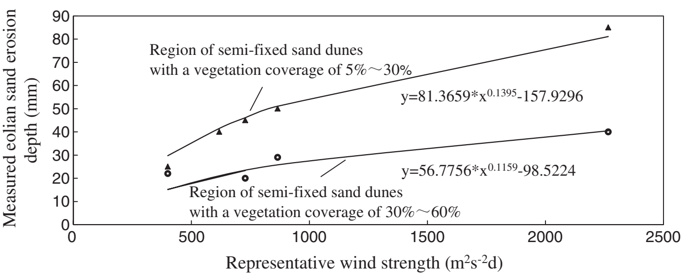

Fig. 8.7 Annual aeolian sand erosion depth changes as a function of the representative wind strength since 2006

Table 8.1 Estimated aeolian sand erosion rate and vegetation coverage in the fringe area of the Mugetan Desert area

Year	1977	1988	1996	2003	2005	2006	2007	2008	2009	2010
Aeolian sand erosion rate (E) (t km^{-2} yr^{-1})	100,876	91,513	77,562	66,874	56,037	52,747	50,814	47,975	48,201	38,214
Vegetation coverage (V) (%)	7.00	12.87	16.77	23.47	24.38	25.76	31.30	31.87	32.59	35.88

Beginning in the late 1970s, forest planting was performed through the Three-North Shelterbelt Program. Beginning in the late 1990s, many control measures were completed through several plans, including afforestation and straw checkerboard barriers (Ma 2006; Wang et al. 2000; Yang et al. 2006). From 1998 to 1999, many trees were inadvertently cut down (La 2002; La et al. 2001). In the 2000s, a series of management projects was continuously performed. Efforts to stabilize the sand dunes and restore the ecological environment included planting trees, straw checkerboard barriers, sandy gravel cover, sand-protecting barriers and forest reservation measures. The annual value of vegetation ecological stress, V_τ and V_R, and the reduction of the aeolian sand erosion rates (E_τ and E_S) were estimated based on project data, literature values and relevant measured data (see Table 8.2).

Based on the previously calculated results (including vegetation coverage, aeolian sand erosion rate, value of vegetation ecological stress and reduction of aeolian sand erosion rate), a trial-and-error method was performed many times for every adjustment of each parameter until the best-fitting value of the parameter was obtained. Derived parameters given in Eq. (8.1) for the Mugetan Desert area were determined as follows:

$$\mathrm{a} = 0.06;\ c = 0.0000000987;\ b = 0.125;\ f = 16{,}000 \tag{8.5}$$

A comparison of the model and measurements shows the measured and calculated processes of vegetation development and aeolian sand erosion of the Mugetan Desert area (Fig. 8.8).

Table 8.2 Annual value of vegetation ecological stress and reduction of the aeolian sand erosion rate

Year	Vegetation ecological stress V_τ, V_R (time^{-1})	Reduction of aeolian sand erosion rate E_τ, E_S (mass area^{-1} time^{-2})
1977~1996	$V_R = 0.2 \sim 0.5\,\%$	$E_\tau + E_S = 4000 \sim 6000\,\mathrm{t\,km^{-2}\,a^{-1}}$
1997~1999	$V_R = 0.2 \sim 0.5\,\%$; $V_\tau = 0.5 \sim 1.0\,\%$	$E_\tau + E_S = 4000 \sim 6000\,\mathrm{t\,km^{-2}\,a^{-1}}$
2000~2005	$V_R = 0.2 \sim 0.5\,\%$,	$E_\tau + E_S = 4000 \sim 7000\,\mathrm{t\,km^{-2}\,a^{-1}}$
2006~2010	$V_R = 0.5 \sim 1.0\,\%$	$E_\tau + E_S = 5000 \sim 8000\,\mathrm{t\,km^{-2}\,a^{-1}}$

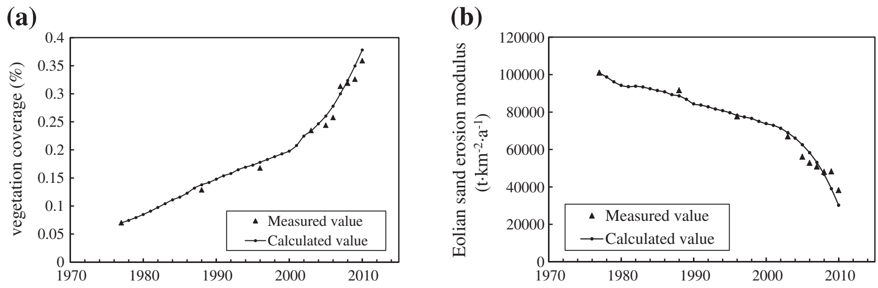

Fig. 8.8 Comparison of the measured and calculated processes of (**a**) vegetation coverage and (**b**) aeolian sand erosion rate in the fringe area of the Mugetan Desert area

8.3.4 Applications of the Vegetation–Aeolian Sand Erosion Chart and Discussions

A vegetation–aeolian sand erosion chart was obtained based on the model of vegetation–aeolian sand erosion dynamics (Fig. 8.9; Wang et al. 2003b). In the case of no human-induced stresses, assuming the stress terms in Eq. (8.1) are equal to zero and $V' = \frac{\mathrm{d}V}{\mathrm{d}t}, \quad E' = \frac{\mathrm{d}E}{\mathrm{d}t}$ can be rewritten as $V' = 0$, and $E' = 0$. V′ and E′ may be positive or negative. Therefore, the V-E plane: V∈[0.1], E∈[0, ∞) can be divided into 3 zones by the two lines V′ = 0, E′ = 0:

1. Zone A: $\mathrm{d}V/\mathrm{d}t < 0$, $\mathrm{d}E/\mathrm{d}t > 0$ (vegetation cover is decreasing and the erosion rate is increasing).

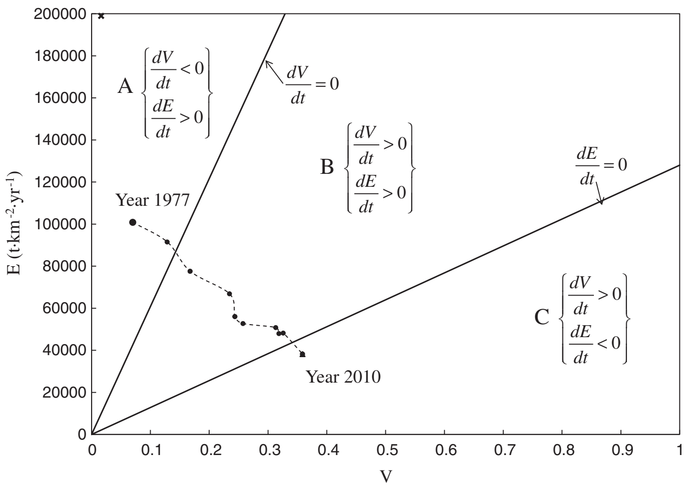

Fig. 8.9 Vegetation–aeolian sand erosion chart for the Mugetan Desert area (x—the ungoverned area of the Mugetan Desert area in 2010). E refers to erosion rate, V refers to % vegetation cover

2. Zone C: $\mathrm{d}V/\mathrm{d}t > 0$, $\mathrm{d}E/\mathrm{d}t < 0$ (vegetation cover is increasing and the erosion rate is decreasing).
3. Zone B: $\mathrm{d}V/\mathrm{d}t > 0$, $\mathrm{d}E/\mathrm{d}t > 0$ or $\mathrm{d}V/\mathrm{d}t < 0$, $\mathrm{d}E/\mathrm{d}t < 0$ (both vegetation cover and erosion rate are either increasing or decreasing).

The vegetation–erosion chart can be used to discuss the development trend of vegetation and erosion in the case of no human-induced stresses. From Eq. (8.1), two lines $V' = 0$, $E' = 0$ which divide the V-E plane: $V \in [0.1]$, $E \in [0,\infty)$ into three parts depend on the four parameters a, c, b, f:

$$E = \frac{a}{c}V;\ E = \frac{f}{b}V \tag{8.6}$$

Evolutionary transitions from 1977–2010 show progressive reductions in sand movement over time (Fig. 8.9).

The vegetation–aeolian sand erosion chart of the source region of Yellow River has a relatively large Zone C. Figure 8.9 indicates that once the vegetation coverage reaches a certain value and the aeolian sand erosion rate decreases to a certain value, vegetation has a strong ability to self-improve, whether through natural or artificially induced vegetation succession process. As long as the vegetation does not suffer severe damage, the vegetation develops well and stabilizes the sand dunes.

In 1977, the ecological system of vegetation coverage and aeolian sand erosion in the fringe area of the Mugetan Desert area operated in Zone A is shown in Fig. 8.9. The intensity of aeolian sand erosion was far greater than the protective action of vegetation at this time. In Zone A, the vegetation cover is deteriorating and the erosion rate is increasing (i.e. desertification is getting worse). After 1977, trees were planted and straw checkerboard barriers were installed. When the vegetation cover increased to 15 % and the aeolian sand erosion rate reduced to less than 85,000 t km^2 y^{-1}, vegetation is able to control the moving sand dunes. In Zone B, the vegetation cover is in an unstable state. Both vegetation cover and erosion are increasing. If erosion increases faster or human stresses cause deforestation and erosion continues to increase, the ecological system may enter Zone A. If vegetation increases faster or human controls are applied to erosion, such as reforestation, the ecological system may enter Zone C.

Since the 1980s, the vegetation projects became effective in the fringe area of the Mugetan Desert. The vegetation coverage increased year by year, gradually reducing aeolian sand movement. When the vegetation cover increased to 35 % and the aeolian sand erosion rate reduced to less than 40,000 t km^2 yr^{-1}, the ecological system entered Zone C. In Zone C, the ecological system moves towards complete vegetation cover with an aeolian sand erosion rate of zero.

Figure 8.9 shows the ecological system now lies on the edge of Zone C (assuming no change in status since 2010). Sand dunes are controlled by vegetation, but are not stable. Vegetation management should continue to be intensively performed until the vegetation develops to rapidly stabilize the aeolian sand dunes. Then, under the action of developed vegetation, the sand dunes in the fringe area of the Mugetan Desert will gradually be stabilized and desert expansion will be stopped.

Point “**x**” on the top left-hand side of Fig. 8.9 is the typical position for most parts of the Mugetan Desert area. As this is far removed from area C, afforestation is unlikely to stabilize sand dunes in its own right. At present, it is necessary to control aeolian sand erosion and push point “**x**” to the right by many measures. When the aeolian sand erosion rate is reduced to less than 85,000–100,000 t km^2 y^{-1}, vegetation management could then make the ecological systems of most of the Mugetan Desert area enter Zone C. When the aeolian sand erosion rate is reduced to less than 40,000 t km^2 y^{-1}, vegetation becomes the main control on erosion. The vegetation–aeolian sand erosion chart also shows that desert management could start from the edges of the desert and gradually advance towards the centre of the desert. First, the ecological system of the fringe area of desert must enter area C. Management strategies can then progressively advance towards the desert core. The approach outlined here could provide a valuable starting point to appraise the effectiveness of vegetation management strategies to arrest desertification processes elsewhere in the Upper Yellow River Basin.

References

Bendali, F., Floret, C., Le Floch, E., et al. (1990). The dynamics of vegetation and sand mobility in arid regions. *Journal of Arid Environments, 18*, 21–32.

Brierley, G. J., Li, X., Cullum, C., et al. (2016a). Introduction: Landscape and ecosystem diversity in the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 1–34). Berlin: Springer.

Brierley, G. J., Yu, G. A., & Li, Z. W. (2016b). Geomorphic diversity of rivers in the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 59–78). Berlin: Springer.

Buckley, R. (1987). The effect of sparse vegetation on the transport of dune sand by wind. *Nature, 325*, 426–428.

Dong, Z. B. (1998). Establishing statistic model of wind erosion on small watershed basis. *Bulletin of Soil and Water Conservation, 18*, 55–62 (in Chinese).

Durán, O., Silva, M. V. N., Bezerra, L. J. C., et al. (2008). Measurements and numerical simulations of the degree of activity and vegetation cover on parabolic dunes in north-eastern Brazil. *Geomorphology, 102*, 460–471.

Gates, D. J. (1980). Competition between two types of plants located at random on a lattice. *Mathematical Biosciences, 48*, 157–194.

Gregory, J. M., Borrelli, J., & Fedler, C. B. (1988). Team: Texas erosion analysis model. In *Proceedings, 1988 Wind Erosion Conference* (pp. 88–103). Lubbock: Texas Tech University.

Guo, S. S., He, L. B., & Xu, Z. F. (2010). Variety trend analysis of sunshine hours in Guinan County in recent 50 Years. *Journal of Anhui Agricultural Sciences, 38*, 8530–8532. 8538 (in Chinese).

Guo, R. H., & Yuan, X. F. (2000). Hopf bifurcation for a ecological mathematical model on microbe populations. *Applied Mathematics and Mechanics, 21*, 693–700 (in Chinese).

Guo, L. Y., Zhong, C., Ding, S. X., et al. (2009). Local climate changes and their impacts on grassland degradation in Gonghe basin of Guinan county of Qinghai province in past half-century. *Chinese Journal of Agrometeorology, 230*, 147–152 (in Chinese).

Hagen, L. J. (1991). A wind erosion prediction system to meet the users need. *Journal of Soil and Water Conservation, 46*, 107–111.

Han, H. H., Yang, T. B., & Wang, Y. (2009). Dynamic analysis of land use and landscape pattern changes in Guinan county, Qinghai, in the past 30 years. *Process in Geography, 28*, 207–215.

He, Z. B., & Zhao, W. Z. (2003). Characteristics of soil moisture of different vegetation types in initial stage of fixed sand dune of semi-arid region. *Journal of Soil and Water Conservation, 17*, 164–167 (in Chinese).

Jiang, J. (1983). Research on biology and physiology characteristics of main sand-fixation plant in Shapotou. *Forest Science, 19*, 113–120 (in Chinese).

La, Y. L. (2002). The current situation of grassland ecological environment and its control strategies. *Pratacultural Science, 19*, 1–4 (in Chinese).

La, Y. L., Liang, Z. Y., & Banma, D. J. (2001). Alpine grassland desertification and control method and countermeasure of Guinan County. *Qinghai Prataculture, 11*, 41–45 (in Chinese).

Leenders, J. K., Sterk, G., & Van Boxel, J. H. (2011). Modelling wind-blown sediment transport around single vegetation elements. *Earth Surface Processes and Landforms, 36*, 1218–1229.

Li, Z. S., Wang, Y., & He, L. (2009). Vegetation-erosion process in semiarid region: Dynamical models. *Journal of Desert Research, 29*, 23–30 (in Chinese).

Li, Z. Z., Wang, W. X., & Xu, C. L. (2003). The dynamic model of crop growth system and numerical simulation of crop growth process under the multi-environment external force action. *Applied Mathematics and Mechanics, 24*, 644–652 (in Chinese).

Liao, C. Y. (1980). *Research on the choice machine characteristics of several sand-fixation plants. Quicksand quality research* (pp. 60–120). Ningxia: Ningxia People's Publishing House (in Chinese).

Liao, C. Y., Li, J., & Zheng, F. L. (2004). Research history and trend of wind erosion prediction abroad. *Research of Soil and Water Conservation, 11*, 50–53 (in Chinese).

Liu, Z. M., Zhao, X. Y., & Liu, X. M. (2002). The relation between interference and vegetation. *Acta Prataculturae Sinica, 11*, 1–9 (in Chinese).

Luna, M. C. D. M., Parteli, E. J. R., Durán, O., et al. (2011). Model for the genesis of coastal dune fields with vegetation. *Geomorphology, 129*, 215–224.

Ma, J. H. (2006). *An ecological oasis with an area of 18 million mu was completed in Guinan*. Qinghai news network, http://news.sina.com.cn/c/2006-07-06/08449385326s.shtml (in Chinese).

Ma, Y. F., Yan, P., & Zhang, D. S. (2011). Pattern of aeolian-fluvial interaction in Gonghe basin, Qinghai Province based on GIS. *Journal of Arid Land Resources and Environment, 25*, 151–156 (in Chinese).

McGregor, G. R. (2016). Climate variability and change in the Sanjiangyuan region. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 35–58). Berlin: Springer.

McMartrie, R., & Wolf, L. (1983). A model of competition between trees and grass for radiation, water and nutrients. *Annals of Botany, 52*, 449–458.

Olson, R. L. J., Sharpe, P. J. H., & Wu, H. (1985). Whole-plant modelling: A continuous-time Markov (CTM) approach. *Ecological Modelling, 29*, 171–187.

Pedersen, B. S. (1998). Modeling tree mortality in response to short- and long-term environmental stresses. *Ecological Modelling, 105*, 347–351.

Schenk, H. J. (1999). Clonal splitting in desert shrubs. *Plant Ecology, 141*, 41–52.

Sharpe, P. J. H., Walker, J., Penridge, L. K., et al. (1985). A physiologically based continuous-time Markov approach to plant growth modelling in semi-arid woodlands. *Ecological Modelling, 29*, 189–213.

Shi, X. F. (2005). *Relation between vegetation conditions and eolian sand activities in north semiarid regions. Master Dissertation*. Beijing: Life and Environmental Science College of Central University for Nationalities (in Chinese).

Van de Ven, T. A. M., Fryrear, D. W., & Spaan, W. P. (1989). Vegetation characteristics and soil loss by wind. *Journal of Soil and Water Conservation, 44*, 347–349.

Walker, B. H., Ludwig, D., Holling, C. S., et al. (1981). Stability of semi-arid savanna grazing systems. *Journal of Ecology, 69*, 473–498.

Wang, F. X. (2006a). Research on the vegetation-erosion dynamics and its application to typical erosion areas of China. Doctoral Dissertation, Tsinghua University, China.

Wang, X. M. (2006b). The international development trend of dynamic vegetation model. *Science Journalism, 5*, 18–20 (in Chinese).

Wang, Z. Y., Guo, Y. B., Li, C. Z., et al. (2005a). Vegetation-erosion chart and its application in typical watershed in China. *Advances in Earth Science, 20*, 149–157 (in Chinese).

Wang, X. F., Ma, M. G., & Yao, H. (2009). The research progress of dynamic global vegetation model. *Journal of Remote Sensing Technology and Application, 24*, 246–251 (in Chinese).

Wang, Z. Y., Wang, G. Q., & Gao, J. (2003a). An ecological dynamics model of vegetation evolution in erosion area. *Acta Ecologica Sinica, 23*, 98–105 (in Chinese).

Wang, Z. Y., Wang, G. Q., & Huang, G. H. (2008). Modeling of state of vegetation and soil erosion over large areas. *International Journal of Sediment Research, 23*, 181–196 (in Chinese).

Wang, Z. Y., Wang, G. Q., Li, C. Z., et al. (2003b). Preliminary exploration and application of the vegetation and erosion dynamics. *Science in China (Series D), 33*, 1013–1023 (in Chinese).

Wang, Z. Y., Wang, G. Q., Li, C. Z., et al. (2005b). A preliminary study on vegetation-erosion dynamics and its applications. *Science in China (Series D Earth Sciences), 48*, 689–700 (in Chinese).

Wang, Z. T., Zhu, C. Y., Yang, Z. W., et al. (2000). A comprehensive summary of control techniques and experience of moving sand dunes in Huangshatou in Guinan. *Science and Technology of Qinghai Agriculture and Forestry, 3*, 45–47 (in Chinese).

Wasson, R. J., & Nanninga, P. M. (1986). Estimating wind transport sand on vegetated surface. *Earth Surface Processes and Landforms, 11*, 505–514.

Woodruff, N. P., & Siddoway, F. H. (1965). A wind erosion equation. *Soil Science Society of America Proceedings, 29*, 602–608.

Xu, S. Y., & Xu, D. (1983). Eolian sand accumulation in east bank of Qinghai Lake. *Journal of Desert Research, 3*, 11–17 (in Chinese).

Yang, H. X., Lu, Q., Wu, B., et al. (2006). Ecological restoration in alpine sandy lands of Gonghe basin, Qinghai Province. *Science of Soil and Water Conservation, 4*, 7–12 (in Chinese).

Yang, X. C., Yan, P., & Liu, L. Y. (2003). Advances and commentaries on wind erosion of soil. *Agricultural Research in the Arid Areas, 21*, 147–153 (in Chinese).

Yao, H. L., Yan, D., Hu, X. L., et al. (2001). Research on the law of wind erosion and deposition of sediment in moving sand dunes in Maowusu sandy land. *Mongolia Forestry Science and Technology, 1*, 3–9 (in Chinese).

Zhang, H. J., Liu, Z. G., & Gong, H. P. (2009). Spatiotemporal change of soil water in fixed sand dune. *Journal of Inner Mongolia Forestry Science and Technology, 35*, 23–26 (in Chinese).

Zhang, C. Q., & Yang, C. (2006). Simulation of plant growth and mathematical modeling study. *Acta Scientiarum Naturalium Universities Neimongol, 37*, 435–440.

Zhang, Y. P., & Zhang, J. T. (2000). The permanence of nonperiodic predator-prey system of three species Lotka-Volterra. *Applied Mathematics and Mechanics, 21*, 792–797 (in Chinese).

Chapter 9
Wetland Ecosystems of the Yellow River Source Zone

Zhiwei Li, Zhaoyin Wang and Baozhu Pan

Abstract Diverse wetlands such as alpine meadows, lakes and peatlands are extremely important resources for water supply and ecological protection of aquatic ecosystems in the source zone of the Yellow River. Field surveys (2010–2014) and interpretations of remote sensing images are used to provide insights into the distribution of wetlands in this region and associated notions of landscape connectivity. Ruoergai Swamp (Zoige) at the eastern margin of the Qinghai–Tibet Plateau in the Yellow River Source Zone is the world's largest plateau peat wetland. A case study of this swamp shows that it has shrunk greatly since the 1950s. Environmental suffering (i.e. desertification, grassland degradation and run-off reduction) is leading to the ecological degradation of the Ruoergai peatlands, severely affecting local herdsmen and the surrounding communities (e.g. Sichuan Basin and the Upper Yellow River). Wetland degradation is affected by both global climate warming and human activities (especially construction of artificial ditches). The second half of this chapter uses field and laboratory analyses of benthic macroinvertebrates as indicators to assess the status of aquatic ecosystems

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in the region, contrasting findings from the Upper Yellow and Yangtze rivers. Human activities such as artificial ditch system, overstocking and peat mining have impacted upon local aquatic ecosystems. Such pressures have been accentuated by the economic and social development since the 1980s.

Keywords Wetland · Peatland degradation · Aquatic ecosystem · Macroinvertebrates · Human activities

9.1 Introduction

The shrinkage of wetlands on the Qinghai–Tibet Plateau since the 1950s endangers both local terrestrial and aquatic ecosystems as well as the supply of water from the Yellow River Source Zone to the 110 million people who live in downstream catchments. The degradation and loss of wetlands has intensified across the world in recent decades. Recently, Niu et al. (2012) reported that the area of wetlands in China in 2008 was around 324,097 km^2, a reduction of about 33 % since 1978. The rapid shrinkage of wetlands in China is attributed to fill, drainage and agricultural development associated with population growth and rapid economic development and to climate warming (Qiu et al. 2009; Zhou et al. 2009).

Wetlands provide many ecological functions and ecosystem services, including the provision of habitat for diverse wildlife, acting as carbon sinks that mitigate effects of climate warming and, filtering sediments in ways that buffer nutrient loads and improve water quality and reducing the frequency and extent of flooding (Barbier et al. 1997; Brinson and Malvarez 2002). Enhanced protection and restoration of wetlands is therefore an important component of programmes to support the maintenance of aquatic and terrestrial ecosystems, mitigate floods and improve water quality (Cao and Fox 2009; Niu et al. 2011).

We start this chapter by considering the different types of wetlands found on the Qinghai–Tibet Plateau, describing the processes that have generated them and ways they have changed in recent years. Next, we focus on the Zoige (Ruoergai) peatlands, a vast wetland of international importance with a rich cultural history. The various processes contributing to the shrinking of wetland area and the degradation of the remaining peatlands are discussed. Several methods to assess erosion rates in this region are outlined. The latter part of this chapter is concerned with the biota found within the aquatic ecosystems of the areas through systematic analysis of macroinvertebrate assemblages in the source regions of the Yellow and Yangtze rivers.

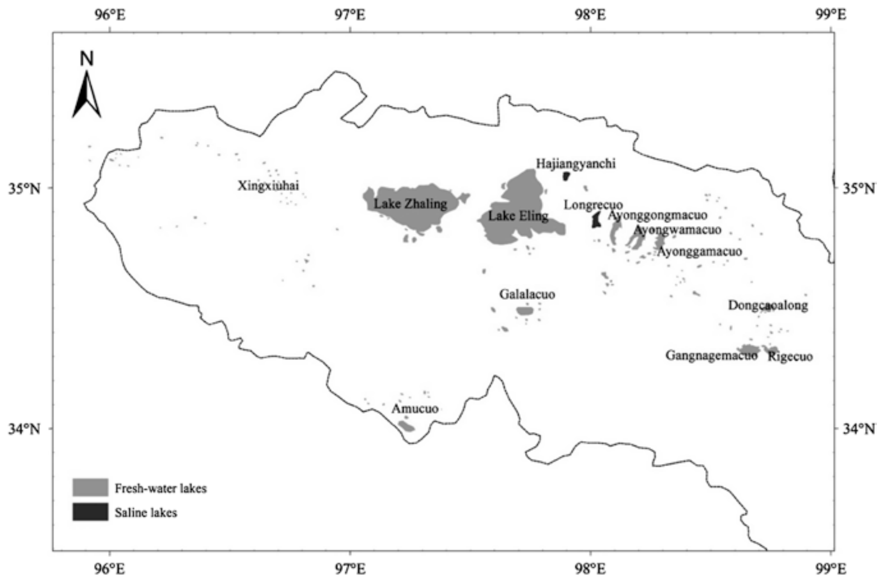

Fig. 9.1 Lakes in the Yellow River Source Zone

9.2 An Overview of Wetlands in the Yellow River Source Zone

Wetlands in the Yellow River Source Zone are concentrated mainly in the upper segments of the river (Fig. 9.1; Brierley et al. 2016, Chap. 3; Huang et al. 2016, Chap. 4). Several different wetland types are found in this region, including alpine meadow wetlands, lakes and peatlands (Blue et al. 2013; Gao et al. 2013; Nicoll et al. 2013). Each of these types of wetland is generated and sustained by different processes and is therefore vulnerable to different risks and likely to respond in different ways to the impacts of climate change and human activities.

9.2.1 Alpine Meadow Wetlands

Alpine meadow wetlands are found in the lowland areas on the gentle footslopes of alpine watersheds (see Gao 2016, Chap. 10). Snowmelt and rainfall produce groundwater seepage at the base of hillslopes, thereby forming a shallow water zone, where flow velocity is very slow due to the narrow outlet and blocked drainage. For example, the Xingsuhai region in the Yellow River Source Zone area has an arid-cold climate with little precipitation, but evaporation is relatively low due to the low-temperature regime. Based on the above conditions, many alpine

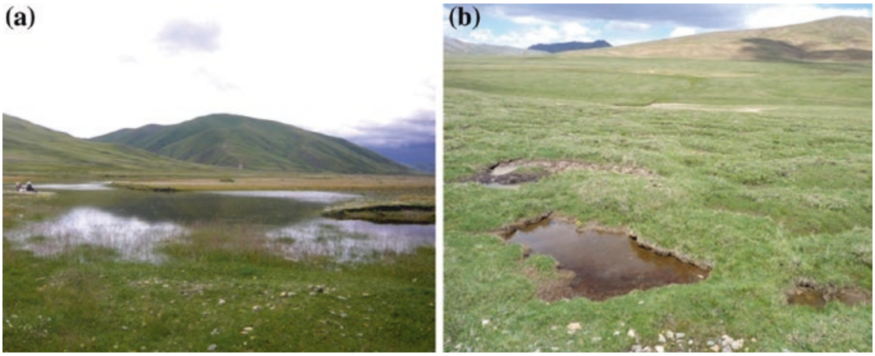

Fig. 9.2 Alpine meadow wetlands in the Yellow River Source Zone. **a** A typical alpine meadow wetland in 2007. **b** A relatively dewatered meadow in 2013

meadows form in the zone where run-off accumulates on low-lying land and in areas with high groundwater levels (Tane et al. 2016, Chap. 13). As the primary vegetation type, perennial herbaceous phreatophytes thrive in such conditions. Typical alpine meadow plants include *Kobresia schoenoides, Kobresia pygmaea, Kobresia humilis, Gramineae, Poaceae, Cyperaceae, Medulla junci, Leguminosae* and broad-leaved herbs. The area covered by alpine meadow wetlands in the Yellow River Source Zone has markedly decreased over the past fifty years (Fig. 9.2). Many wetland areas have been transformed into grazing pasture or have been impacted by road construction.

9.2.2 Lake Wetlands

There are 31 lakes with an area >1 km^2 in the Yellow River Source Zone, totalling around 1456 km^2 in 2012–2013 (Fig. 9.1). Zhaling and Eling lakes are the largest, making up almost three-quarters of the total lake area in the region. Eling Lake has an area of 628 km^2, a mean depth of 17.6 m (maximum 30 m) and water storage capacity of 10.7 billion m^3, while Zhaling Lake has an area of 526 km^2, a maximum depth of 8.6 m and a storage capacity of 4.6 billion m^3. The Yellow River connects these two lakes, running through a 20 km long and 300 m wide river valley. The river exits in the south-west corner of Eling Lake, where the mean annual discharge is about 485 million m^3. There are many small lakes to the east of Eling Lake, including Longrecuo (19 km^2), Aronggongmacuo (30 km^2), Arongwamacuo (31 km^2) and Aronggamacuo (23 km^2) (Fig. 9.1). In addition, many small lakes are located within the Xingxinghai wetland, which is not connected to the Yellow River trunk stream.

Remote sensing images indicate that although the total lake area in the Yellow River Source Zone has not changed in the last 20 years, the area of some lakes has

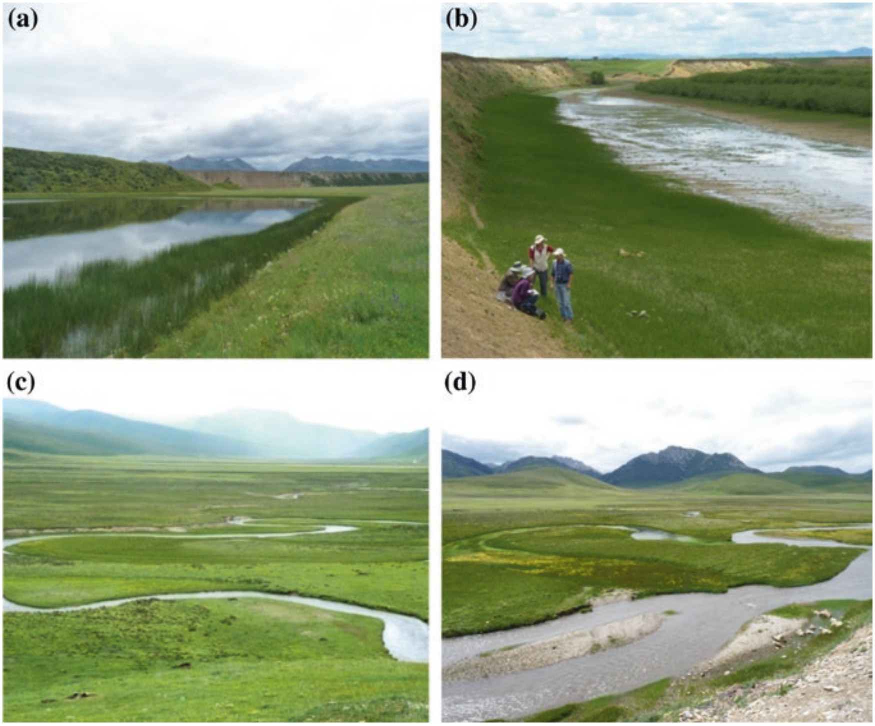

Fig. 9.3 Oxbow lakes in the Yellow River Source Zone. **a** An oxbow lake near Kesheng Town, Henan County. The lake is 1 km long and 100 m wide. It is separated from the contemporary channel by a natural levee. Its surface is covered by aquatic plants. **b** An oxbow lake near Tangke town on the first bend of the Yellow River trunk stream. The lake is partially connected to the trunk stream. It is 3 km long and 100 m wide. Rapid siltation is evident at this site. **c** Oxbow lakes along the Lanmucuo River, a tributary of the Yellow River. **d** An older oxbow lake that is infilling with aquatic vegetation along a tributary of the Upper Yellow River near Kesheng

increased (e.g. Zhaling, Eling and Xingxing lakes), while others have decreased in area. The expansion of some lakes has been attributed to increasing snow and glacier melts and/or dam construction.

9.2.3 Oxbow Lakes

The Yellow River trunk stream and its tributaries contain numerous oxbow lakes formed when meander loops are cut off from the main channel (Fig. 9.3). For instance, the Bai River has more than 90 oxbow lakes and the Hei River has more than 250 oxbow lakes.

Fig. 9.4 Early development stages of two crescent lakes in Maduo County

9.2.4 Crescent Lakes

Crescent lakes occur in the desert regions of the Yellow River Source Zone and are formed by groundwater rising above the crescent base of sand dunes (Fig. 9.4). Satellite imagery indicates that there are more than 8400 crescent lakes in the desert areas of Yellow River Source Zone (e.g. the Maduo desert between Eling Lake and the Yellow River). These lakes are typically 100–300 m long, 30–100 m wide and 1–10 m deep. Perhaps, the most famous example is Crescent Lake in the Dunhuang Desert, Gansu Province at the northern margins of the plateau. This lake has the shape of a crescent moon. It is nearly 100 m long, 25 m wide and has a maximum depth of about 5 m.

These distinctive hydrogeomorphic phenomena rely upon constant recharge by groundwater, so that the water table continues to lie above the base of the dunes. Climate warming since 1960 has increased the volume of meltwaters from snow and glaciers, leading to rising groundwater levels and an increasing number and area of crescent lakes. Rising groundwater levels also result from dam construction. For example, construction of the 20-m-high Huangheyan Dam downstream of Eling Lake in 2002 has increased the number of crescent lakes in this area from about 6800 to over 8400.

9.2.5 The Ruoergai Peatland

Peatland in the Yellow River Source Zone is found mainly in the Zoige (Ruoergai) Basin located at the eastern margin of the Qinghai–Tibet Plateau. Ruoergai peatland covers a total area of 16,000 km^2, of which about 80 % is in Sichuan Province and 20 % is within Qinghai and Gansu provinces.

Ruoergai is the largest high-altitude peatland in the world. Because of the long-term inundation and hypoxic or anoxic conditions, dead aquatic plants in the peatland cannot be oxidised. These plants eventually form a peat layer composed of densely interwoven dead grass roots that is typically 0.1–3.0 m thick at the bottom of the peatland. Prior to the 1950s, the Ruoergai peatland covered more than 4600 km^2. Today, it covers just 2200 km^2. This 52.2 % decrease in area has seriously degraded the functionality of this wetland ecosystem (Yan and Wu 2005; Li et al. 2011). Historical records and documents indicate that prior to the 1930s, the peatland was almost-pristine, with negligible impacts from human activities such as herding in the adjacent Riganqiao peatland. At this time, access to the main peatland was restricted by the presence of perennial water more than 1 m deep. The Ruoergai peatland has an infamous place in history as more than 23,300 members of the Chinese Red Army died while trying to cross it during the rainy season in August 1935 and July 1936 (Baidu Encyclopaedia 2014). Today, much of the peatland has been converted to grasslands, and some local areas are even prone to desertification.

9.3 Degradation of the Ruoergai Peatland

Shrinkage and degradation of the Ruoergai peatland is evident from analysis of photographic images taken in the early 1960s, which reveal a marked reduction in surface water area. Declining groundwater levels were also experienced at this

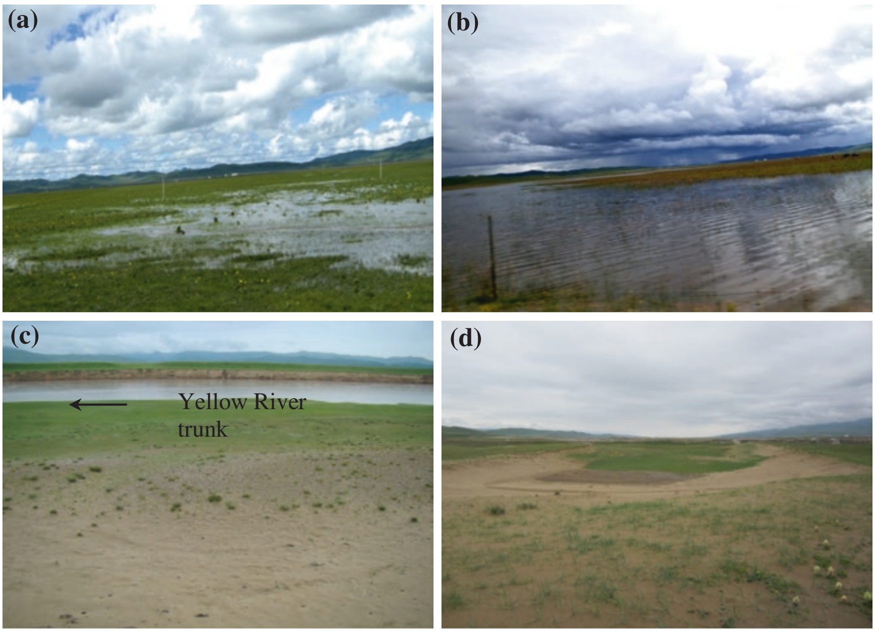

Fig. 9.5 Images of the Ruoergai peatland at various states. **a** Peatland with shallow water. **b** Peatland with deep water. **c** Desertification. **d** Vegetation on desertified ground

time. Shrinkage of the peatland rapidly accelerated in the 1980s. By 2000, apart from the large area of lakes and swamps along upper and middle sections of the Hei River, the area had been transformed into "wet grassland", with no distinct surface water evident across the peatland, even during the rainy season (Yang 1999; Shen et al. 2003). Today, serious desertification is evident in the wetlands bordering both banks of the Upper Yellow River and along the Hei and Bai river tributaries (Fig. 9.5).

Rapid shrinkage of the Ruoergai peatland has not only affected ecological functions, but also caused loss of biodiversity, altered water supply to the Upper Yellow River and threatened local livelihoods, especially livestock farming (Zhang and Lu 2010). Some researchers contend that shrinkage of the Ruoergai peatland in recent decades is a product of global climate warming, as rising temperatures have enhanced evaporative losses (e.g. Yan and Wu 2005). Ning et al. (2011) showed that evaporation at the Maqu weather station showed a linear decreasing trend of 44.0 mm per decade from 1969 to 2008. This effect was most prominent in summer, reflecting reductions in the diurnal temperature range and changes to wind speed. However, Li et al. (2015) argue that human practices have been the primary driver of peatland shrinkage in recent decades. The excavation of artificial drainage ditches through the peatland breaks up the peat materials that naturally inhibit gully development and headward erosion. Once this surface layer is cut through, the exposed underlying materials become highly vulnerable to erosion, triggering a sequence of events that can culminate in desertification (see Fig. 9.5).

9.3.1 Impact of Ditch Excavation upon Ruoergai Peatland

Hundreds of kilometres of ditches were excavated in Ruoergai, Hongyuan and Maqu counties in the 1960s–1990s to rapidly drain wetlands and so increase pasture available for animal husbandry. Official records indicate that 380 km of ditches were excavated in Ruoergai County from 1965 to 1973, directly draining some 2.1 km^2

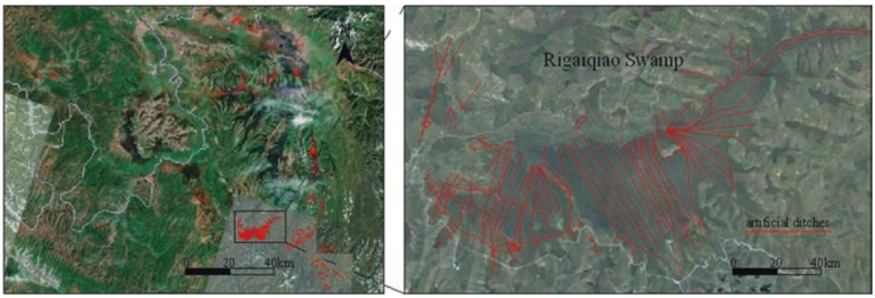

Fig. 9.6 Artificial ditches in Ruoergai and Riganqiao peatlands (Google Earth, 20 September 2010). The *centre line* of ditches is indicated by a *red solid line*, so that areas with many ditches appear as *solid red*

Fig. 9.7 Straight, artificial drainage ditches in Ruoergai peatland

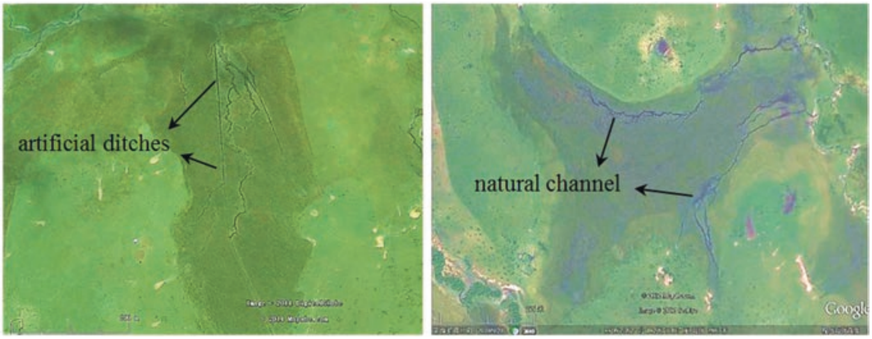

Fig. 9.8 Comparison of the drainage effects of artificial ditches and extended river networks

of perennial peatlands. Corresponding figures for the 1990s are 50.5 km of ditches converting a further 0.22 km^2 of peatland to grassland. Altogether, the length of artificial ditches in Ruoergai and Hongyuan counties now exceeds 1000 km, draining about 2000 km^2 (over 43 % of the peatlands). Figure 9.6 shows an example from the Riganqiao peatland in Hongyuan County where about 85 km^2 of peatland was converted to grazing land using artificial ditches. Today, interweaving artificial channels drain about 85 % of this area, so that surface water accumulates only in the central part of the peatland, and then only during the rainy season.

Based on the analyses of Google Earth imagery, on 20 September 2010, the total area of artificial ditches in Hongyuan, Ruoergai and Maqu counties stood at 1108.7, 884.7 and 834.1 km^2, respectively (Li et al. 2015). Two types of peatland drainage can be differentiated in this image:

(1) Areas that are *completely* drained by artificial channels, such as the Riganqiao peatland (Fig. 9.7). These areas total 219.7 km^2, 4.8 % of the contemporary area of the Ruoergai peatland (4600 km^2);

(2) Areas where artificial ditches *extend natural channel networks* to drain the wetlands, the Maiwa and Sedi wetlands in Hongyuan, the Heihe wetland

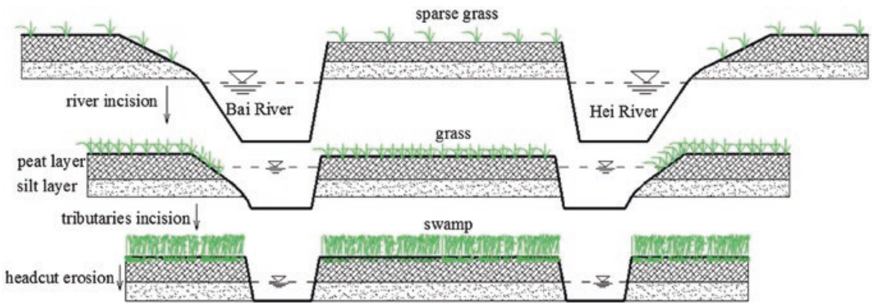

Fig. 9.9 Stages of river incision leading to the shrinkage of Ruoergai peatland

Fig. 9.10 A typical headcut in the Ruoergai peatland (33° 5′ 6.7″N, 102° 50′ 10.6″S)

in Ruoergai and the Awancang wetland in Maqu (Fig. 9.8). These areas total 428.6 km^2, some 9.3 % of the Ruoergai peatland.

Based on these figures, artificial ditches account for some 14.1 % of the total degraded area of the Ruoergai Swamp.

Drainage of peatland by artificial ditches and by channel extensions leads to wetland degradation and shrinkage, but different processes are involved in each case. Artificial ditches drain peatland along both banks of a channel, exposing the peat, which then dehydrates and hardens. The peatland is slowly transformed into a wet meadow, which then dries further to become grassland and can then eventually lose grass cover completely and become desertified. In contrast, the connection of artificial ditches to natural channels extends the drainage network, thereby strengthening the transport efficiency of the system. This leads to rapid headward incision of headcuts, undercutting of banks and subsequent channel expansion, which lowers the groundwater level and accelerates dehydration of wetlands (Safran et al. 2005; Schumm et al. 1984; Tooth et al. 2002; Fig. 9.9).

Extended channel networks in the Bai and Hei tributary systems have progressively drained the Ruoergai peatland and enlarged the desiccated area. Although the peat layer is resistant to erosion, once this layer is breached the underlying fine sand and silt layers are rapidly eroded. This promotes undercutting, bank collapse

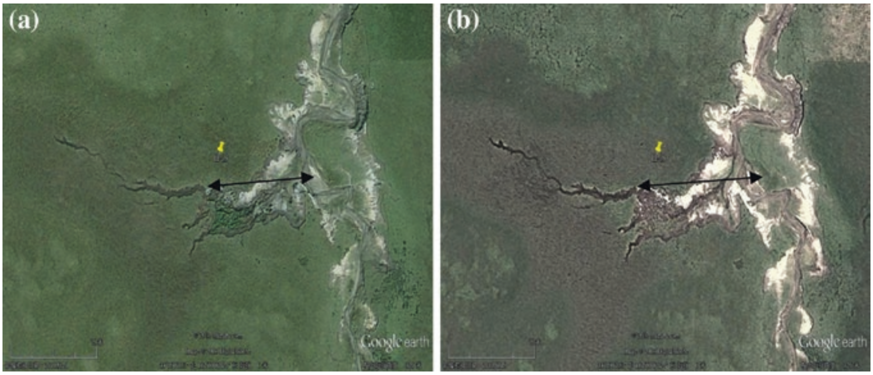

Fig. 9.11 Examples of the Google Earth images used to estimate headcut erosion rates (20 September 2000 on the *left*; 15 June 2014 on the *right*)

and accentuated rates of headward erosion. A typical 10 m high drop at a headcut site is shown in Fig. 9.10.

The rate of headcut erosion is critical to the pace of wetland shrinkage. Although widespread incision is evident along Hei River tributaries (Gequ, Haqu and Jiqu), lack of historical incision depth data precludes accurate determination of the incision rate. However, estimates can be derived from measuring channel extension rates relative to the position of bridges and culverts along Provincial Highway S301 which runs through the Ruoergai peatland (constructed on 15 October 2010). Incision rates for 13 bridges and culverts over the 3 years indicate an average channel incision rate of 0.24 m year^{-1} (Li et al. 2015). These incision rates are considered to represent the upper limit of the actual rates, as there is no peat layer to protect the river bed at these locations, and flow scour is likely to be accentuated adjacent to bridges and culverts.

Other estimates of the rate of headcut erosion were made by comparing Google Earth images from 20 September 2010 and 15 June 2013 (an example is shown in Fig. 9.11). Based on measurements at 30 sites shown in these images, the average rate of headcut extension was 1.52 m year^{-1} (range from 0.68 to 17.12 m year^{-1}). Although rates can be easily measured across many sites using this method, accuracy is limited by the resolution and horizontal accuracy of the image (the images used in this analysis have a resolution of 0.65 m).

Rates of headcut erosion were also measured in the field between 2012 and 2013, where average rates of 0.42 m year^{-1} were observed. Each of the methods used to measure erosion rates is subject to errors of different kinds. Although field measurements appear the most credible, comparatively few sites can be measured, relative to analyses of remotely sensed images. This means that there is less opportunity to relate the observed rates to upstream catchment area, which is likely to be an important control on the individual rates measured at each site.

Fig. 9.12 Incised stream banks along the Upper Yellow River at Maqu Station, middle Hei River, Gequ and Haqu (an artificial ditch)

9.3.2 Long-Term Trends of River Incision and Headcut Erosion

Although human activities have undoubtedly accelerated the shrinkage and degradation of the Ruoergai peatland, an underlying long-term shrinking trend has been driven by river bed incision of the Yellow River, Bai River, Hei River and their tributaries in response to base level changes (Brierley et al. 2016, Chap. 3; Li et al. 2015). Groundwater levels have decreased and the drainage network has evidently expanded along both sides of river channels. For instance, terraces along the Upper Yellow River in the Maqu section are more than 10 m high, much higher than the 4 m height of corresponding features along the middle Hei River. As a comparison, the height of terraces along the tributaries of the upper Hei River, Gequ, Maqu and Haqu rivers are only around 0.5–3.0 m (see Fig. 9.12). Incision and channel expansion are also evident along the Dashui River, a tributary of Hei River. Upstream areas are yet to cut through the peat layer, with incised channels only about 0.5–1.5 m deep. Middle reaches have a depth of around 2 m, with channel widths of 10–30 m. The downstream section of channel is much deeper (about 5 m) and wider (over 500 m).

9.4 Protection and Restoration of Ruoergai Peatland

Degradation of wetlands in the Yellow River Source Zone can be attributed to both climate change and human activities. Unless urgent actions are taken, further intensification of human activities will only exacerbate degradation of these wetlands. The best strategy to protect the Ruoergai wetland is to convert it into protected natural areas or reserves. Hence, the Chinese government approved the establishment of a nature reserve for the Ruoergai peatland in Sichuan Province in 1998, which was listed as an “International important wetland” in 2008. This reserve has a total area of 1665.7 km^2. It measures 47 km from east to west and 63 km from north to south. Within the natural reserve, peatlands, meadows and marshes provide important habitat and breeding grounds for wildlife. Even though the Ruoergai Natural Reserve is now established, artificial drainage and peat mining, groundwater exploitation, overgrazing and tourism development continue, so the degradation of these wetlands will not stop unless additional measures are taken.

Drainage via artificial ditches and incision of rivers and ditches within the wetlands have been identified as the major forces behind the recent shrinkage of both peatland and meadow wetlands (Li et al. 2015). Hence, basic strategies to mitigate against future deterioration and to promote improvements in their condition include stopping artificial drainage, controlling incision through base control measures, prohibiting peat mining and reducing grazing pressure by limiting the expansion of grazing pastures. Roads should be elevated above the ground to protect the peatland rather than draining it. Concrete weirs can be placed at the main drainage outlets to control and reduce discharge of water from the peatland. Wherever appropriate, low-level dams can be built to increase the number of lakes, raise groundwater levels and restore wetlands. For instance, the Flower Lake in the Ruoergai wetland originally had a surface area of 156 ha that shrank by two-thirds in 2011. Some of the areas around the lake even became desertified. After the construction of a low dam downstream of the Flower Lake outlet, the watered area quickly expanded to 2000 ha. Today, Flower Lake is like a bright mosaic diamond in north-west Sichuan, where it has become a major tourist attraction. Construction of a high dam on the Yellow River downstream of Maqu County may also support efforts to restore the Ruoergai peatland.

In addition to protecting lakes and wetlands, it is also important to consider the aquatic ecosystems they contain, and it is to this challenge that we now turn our attention.

9.5 Aquatic Ecosystems of the Sanjiangyuan

9.5.1 Background

The source zones of the Yellow River and the Yangtze River are important water conservation areas in China. Not only do they supply water to millions of people, but they also play key roles in maintaining the unique biological communities of the region. However, given the harsh natural environment and the very fragile ecosystems in this area, it is critical to monitor their ecological condition, so that precautionary approaches to environmental management can be adopted.

In recent years, a significant body of research has documented changing environmental conditions in the source region of the Yellow River and Yangtze River basins, including climate (e.g. Li et al. 2006; Zhang et al. 2011), hydrology (e.g. Shi et al. 2007) and land use change (especially grassland productivity and degradation; Feng et al. 2009; Guo et al. 2008; Sheng et al. 2007; Yang et al. 2011). In the past 40 years, wetland areas in the source regions of the Yellow River and the Yangtze River have decreased by 13.6 and 28.9 %, respectively (Wang et al. 2009). This reduction reflects the combined effects of human activities and reduced rainfall resulting from climate change. Although spatio-temporal changes of habitat conditions for terrestrial organisms have been well documented (Liu et al. 2009), no systematic studies on aquatic biotic assemblages have been completed. Here, we present the first steps towards building a better understanding of aquatic ecosystems of the Yellow River Source Zone.

Benthic macroinvertebrates are important components of river ecosystems, cycling nutrients and providing food for higher trophic level creatures such as fish and birds. Because of their limited range and long life cycles, they are good indicators of human impacts and long-term environmental changes (Pan et al. 2012).

9.5.2 Macroinvertebrate Communities in the Sanjiangyuan

9.5.2.1 Method

Field investigations of benthic macroinvertebrates were carried out in August 2009 and July 2010 in the source regions of the Yellow and the Yangtze rivers (Fig. 9.13).

Water depth (Z) and Secchi depth (Z_{SD}) were measured in the field using a sounding lead and a Secchi disc, respectively. Flow velocity (U) was measured using a propeller-type current metre (Model LS 1206B). Analysis of suspended sediments (SS) followed the procedures outlined in the Standard Methods for Water and Wastewater Monitoring and Analysis (APHA) (2002). Conductivity was measured using a conductivity metre (Model DDS-11A). Total nitrogen (TN) was analysed using the alkaline potassium persulfate digestion-UV spectrophotometric method. Total phosphorus (TP) was analysed using the ammonium molybdate

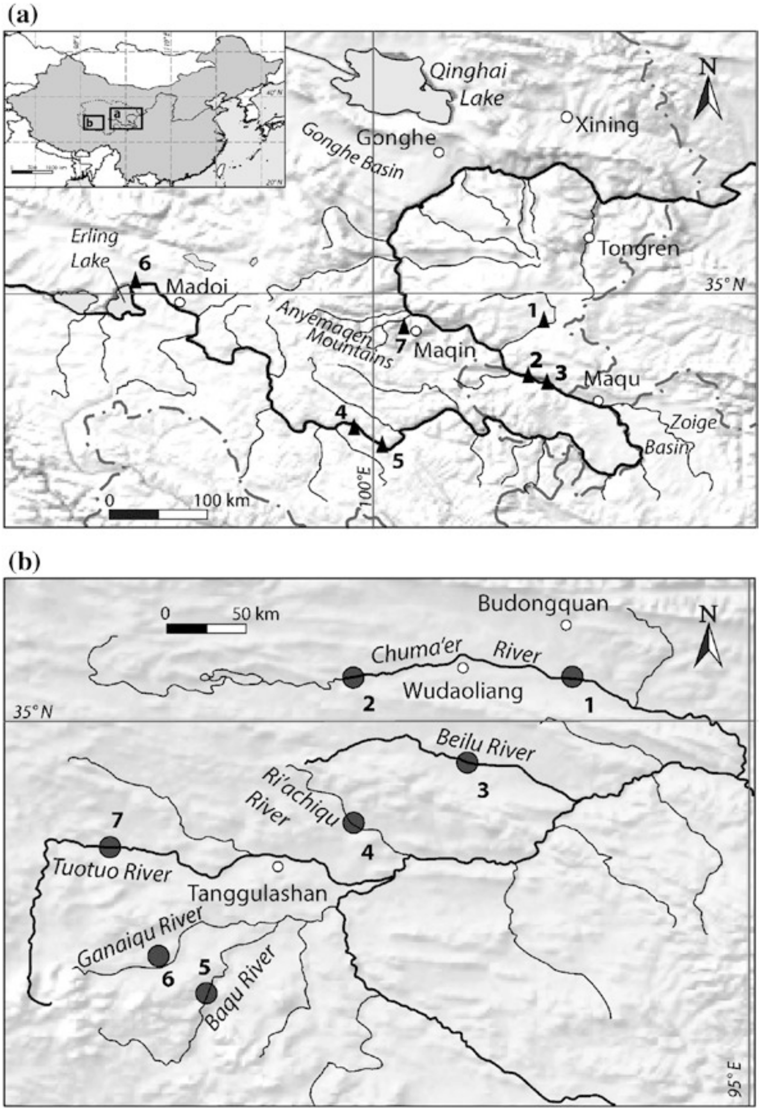

Fig. 9.13 Study areas and sampling sites in the source regions of **a** the Yellow and **b** the Yangtze rivers. Sampling sites in the source region of the Yellow River: *1* Zequ; *2* gravel bar along meandering Yellow River; *3* oxbow lake adjacent to the Yellow River; *4* riparian wetland of the Yellow River; *5* main river channel with low-sediment concentration; *6* shore of Erling Lake; *7* Jiangrang hydroelectric power station in a tributary of the Qiemuqu River. Sampling sites in the source region of the Yangtze River: *1* downstream Chuma'er River; *2* upstream Chuma'er River; *3* Beilu River; *4* Ri'achiqu River; *5* Buqu River; *6* Gananoque River; *7* Tuotuo River

Table 9.1 Environmental parameters of sampling sites in the source regions of the Yellow River and the Yangtze River (mean ± SE)

Environmental parameters	The source region of the Yellow River	The source region of the Yangtze River
Water depth (m)	0.4 ± 0.2	0.4 ± 0.2
Secchi depth (m)	0.30 ± 0.1	0.15 ± 0.10
Water velocity (m s^{-1})	0.26 ± 0.15	0.38 ± 0.05
Suspended sediments (mg L^{-1})	59.3 ± 39.3	351.6 ± 84.5
Conductivity (μS cm^{-1})	487 ± 12	2257 ± 838
Total nitrogen (mg m^{-3})	2940 ± 540	1967 ± 347
Total phosphorus (mg m^{-3})	8 ± 1	37 ± 17

method. All parameters were analysed according to APHA (2002). Near-surface and near-bed water samples were combined for laboratory analyses (Table 9.1).

At each sampling site, three replicate samples of macroinvertebrates were collected in a kick-net with 420 μm mesh size within an area of 0.33 m^2. Specimens were manually sorted from sediment on a white porcelain plate and preserved in 75 % ethanol. After blotting, the wet weight of the sampled animals was determined using an electronic balance. The dry weight was later calculated according to the ratio between wet weight and tissue-shell weight (see Yan and Liang 1999). All taxa were assigned to one of five functional feeding groups: shredders, collector-gatherers, collector-filterers, scrapers and predators (Morse et al. 1994). When a taxon could potentially be assigned to multiple feeding groups, its abundance was divided equally between these groups (e.g. if a taxon is both a collector-gatherer and a scraper, its abundance was divided equally between these groups). The Jaccard similarity coefficient (S_J) was then used to compare macroinvertebrate assemblages between the river source regions:

$$S_J = c/(a + b - c) \tag{9.1}$$

where a is the number of species in assemblage A; b is the number of species in assemblage B; and c is the number of species found in both assemblages.

Species richness (S, the number of species) is one of the most important characteristics of biodiversity, as it provides a measure of the diversity of both species and habitat. Another measure of diversity, the Shannon–Weaver index, H, integrates species richness with the evenness of the distribution of animals of different species. It is defined by Krebs (1978) as:

$$H' = -\sum_{i=1}^{S} \frac{n_i}{N} \ln\left(\frac{n_i}{N}\right) \tag{9.2}$$

in which S is the number of species (richness), N is the total number of individual animals, and n_i is the number of individual animal of the ith species. However, the Shannon–Weaver index can sometimes provide misleading results, since it provides no information on the total abundance of the biocommunity, which can

Table 9.2 Species composition of macroinvertebrates in the source regions of the Yellow River and the Yangtze River

Phylum	Class	Family	Number of species	
			Yellow River Source Zone	Yangtze River source zone
Nematoda			ud	0
Annelida	Oligochaeta	Naididae	1	0
		Tubificidae	4	4
Mollusca	Gastropoda	Lymnaeidae	3	0
		Planorbidae	2	0
Arthropoda	Crustacea	Gammaridae	ud	ud
	Arachnoida		ud	0
	Insecta	Caenidae	(1)	0
		Baetidae	(1)	(1)
		Heptageniidae	(1)	(1)
		Ephemerellidae	(1)	0
		Leptophlebiidae	0	(1)
		Hydropsychidae	(1)	0
		Leptoceridae	(1)	0
		Brachycentridae	(1)	0
		Nemouridae	0	ud
		Taeniopterygidae	0	ud
		Dytiscidae	ud	0
		Elmidae	ud	ud
		Chrysomelidae	ud	0
		Naucoridae	ud	0
		Corixidae	ud	0
		Pyralidae	ud	0
		Sialidae	0	ud
		Tipulidae	(1)	(1)
		Simuliidae	(1)	0
		Culicidae	ud	0
		Ephydridae	ud	0
		Chironomidae	(20)	(16)
Total number of species			50	29

vary substantially in habitats with different physical conditions. This drawback is resolved in the biocommunity index, *B*, which considers both total community abundance and species biodiversity (Wang et al. 2008):

$$B = -\ln N \sum_{i=1}^{S} \frac{n_i}{N} \ln \left(\frac{n_i}{N} \right) \tag{9.3}$$

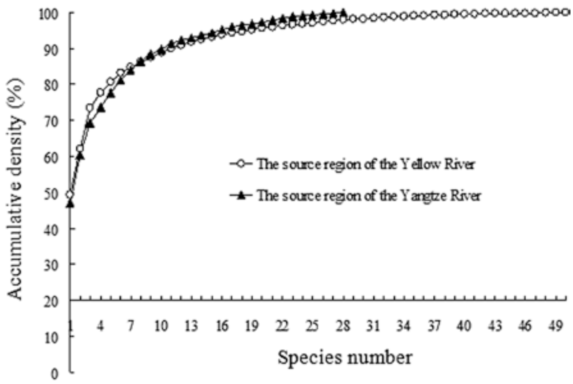

Fig. 9.14 K-dominant curve of macroinvertebrates in the source regions of the Yellow and Yangtze rivers

9.5.2.2 Results

(a) *Composition and diversity of macroinvertebrate assemblages*

Altogether, 68 species of macroinvertebrates belonging to 29 families and 59 genera were identified in the two source regions (Table 9.2). Among them were 8 annelids, 5 mollusks, 54 arthropods and 1 other animal. In the Yellow River Source Zone, we found 50 species belonging to 25 families and 46 genera, while in the source region of the Yangtze River, we found 29 species belonging to 11 families and 24 genera. Only 11 species of macroinvertebrates coexisted in the two river source regions. The Jaccard coefficient between the source regions of the Yellow River and the Yangtze River was only 0.16, indicating little similarity between the macroinvertebrate communities of these two source regions.

The Shannon–Weaver index (H) of macroinvertebrates in the source regions of the Yellow River and the Yangtze River was very similar (2.06 and 2.05, respectively). However, the biocommunity index (B) of macroinvertebrates in the two regions was quite different [11.86 (Yellow River) and 8.41 (Yangtze)].

Species diversity can also be assessed using K-dominant curves which combine measures of diversity, species richness and distribution evenness. Using this method, dominant patterns are represented by plotting the accumulative abundance of each species (%) ranked in decreasing order of abundance (see, Fig. 9.14).

Biodiversity comparisons indicated that macroinvertebrate diversity in the source region of the Yellow River was higher than that in the source region of the Yangtze River. Although the Shannon–Weaver index suggests similar levels of macroinvertebrate diversity in the two areas, the number of macroinvertebrate species found in the source area of the Yellow River (50 species) was higher than that found in the Yangtze River (29 species), and both the biocommunity index and the K-dominant curve analysis indicate higher levels of diversity in the Yellow River Source Zone.

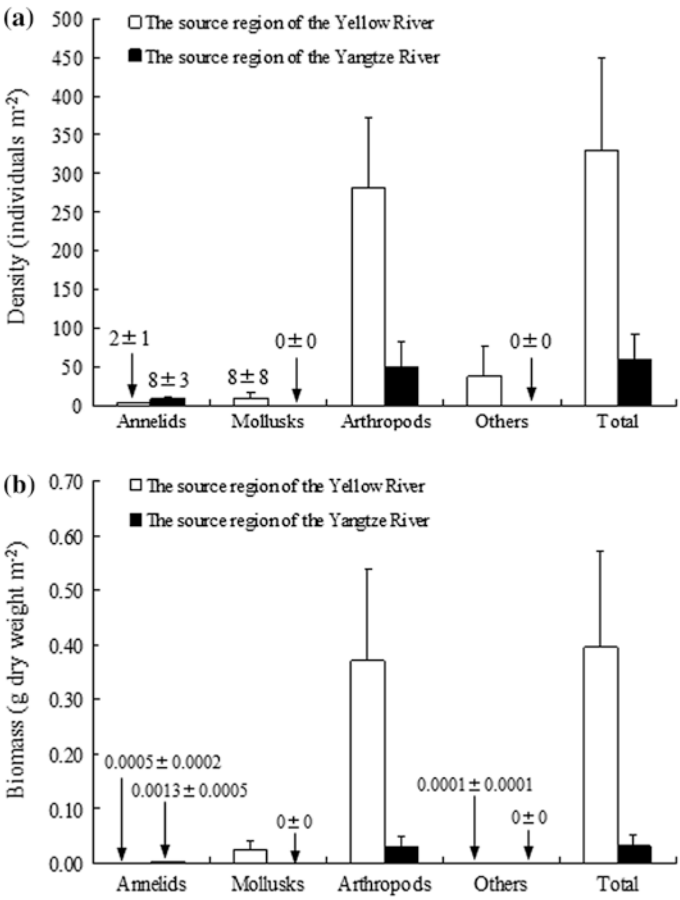

Fig. 9.15 Density (**a**) and biomass (**b**) of each phylum of macroinvertebrates in the source regions of the Yellow River and the Yangtze River (Mean ± SE)

(b) *Density and biomass of macroinvertebrate assemblages*

Overall, macroinvertebrates have a density of 329 ± 119 and 59 ± 32 individuals m^{-2} in the source regions of the Yellow River and the Yangtze River, respectively (Fig. 9.15). The biomass of total macroinvertebrates was 0.3966 ± 0.1763 and 0.0307 ± 0.0217 g dry weight m^{-2} in the source regions of the Yellow River and the Yangtze River, respectively. Arthropods were the dominant group in each source region, both in terms of the number of species present and in terms of density and biomass. In the source region of the Yellow River, arthropods made up 85.4 % of the total density and 93.5 % of the total biomass. In the source region of the Yangtze River, arthropods comprised 86.2 % of the total density and 95.8 % of the total biomass.

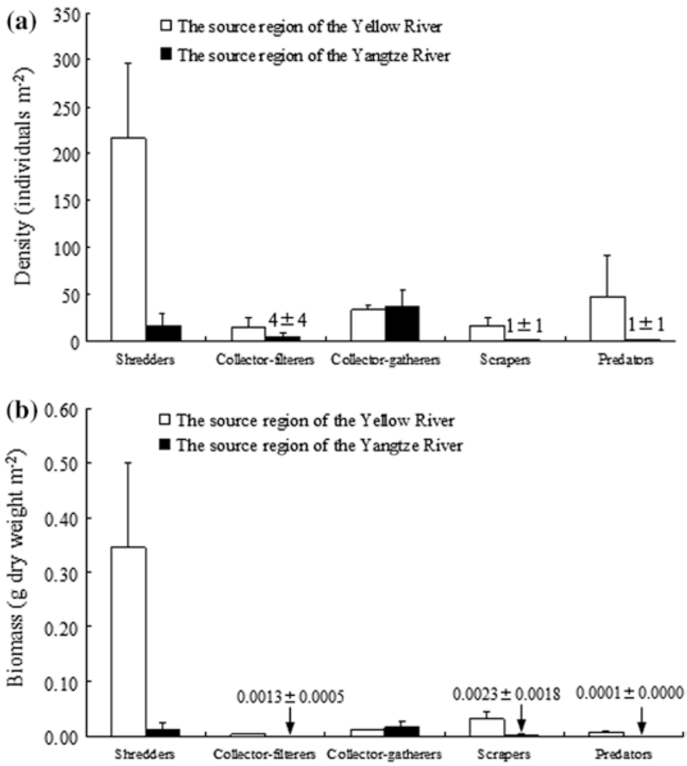

Fig. 9.16 Density (**a**) and biomass (**b**) of each functional feeding group of macroinvertebrates in the source regions of the Yellow River and the Yangtze River (Mean ± SE)

With regard to functional groups, shredders were the predominant group in the source region of the Yellow River, accounting for 65.7 % of the total density and 87.1 % of the total biomass (Fig. 9.16). In the source region of the Yangtze River, collector-gatherers and shredders were the dominant groups. Collector-gatherers made up 62.0 % of the total density and 50.6 % of the total biomass, while shredders made up 28.2 % of the total density and 40.7 % of the total biomass.

9.5.2.3 Discussion

Aquatic insects dominated macroinvertebrate assemblages in both source regions. Similar findings have been found for the mid-lower reaches of the trunk streams (Pan et al. 2011). Both potamophilic (water loving) and psychrophilic (cold-tolerant) species occurred in both source regions. The potamophilic taxa included *Ephemeroptera*, *Simuliidae*, *Rheotanytarsus*, *Stictochironomus*

Table 9.3 Comparisons of species richness, density and biomass of macroinvertebrates in a main channel with no macrophytes and a riparian wetland

Study site	Number of species	Density (individuals m^{-2})	Biomass (g dry weight m^{-2})
Mainstream of a tributary without macrophytes	7	11 ± 11	0.0051 ± 0.0051
Riparian wetland	14	232 ± 92	0.1374 ± 0.0651

and *Xenochironomus* and the psychrophilic species included *Stylaria lacustris*, *Limnodrilus grandisetosus* and *Limnodrilus profundicola*. The existence of psychrophilic species is consistent with the high altitude and low water temperature of the regions. In comparison with the source region of the Yangtze River, higher macroinvertebrate diversity in the source region of the Yellow River can be ascribed to more extensive wetlands which support more benthic biota, and lower altitudes where environmental conditions such as climate, oxygen concentration and atmospheric pressure are more favourable to biota.

In areas of limited human disturbance, macroinvertebrate assemblages are influenced primarily by habitat conditions such as water velocity (Brooks et al. 2005), substrate size (Quinn and Hickey 1990), bank morphology and other geomorphological considerations. Variance of macroinvertebrate assemblages in the Upper Yellow and Yangtze rivers is considered to reflect different habitat conditions. Among all measured parameters in the two river source regions, the difference of sediment concentration was particularly prominent. The sediment concentration of the source region of the Yangtze River was six times that of the source region of the Yellow River. High-sediment concentration limits the light needed for algal and macrophyte growth, and sand pellets may damage the cell walls of phytoplankton (Pan et al. 2009; Wang et al. 2006). These effects not only constrain the food available to macroinvertebrates, but macrophytes also create significant horizontal and vertical heterogeneities that provide a physical template for distinct niches (Rooke 1984) and serve as a refuge against predators (Pan et al. 2011). Moreover, macrophytes can serve as a site for oviposition (Scheffer 2004) and provide chances for snails to crawl on the air–water interface (particularly for pulmonates) (Wang et al. 2006).

Table 9.4 Comparisons of species richness, density and biomass of macroinvertebrates upstream and downstream of Jiangrang power station

Study site	Number of species	Density (individuals m^{-2})	Biomass (g dry weight m^{-2})
The upstream of Jiangrang hydroelectric power station	10	59 ± 30	0.0100 ± 0.0053
The downstream of Jiangrang hydroelectric power station	8	43 ± 31	0.0075 ± 0.0050

Further evidence of the role played by macrophytes in supporting large and diverse macroinvertebrate assemblages comes from a comparison between assemblages in riparian wetland sites and in the main channel of a tributary with no macrophytes (Table 9.3). The density and biomass of macroinvertebrates in the riparian wetland were 21 and 27 times higher than in a tributary channel with no aquatic vegetation.

9.5.3 Impacts of Human Activities on Macroinvertebrate Communities

Flow regulation impacts in the two river source regions are restricted to a few run-off hydroelectric power stations. To measure any effect of these dams on aquatic ecosystems, macroinvertebrate assemblages were compared upstream and downstream of the Jiangrang run-off hydroelectric power station in Maqin County. This dam has a much smaller water storage capacity than reservoir hydroelectric dams, raising the water level by less than 1 m. Only small differences were seen between species richness, density and biomass of macroinvertebrates upstream and downstream of the dam (Table 9.4). The limited impact noted in this instance reflects the fact that run-off hydroelectric power stations have a less adverse impact on the natural flow regime than reservoir power stations.

Human-induced wetland degradation presents a significant threat to aquatic ecosystems in the river source regions, as wetlands are able to support a far greater abundance of benthic individuals than habitats without vegetation (e.g. Sharma and Rawat 2009; Tarr et al. 2005; see Table 9.3). Furthermore, grassland degradation and erosion in recent years have induced serious soil loss, increasing sediment concentration in rivers (Luo and Tang 2003), which in turn decreases the abundance and diversity of aquatic biota. Measures to counteract these trends include conservative grazing and vegetation management.

9.5.4 Summary

Taxa number, density and biomass of macroinvertebrates in the source region of the Yellow River were, respectively, 1.7, 5.6 and 12.9 times higher than in the source region of the Yangtze River. Compared with the source region of the Yellow River, lower benthic animal resources in the source region of the Yangtze River were ascribed to higher altitude, higher sediment concentration and wetland degradation. Vegetation management and wetland restoration aiming to reduce soil erosion and maintain water supply are key considerations in the ecological protection of these source regions, which are critical to maintaining healthy ecological conditions throughout the entire basins.

9.6 Conclusions

This chapter has outlined concerns for the degradation and protection of the diverse wetlands and aquatic ecosystems in the Sanjiangyuan region. Degradation of the Ruoergai peatlands is causing environmental suffering (i.e. desertification, grassland loss and water shortage), impacting upon local herdsmen. Moreover, it is affecting the supply of water to the Upper Yellow River. Beyond question, wetland formation and evolution warrant further investigation in relation to global climate warming. The use of macroinvertebrates as an indicator species for the status of aquatic ecosystems in this region has indicated the range of conditions in the Upper Yellow and Yangtze Rivers. Undoubtedly, human activities such as overstocking, road construction, hydropower development, peat mining and tourism are impacting upon local aquatic ecosystems. These pressures accentuate concerns raised by the large-scale development strategy in West China. Further work is required to assess the influences of human activities on wetland and aquatic ecology in order to improve future prospects for wetland areas.

References

Baidu Encyclopedia. (2014). Chinese army across the grassland. http://baike.baidu.com/subview/180650/11248854.htm?fr=aladdin (in Chinese).

Barbier, E. B., Acreman, M., & Knowler, D. (1997). *Economic valuation of wetlands: A guide for policy makers and planners*. Gland, Switzerland: Ramsar Convention Bureau.

Blue, B., Brierley, G., & Yu, G. (2013). Geodiversity in the Yellow River Source Zone. *Journal of Geographical Science, 23*, 775–792.

Brierley, G. J., Yu, G. A., & Li, Z. W. (2016). Geomorphic diversity of rivers in the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 59–78). Berlin: Springer.

Brinson, M., & Malvarez, A. I. (2002). Temperate freshwater wetlands: Types, status and threats. *Environment Conservation, 29*, 115–133.

Brooks, A. J., Haeusler, T. I. M., Reinfelds, I., et al. (2005). Hydraulic microhabitats and the distribution of macroinvertebrate assemblages in riffles. *Freshwater Biology, 50*, 331–344.

Cao, L., & Fox, A. D. (2009). Birds and people both depend on China's wetlands. *Nature, 460*, 173.

Feng, Y. Z., Yang, G. H., Wang, D. X., et al. (2009). Ecological stress in grassland ecosystems in source regions of Yangtze, Yellow and Lancang Rivers over last 40 years. *Acta Ecologia Sinica, 29*, 492–498. (in Chinese).

Gao, J. G. (2016). Wetland and its degradation in the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 209–232). Berlin: Springer.

Gao, J., Li, X., Brierley, G., et al. (2013). Geomorphic-centered classification of wetlands on the Qinghai-Tibet Plateau, Western China. *Journal of Mountain Science, 10*, 632–642.

Guo, L. Y., Wu, R., Wang, Q. C., et al. (2008). Influence of climate change on grassland productivity in Xinghai County in the source regions of Yangtze River. *Chinese Journal of Grassland, 32*, 5–10. (in Chinese).

Huang, H. Q., Liu, X. F., Brierley, G. J., et al. (2016). Hydrology of the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 79–100). Berlin: Springer.

Krebs, C. J. (1978). *Ecology: The experimental analysis of distribution and abundance* (2nd ed.). New York: Harper and Row.

Li, L., Li, F. X., Guo, A. H., et al. (2006). Study on the climate change trend and its catastrophe over “Sanjiangyuan” region in recent 43 years. *Journal of Natural Resources, 21*, 79–85. (in Chinese).

Li, Y., Yan, Z., Gao, S., et al. (2011). The peatland area change in past 20 years in the Ruoergai Basin, eastern Tibetan Plateau. *Frontier Earth Science, 5*, 271–275.

Li, Z.-W., Wang, Z.-Y., Brierley, G., et al. (2015). Shrinkage of the Ruoergai Swamp and changes to landscape connectivity, Qinghai-Tibet Plateau. *Catena, 126*, 155–163.

Liu, S. Y., Zhang, Y., Zhang, Y. S., et al. (2009). Estimation of glacier runoff and future trends in the Yangtze River source region, China. *Journal of Glaciology, 55*, 353–362.

Luo, X. Y., & Tang, W. J. (2003). Eco-environmental problems at source area of the Yangtze River and countermeasures for their prevention and treatment. *Journal of Yangtze River Scientific Research Institute, 20*, 47–49. (in Chinese).

Morse, J. C., Yang, L. F., & Tian, L. X. (1994). *Aquatic insects of China useful for monitoring water quality*. Nanjing: Hohai University Press.

Nicoll, T., Brierley, G., & Yu, G. (2013). A broad overview of landscape diversity of the Yellow River Source Zone. *Journal of Geographical Science, 23*, 793–816.

Ning, H., Li, G., & Wang, J. (2011). Change features of pan evaporation in Maqu area in the upper reaches of Yellow River in recent 40 years. *Journal of Arid Land Resources and Environment, 25*, 113–117. (in Chinese).

Niu, Z. G., Zhang, H. Y., & Gong, P. (2011). More protection for China’s wetlands. *Nature, 471*, 305.

Niu, Z. G., Zhang, H. Y., Wang, X. W., et al. (2012). Mapping wetland changes in China between 1978 and 2008. *Chinese Science Bulletin, 57*, 2813–2823.

Pan, B. Z., Wang, H. J., Liang, X. M., et al. (2009). Factors influencing chlorophyll *a* concentration in the Yangtze-connected lakes. *Fresenius Environmental Bulletin, 18*, 1894–1900.

Pan, B. Z., Wang, H. J., Liang, X. M., et al. (2011). Macrozoobenthos in Yangtze floodplain lakes: Patterns of density, biomass and production in relation to river connectivity. *Journal of the North American Benthological Society, 30*, 589–602.

Pan, B. Z., Wang, Z. Y., & Xu, M. Z. (2012). Macroinvertebrates in abandoned channels: Assemblage characteristics and their indications for channel management. *River Research and Applications, 28*, 1149–1160.

Qiu, P. F., Wu, N., Luo, P., et al. (2009). Analysis of dynamics and driving factors of wetland landscape in Zoige, eastern Qinghai-Tibetan Plateau. *Journal of Mountain Science, 6*, 42–55.

Quinn, J. M., & Hickey, C. W. (1990). Magnitude of effects of substrate particle size, recent flooding, and catchment development on benthic invertebrates in 88 New Zealand rivers. *New Zealand Journal of Marine and Freshwater Research, 24*, 411–427.

Rooke, B. J. (1984). The invertebrate fauna of four macrophytes in a lotic system. *Freshwater Biology, 14*, 507–513.

Safran, E. B., Bierman, P. R., Aalto, R., et al. (2005). Erosion rates driven by channel network incision in the Bolivian Andes. *Earth Surface Processes and Landforms, 30*, 1007–1024.

Scheffer, M. (2004). *Ecology of Shallow Lakes*. Kluwer Dordrecht: Academic Publishers.

Schumm, S. A., Michael, D. H., & Chester, C. W. (1984). *Incised channels: Morphology, dynamics, and control*. Littleton, Colorado: Water Resources Publications.

Sharma, R. C., & Rawat, J. S. (2009). Monitoring of aquatic macroinvertebrates as bioindicator for assessing the health of wetlands: A case study in the Central Himalayas, India. *Ecological Indicators, 9*, 118–128.

Shen, S., Wang, J., & Yang, M. (2003). Principal factors in retrogression of the Zoige Plateau marsh wetland. *Journal of Sichuan Geology, 23*, 123–125. (in Chinese).

Sheng, H. Y., Yang, G. H., Wang, D. X., et al. (2007). Current status of grassland resources utilization and the corresponding solutions in a sustainable development context in the regions of three river source. *Journal of Northwest Sci-Tech University of Agriculture and Forest, 35*, 147–153. (in Chinese).

Shi, X. H., Qin, N. S., Xu, W. J., et al. (2007). The variations characteristic of the runoff in the source regions of the Yangtze River from 1956 to 2004. *Journal of Mountain Science, 25*, 513–523. (in Chinese).

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) headwaters. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 275–330). Berlin: Springer.

Tarr, T. L., Baber, M. J., & Babbitt, K. J. (2005). Macroinvertebrate community structure across a wetland hydroperiod gradient in southern New Hampshire, USA. *Wetlands Ecology and Management, 13*, 321–334.

Tooth, S., McCarthy, T. S., Brandt, D., et al. (2002). Geological controls on the formation of alluvial meanders and floodplain wetlands: The example of the Klip River, Eastern Free State, South Africa. *Earth Surface Processes and Landforms, 27*, 797–815.

Wang, H. J., Pan, B. Z., Liang, X. M., et al. (2006). Gastropods on submerged macrophytes in Yangtze Lakes: Community characteristics and empirical modelling. *International Review of Hydrobiology, 91*, 521–538.

Wang, G. X., Li, N., & Hu, H. C. (2009). Hydrologic effect of ecosystem responses to climatic change in the source regions of Yangtze River and Yellow River. *Advances in Climate Change Research, 5*, 202–208. (in Chinese).

Wang, Z. Y., Lee, J. H. W., Cheng, D. S., et al. (2008). Benthic invertebrates investigation in the East River and habitat restoration strategies. *Journal of Hydro-environment Research, 2*, 19–27.

Yan, Y. J., & Liang, Y. L. (1999). A study of dry-to-wet weight ratio of aquatic macroinvertebrates. *Journal of Huazhong University of Science & Technology (Natural Science Edition), 27*, 61–63. (in Chinese).

Yan, Z., & Wu, N. (2005). Rangeland privatization and its impacts on the Ruoergai wetlands on the Eastern Tibetan Plateau. *Journal of Mountain Science, 2*, 105–115.

Yang, Y. (1999). Ecological environment deterioration, mire degeneration and their formation mechanism in the Zoige Plateau. *Journal of Mountain Science, 17*, 318–323. (in Chinese).

Yang, Z. P., Gao, J. X., Zhou, C. P., et al. (2011). Spatio-temporal changes of NDVI and its relation with climatic variables in the source regions of the Yangtze and Yellow rivers. *Journal of Geographical Sciences, 21*, 979–993.

Zhang, S. F., Hua, D., Meng, X. J., et al. (2011). Climate change and its driving effect on the runoff in the "Three-River Headwaters" region. *Journal of Geographical Sciences, 21*, 963–978.

Zhang, X.Y., Lu, X.G. (2010). Multiple criteria evaluation of ecosystem services for the Ruoergai Plateau marshes in southwest China. *Ecological Economics*, *69* (7), 1463–1470.

Zhou, D. M., Gong, H. L., Wang, Y. Y., et al. (2009). Driving forces for the marsh wetland degradation in the Honghe National Nature Reserve in Sanjiang Plain, Northeast China. *Environmetal Modelling & Assessment, 14*, 101–111.

Chapter 10
Wetland and Its Degradation in the Yellow River Source Zone

Jay Gao

Abstract Plateau wetlands in the Yellow River Source Zone are distributed in a wide range of geomorphic zones. They can be classified as alpine, piedmont, valley, floodplain, lacustrine, riverine and terrace wetlands on the basis of this geomorphic association. Some wetland types have shown signs of degradation triggered by environmental desiccation and improper land management strategies. The degradation process is characterized by four stages: intact, slight (dryland), severe (wasteland) and extreme (badland). Wetland degradation can be reversible or irreversible, depending on whether the tolerant threshold of the wetland ecosystem has been exceeded. The change from healthy wetland to dryland is considered quantitative and reversible, in that only the water reserve in the wetland system has been reduced whilst most of its ecosystem functions are retained. Beyond the dryland stage, degradation is considered irreversible in that external intervention is essential to rehabilitate the degraded system via minimizing human disturbance, and even engineering work may be needed. Both the process and the severity of degradation can be considerably accelerated by the joint effect of multiple degradation drivers that far exceeds the sum effect of individual factors. The severity of wetland degradation is commonly assessed from biological and hydrological indicators, including vegetative cover and proportion of original plants, surface water reserve and soil moisture, and the level of soil erosion induced by rodent burrowing. To be effective, any rehabilitative measures of degraded wetland must target the roots of the degradation problem, which are likely to be site-specific.

Keywords Wetland degradation · Severity assessment · Degradation process · Degradation risk · Rehabilitative measures

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10.1 Introduction

Wetlands are critical features in arid and drying landscapes (Quivira Coalition 2014). In addition to being essential for plant and animal species, they provide many ecosystem services, such as water supply and purification, climate regulation and flood regulation. In the face of climate change and extended droughts, restoration activities in headwater systems increase the likelihood that waterways downstream can continue to support both human and wildlife populations. Global warming has induced a significant increase in the severity and duration of drought, the severity and intensity of precipitation events, increased stream water temperatures, and earlier snowpack run-off, all of which increase stress on riparian and wetland systems and put them at risk. In addition, human activities have placed great stress on wetland systems, especially associated with land use changes. This chapter explores controls upon wetland degradation in the Yellow River Source Zone—an integral part of the "Water Tower of China". Concerns for water management in this area were part of the rationale for the establishment of the Sanjiangyuan National Nature Reserve (Li et al. 2012; Ran et al. 2016, Chap. 14).

Wetlands in the upper reaches of the Yangtze and Yellow rivers, and on the Zoige (Ruoergai) plateau are vast, occupying 7.33 million ha (Pan et al. 2011). These plateau wetlands are the largest high-altitude wetlands (3200–4500 m asl) in the world (Zhou et al. 2005). In the Yellow River Source Zone, wetlands provide various economic, hydrological and ecological services. Wetlands such as alpine swampy meadows are important grassland resources that are vital for animal husbandry. Wetlands also play important roles in regulating the hydrological regimes of rivers, controlling both water quantity and quality in the upper reaches of the Yellow River. Ecologically, plateau wetlands are critical to maintaining biodiversity, providing habitats for many endangered species. In particular, they provide breeding sites for many endemic and endangered birds. For instance, the Ruoergai swamps host the black-necked crane (*Grus nigricollis*), a species with the highest level of protection in China (Xiang et al. 2009). Wetlands also protect grasslands by deterring rodent invasions (Li et al. 2016, Chap. 7; Tane et al. 2016, Chap. 13).

Climatically, wetlands abate global warming or the greenhouse effect by taking up and storing carbon (Avis et al. 2011). Wetlands with a low reflectance are excellent at confining incident solar energy to the Earth's surface instead of bouncing it back into the atmosphere. They are effective at regulating air temperature, and hence at controlling climate warming. They also store a large amount of greenhouse gases, such as methane and carbon dioxide. It is estimated that the Ruoergai swamps in the Zoige Basin have a total peat reserve of approximate 14.08 million tons storing about 8.08 million tons of carbon (Sun and Zhang 1987).

Climate change and human activities present threats to wetlands on the Qinghai–Tibet Plateau. In turn, degradation of plateau wetlands not only affects the local animal husbandry industry but also exerts a profound impact on local and downstream hydrology, and even on climate. In the source region of the Yangtze

River and the Zoige region, severe decline in wetlands has altered downstream channel hydrology in the form of reduced channel flow and increased frequency of rare larger run-offs (Li et al. 2016, Chap. 9; Wang et al. 2007). In addition, the water-regulating capacity of wetlands has been debilitated. Severe wetland degradation aggravates climate warming. Conversion of peatland to pasture can release a huge quantity of carbon dioxide into the atmosphere (Bai et al. 2010), transforming wetlands from a carbon sink to a carbon source. Soil organic carbon is halved when peat wetland is degraded to swampy wetland, or completely depleted if the swamp is continuously degraded to dry sandy land.

Plateau wetlands are inherently fragile and prone to degradation. Numerous factors have contributed to wetland degradation on the Qinghai–Tibet Plateau, such as desiccation, periglacial processes, attacks by small mammals and overgrazing by livestock (Miehe et al. 2011). If subjected to frequent (or occasionally intensive) anthropogenic disturbances, they can degrade quickly (Zhou et al. 2005). Wetland degradation on the Qinghai–Tibet Plateau started in the 1960s (Zhang et al. 2011). This was characterized by changes to wetland composition, the spatial distribution of wetlands and their hydro-ecologic functions (Wang et al. 2007). For example, Feng et al. (2008) note that wetlands in Maqu County of southern Gansu Province faced grave risks of desiccation, shrinkage and degradation.

Nationally, wetlands in China declined in area by over 9.3 % from 2003 to 2013 (SFA 2014). The Qinghai–Tibet Plateau was consistent with this national trend. From 1990 to 2006, lake wetlands and marsh wetlands over the entire Plateau decreased by 1.3 million ha and 74,200 ha, respectively, despite an increase of 720,054 ha in the area of lakes, resulting in a net loss of 297,000 ha (Xing et al. 2010). Analysis of satellite images reveals that wetlands in the source zone of the "Three Rivers" decreased from 3.2 million ha in 1990 to 2.7 million ha in 2009, or by 14.13 %, even though the rate of wetland loss slowed down recently (Yang et al. 2013). In the source region of the Yangtze and Yellow rivers alone, wetlands decreased by 274,477 ha (or 1.74 % annually) during 1986–2000 (Pan et al. 2007), with frigid marshy meadow suffering the most loss. Alpine wetlands on the Plateau suffered widespread degradation during the period 1967–2004, with more than 10 % wetlands lost (Wang et al. 2007; Zhang et al. 2011). Of particular note, the wetlands in the Zoige Marsh shrank 62 % since the 1960s, as a consequence of their conversion to pasture (Li et al. 2015; Liu and Bai 2006). From 1985 to 2000, 38.9 % of lakes dried up at an annual rate of 56.13 ha (Yong et al. 2003). Natural wetlands in Maduo County shrank from 346,025 ha in 1990, to 315,822 ha in 2000, but expanded to 339,860 ha in 2010 (Tian et al. 2011).

Climate change has exerted a major influence upon wetland degradation. Over the last five decades, temperatures over the Qinghai–Tibet Plateau have warmed at a rate of 0.3–0.4 °C per decade or higher, with average daily minimum temperature warming faster than mean daily maximum temperature (Fang et al. 2011). During the same period, precipitation gradually decreased from south-east to north-west. In the headwater basin of the Three Rivers, annual mean temperature, maximum temperature, minimum temperature and precipitation all rose, in contrast to the decreasing trend of relative humidity (Xu et al. 2007). Average annual temperature rose by 1.69 °C during the past 30 years (Shen et al. 2012). In particular, annual minimum temperature rose from 0.28 to 1.96 °C during the same period.

A healthy wetland provides an environment for grasses to thrive. They protect the swampy meadow and help conserve moisture within it by reducing evaporation. Healthy grassland also promotes conservation of rainwater within the catchment, instead of flowing off to a channel out of the catchment. In addition, wetlands exert an obvious cooling effect on the ambient environment, with soil surrounded by less wetlands having a higher temperature (Bai et al. 2013). This cooling effect is attributed to the much stronger evaporative capacity of wetlands relative to grassland or cultivated land, and associated impacts upon wetland evapotranspiration and cold radiation (Gao et al. 2003). This cooling is conducive to abating evaporation. The process of daytime warming and night-time cooling is suppressed considerably in permanent wetlands relative to seasonal wetlands owing to the abundant supply of moisture. Conversely, wetland degradation is correlated closely with warmer temperature, which rose more quickly from 1982–2004 relative to 1965–1982 (Zhang et al. 2011).

Climate warming depletes moisture storage in wetlands by accelerating evaporative losses, reducing swamp size (Shen et al. 2012). Increased variability of annual precipitation, prolonged sunshine duration and rising air temperature are all important to water loss and degradation of plateau wetlands (Luo 2005). Conversely, accelerated snow melt and permafrost thaw recharge wetlands at high and cool elevations, increasing water supplies to wetland systems, and converting some swamps into lakes (Xu et al. 2007).

This chapter begins with an overview of wetlands in the upper Yellow River, followed by a conceptualization of the various processes that result in wetland degradation. The roles played by microclimate, topography, degradation agents and proximity to water sources are discussed. The pros and cons of four degradation influences are outlined in an empirical appraisal of degradation severity. Finally, implications for wetland conservation and rehabilitation are outlined.

10.2 Types, Abundance and Distribution of Wetlands Atop the Qinghai–Tibet Plateau

There is a high concentration of high-altitude wetlands on the Qinghai–Tibet Plateau, occupying 8.1 million ha in 2003, some 88 % of the national total. Swamp meadows and salty lakes account for the highest proportion of wetlands by area, both in Qinghai Province, and across the Qinghai–Tibet Plateau as a whole (Table 10.1).

Table 10.1 Total area of high-altitude wetlands (≥ 3000 m asl) in Tibet and Qinghai (2003) (*Source* State Forestry Administration 2004)

	Wetland type							
	Freshwater lakes (ha)	Salty lakes (ha)	Herbaceous swamps (ha)	Swamp meadows (ha)	Inland salty swamps (ha)	Geothermal wetlands (ha)	River/stream wetlands (ha)	Total area (% all China)
Tibet	569,300	1,942,437	540,400	1,681,400	225,400	14,500	1100	4,974,537 (53.8 %)
Qinghai	248,675	874,629		1,901,400			101,246	3,125,949 (33.8 %)
Qinghai–Tibet Plateau	817,975	2,817,066	540,400	3,582,800	225,400	14,500	102,346	8,100,486 (87.6 %)

10.2.1 Biophysical Properties

Plateau wetlands often occur in valley bottoms, as lakes, rivers or meadow swamps. Meadow swamps occupy the greatest area and are characterized by hygrophyte and mesohydrophyte plant communities that are dominated by *Kobresia tibetica*, *Blysmus sinacompressus* and *Carex scabriostris*, which are 20–25 cm high (Zhou et al. 2005). Common aquatic plants include *Potamogeton distinctus* and *Hippuris vulgaris*. Other predominant swamp vegetation species in the headwater regions include *Kobresia tibetica Maxim*. and *Carex tibetica Franch* (Wang et al. 2001), whilst the Zoige Marsh wetland is dominated by species such as *K. tibetica* and *Carex muliensis Tang* (He and Zhao 2000; Yang 1999). Due to the frigid climate, these plant communities have a relatively low biomass that increases only during the short growing season from (early) May to late August. Their root system is highly developed, forming a sod layer that is rather resistant to physical damage (i.e. they are a form of peatland).

10.2.2 Wetland Diversity

The diverse wetlands of the upper Yellow River have been classified at different scales and in many different ways, with varying emphasis placed on the nature of water (salty vs. freshwater), the dominant vegetation, substrate, ecological and/or hydrological function, landscape position and geomorphological formation (e.g. Bai et al. 2004; Pan et al. 2007; Tian et al. 2011). For the purposes of wetland management and conservation, it is most useful to classify wetlands in a way that reflects differences in their formative processes and the contemporary hydrological

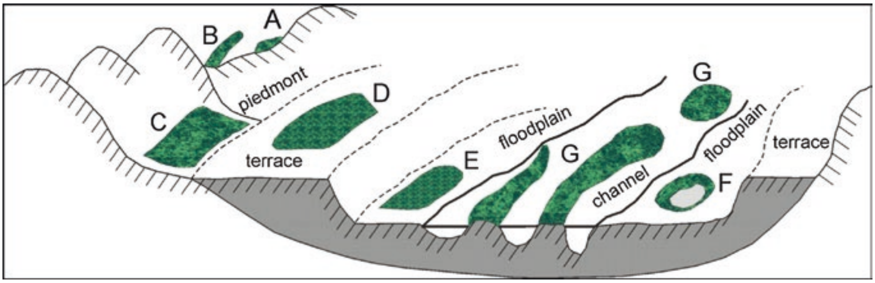

Fig. 10.1 Spatial distribution of various wetland types on the plateau. *A* alpine wetland; *B* valley wetland; *C* piedmont wetland; *D* terrace wetland; *E* floodplain wetland; *F* lacustrine wetland; and *G* riverine wetland

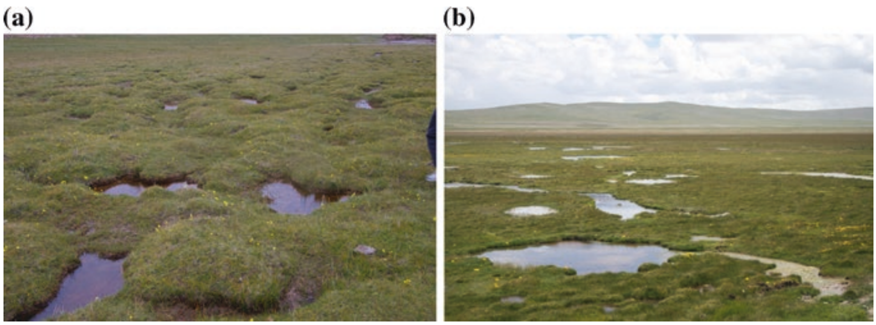

Fig. 10.2 Typical wetland in the upper Yellow River headwater zone with a small water reserve. **a** Piedmont wetland on a gentle slope. **b** Floodplain wetland with a flat topography

regime at a hillslope scale. The classification scheme proposed by Gao et al. (2013a) is therefore adopted (Figs. 10.1 and 10.2; Table 10.2):

- *Alpine wetlands* are high-altitude marshes situated in the middle to lower section of the mountain side with a V-shaped cross section and a J-shaped profile. Alpine wetlands have a low water reserve that is recharged in the rainy season or summer via snow melt and permafrost thaw.
- *Piedmont wetlands* are highland marshes located at the foot of high mountain slopes (Fig. 10.2a). They are recharged by a moderate to steady subsurface flow of water.
- *Valley* wetlands are found on valley floors. Flanked by mountain ranges, they have a linear form and a rectangular shape. They are replenished by surface flows and subsurface seepage from the adjacent mountains.
- *Terrace* wetlands are marshes located in a terrace adjoining a major channel. They are nourished by overland flow of water from higher ground.

Table 10.2 Summary of major plateau wetland types, their geomorphic and hydrological characteristics, and typical grass species (Gao et al. 2013a)

Type	Position	Mean elevation (m asl.)[a]	Slope (%)	Hydrology	Typical grasses
Alpine	Upper slopes	4310	18.4	Moist ground formed by percolated water	Kobresia pygmaea
Piedmont		4269	10.4	Ponds of water recharged via subsurface flow	Kobresia tibetica Maximowicz, Pedicularis chinensis, Kobresia humilis, Elymus dahuricus Turcz
Valley	Mid-slopes	4252	4.2	Saturated ground and pocket of water	Kobresia pygmaea, Kobresia tibetica, Kobresia capillifolia Poa annua linn
Terrace		4248	4.9	Wet ground by overland flow	Kobresia tibetica, Pedicularis chinensis, Poa annua linn, Ligularia virgaurea(Maxim.) Mattf. Artemisia
Floodplain	Valley bottoms	4243	1.5	Extensive wet surface, small pools of water	Kobresia tibetica, Ligularia virgaurea Leontopodium alpinum Ligularia virgaurea Artemisia
Lacustrine		4230	1.0	Shallow lake peripheral areas, lakeshore of saturated ground	Polygonum spp, Carex, Glaux maritime sibiricum Laxm, Polygonum sibiricum Laxm
Riverine		4221	4.9	Elongated stagnant channels	Kobresia tibetica (Polygonum spp.) Artemisia spp., Poa annua linn, Elymus dahuricus Turcz, Carex

[a]Measured with a Garmin GPS map 60 CSx receiver in the stationary mode during August 2011. The number of measurements used in calculating the mean varies with wetland types

- *Floodplain* wetlands are swamps located in a flat, spatially expansive floodplain (Fig. 10.2b). They have a relatively large water reserve that is often held in small ponds.
- *Lacustrine* wetlands are associated with the shallow part of a lake. Both the aquatic and terrestrial sections of lacustrine wetlands are charged by downstream flows as well as by lateral water inputs.

- *Riverine* wetlands are swamps that are sandwiched between braiding or anabranched channels (see Brierley et al. 2016, Chap. 3). Alternatively, they are associated with cut-off sections of the river or oxbow lakes that are not part of the contemporary active channel (Li et al. 2016, Chap. 9). Over an extended period, riverine wetlands may degenerate into terrace wetlands if the channel bed is deeply incised or if the river water drops to such a low level that it reaches the wetlands only during flooding.

Freshwater marshes in semi-arid grassland areas are sometimes referred to as cienega (or cienaga; a Spanish term). These areas are typically permanently wetted, either by springs or by water forced to the surface by channel constrictions or subsurface features such as bedrock or sills (Quivira Coalition 2014). Hillslope wetlands can be differentiated into surface water wetlands and ground water wetlands. The formation and function of headwater hillslope wetlands is driven by water supply from snowmelt or melting permafrost. Hillslope wetlands are usually incapable of depressional storage because they lack closed contours (Fig. 10.3). In these disconnected landscapes with expansive hillslope wetlands, wetland soils act as a sponge, with their high organic matter content supporting their ability to hold more water than mineral soils. This occurs because the rate of biomass production is high relative to the rate of biomass decomposition, due to the anaerobic processes at work in saturated soils. Small increases in organic matter content can have enormous significance in affecting the potential of a soil to store additional water, with peat soils able to store considerable amounts of water. Slow release of water by gravimetric flow to downslope systems is important for sustaining wetland communities, including terrestrial and aquatic plants and animals. Capturing and retaining water in hillslope wetlands in headwater areas aids the stability of wetland downslope and in floodplain valleys by regulating the water delivery rate. Water storage in wetland soils makes moisture available for a longer period of time for plants and soil-dwelling organisms and enhances baseflow lower in the watershed. Wetland vegetation also helps dissipate water energy before the water reaches tributaries, thereby reducing erosion. Riparian and wetland habitats are also a very important source of food and water for wildlife species that are not wetland obligates (Quivira Coalition 2014). Headwater hillslope wetlands may also play an important role in maintaining the cold temperatures necessary for cold

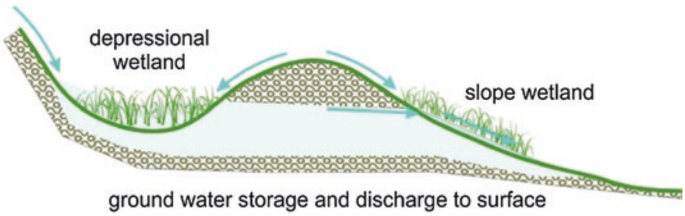

Fig. 10.3 Topographic differentiation of a depressional wetland and a slope wetland (Quivira Coalition 2014). Permafrost modifies process relationships in the high-elevation plateau environments of the Yellow River Source Zone

water aquatic life downstream (e.g. some species of fish; see Qi 2016, Chap. 11). Water stored in soil maintains a more steady temperature than water exposed to surface environmental conditions. Water that reaches the creek at the valley floor is cooler when it has been stored in wetland soils in transit down to the stream than when it has flowed on the surface in a creek channel.

Soil depth, moisture availability and plant growth vary with hillslope angle. Breaks in slope may exert a critical influence upon flow and sediment movement, and associated soil development, thereby influencing prospects for wetland development on hillslopes and associated vegetation patterns. Aspect exerts a significant influence upon wetland development and maintenance. In the Northern Hemisphere, south-facing hillslopes are warmer and dry more quickly than north-facing hillslopes. Snow accumulations are less because soils are warmer and snow melts more quickly. Site productivity is lower on south-facing hillslopes and higher on north-facing hillslopes (Quivira Coalition 2014). As a result, plant species composition and canopy densities vary greatly between northerly and southerly hillslopes (Tane et al. 2016, Chap. 13). Northerly hillslopes are more shaded and have colder and wetter soils, with surface accumulation of acidic organic matter, whilst southerly hillslopes are more exposed (sunnier), have warmer and drier soils, and organic matter is more readily incorporated within the soil. As soil erosion rates tend to be higher on south-facing hillslopes, soil depths tend to be greater on north-facing hillslopes (Quivira Coalition 2014). As soils on northerly slopes also contain higher proportions of accumulated organic matter, more water permeates is retained by soils. East and west slopes are intermediate between those facing north and south, but east slopes tend to hold more moisture than west slopes because air temperatures are lower in the morning than in the afternoon and prevailing winds from the west tend to be more drying (Quivira Coalition 2014). In relatively flat to rolling terrain, slight differences in relief, slope and aspect can make relatively large differences in soil depth, moisture retention and erosion rates. This impacts directly upon the composition and distribution of species in the vegetation community.

10.3 Processes of Wetland Degradation

Hillslope wetland degradation is usually the result of multiple cumulative impacts that have synergistic effects (Quivira Coalition 2014). Climate stressors may include an increase in the intensity of precipitation events, an earlier seasonal snowmelt run-off, or a prolonged drought. A constant source of groundwater discharge would buffer these effects. Without sustained, dispersed flow over the intact wetland surface, the wetland will eventually cease to function as a hillslope wetland. Land use change and management are also critical. Wide-scale removal or alteration of vegetative cover can cause watershed degradation by exposing soils to compaction and accelerated surface run-off and soil erosion.

Wetland degradation can involve both deterioration in wetland quality and reduction in wetland area. Deterioration in wetland quality may be manifested as a reduction in wetland water reserve, an increase in water salinity, reduction in aquatic vegetation, the expansion of denudated patches and/or the emerging dominance of drought-tolerant grass species. All these types of deterioration are ultimately consequent on a change in the hydrological regime of the wetland.

10.3.1 A Hydrological Conceptualization of Wetland Degradation

Unlike terrestrial land degradation, wetland degradation starts with a change in hydrological regime. This availability of moisture (water) or its balance is calculated as follows:

$$\Delta M = \text{Input} - \text{Output} \begin{cases} > 0 \\ = 0 \\ < 0 \end{cases} \tag{10.1}$$

where ΔM refers to the net budget of moisture/water. Of the three possible scenarios, $\Delta M > 0$ signifies a healthy and stable state of wetlands; $\Delta M = 0$ means that the wetland lies in a stable equilibrium state; and $\Delta M < 0$ means that the wetland suffers from the stress of moisture/water depletion and has a propensity to degrade. However, degradation of the wetland may not immediately follow the drying. Wetlands with a significant water reserve are sufficiently resilient to withstand moisture/water deficit without showing any signs of degradation, at least initially. If the deficit lasts only a short whilst, then degradation may not occur at all if no external disturbance has occurred to the wetland. If sufficient water is replenished to the system, the wetland is able to revert to its former healthy state, without any trace of degradation. Such wetlands may be seasonal. There is no damage done to ecosystem functionality and the composition of the plant community is unchanged. Irreversible degradation means that the degraded wetland ecosystem cannot return to its former state without external intervention. This is because a negative water/moisture balance over an extended period causes the original vegetation to perish or be partially or wholly replaced by new plant communities. Even if the water reserve is restored to its former level, it is unlikely that deteriorated wetland will revert to its former state without external intervention.

10.3.2 A Sequence of Degradation

The process of degradation from wetland to desert conditions can be conceived as a gradual transition from swampy wetlands to swampy meadows to steppe

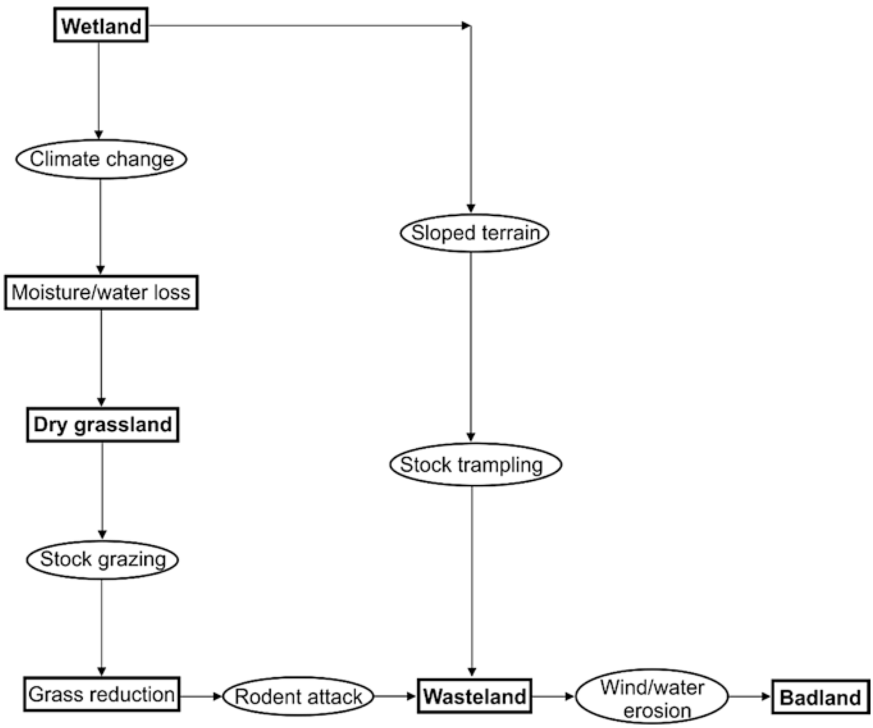

Fig. 10.4 General processes and major stages of wetland degradation

meadows to degraded grassland, and finally to barren land (Fig. 10.4) (Yang 1999). The limited water reserve of many plateau wetlands can be quickly depleted via outflow and evaporation if it is insufficiently recharged, creating bare patches in the grassland as former ponds dry up. With further removal of moisture from the wetland, these patches expand, and the former wetland gradually turns to dryland. Whilst waterlogged swamps are inhospitable for small mammals, the dry surface offers habitat that may be suited to them. Rodents such as plateau pikas often start to dig burrows along the periphery of dried denudated patches. Population booms in these animals can rapidly aggravate soil erosion, expanding the dry areas still further (Miehe et al. 2011).

Dried up patches are the most vulnerable spots for wetland degradation to expand and/or to progress to a more severe level. In case of a severe and lasting drought, some original vegetation will die out, leaving more denudated patches that may be colonized by other drought-tolerant species. In this way, the dryland is converted to wasteland. Under the forces of wind and water, the denuded patch enlarges in size at the expense of nearby vegetation, whose cover may also be reduced by foraging rodents. If rodents continue to infest the area, the former grassland will eventually disappear, being replaced with species that have little or no nutritional value for the stock. In the worst cases, desertification may occur if the substrate is underlain by a layer of sand. Towards the later stage of degradation, even rodents themselves abandon the extremely degraded habitat in search of food elsewhere. Afterwards, the natural processes of water and wind erosion slowly transform the wasteland to badland.

10.3.3 The Major Stages of Degradation

The general process of wetland degradation outlined above contains four distinctive stages in a continuum of wetland degradation: wetland, dryland, wasteland and badland (Fig. 10.5). This corresponds to four levels of degradation severity: intact, slight, serious and extreme.

The stages are presented as a heuristic conceptualization. In reality, some stages may be skipped, and the various factors responsible for degradation may interact. Different thresholds between each stage of degradation are likely to apply for the various types of wetlands discussed above, and in different landscape settings.

Dryland is temporarily dried up wetland that can naturally revert into *healthy wetland*. This transition from wetland to dryland is quantitative in that only the

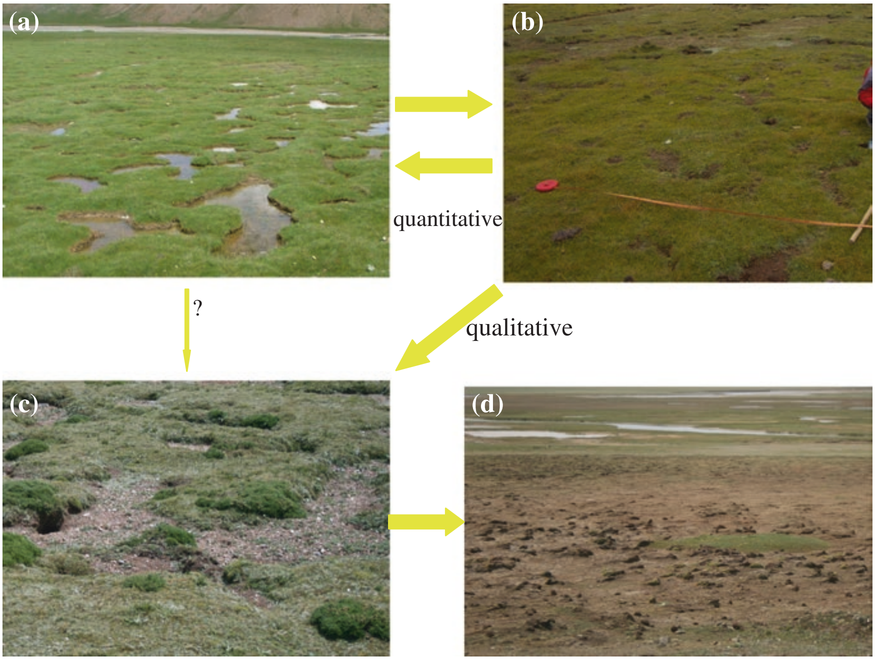

Fig. 10.5 The main stages in the process of wetland degradation from intact to badland. **a** Healthy wetland without signs of degradation; **b** dry grassland; **c** wasteland of no economic value; and **d** badland. The questionmark refers to uncertainty over whether degradation can jump to the badland state without going through the second (dryland) stage. In some instances it healthy wetland may be degraded to this state by excessive trampling by stock. The size of arrows refers to the ease (likelihood) with which a transition can occur

amount of water reserve/moisture in the wetland system is reduced (Fig. 10.5b). No change has occurred to topography or plant composition. In other words, drought has reduced the water reserve, but vegetative cover remains intact. The change from healthy wetland to dryland is caused primarily by environmental desiccation that may be exacerbated by overgrazing. Thus, these two states are considered interchangeable as indicated by the direction of the arrows on Fig. 10.5.

The progression from *dryland* to *wasteland* is considered “qualitative” in that the species composition of the wetland has been altered. The original moisture-loving and nutritious grass species have been gradually replaced by drought-tolerant, unpalatable weeds. The more degraded the wetland, the higher the proportion of these secondary species of grasses. It is not easy for the wetland to revert to its previous healthy condition, even if the water reserve is restored to the previous level. The transition from dryland to wasteland is often triggered by two factors: overgrazing and rodent attack. Overgrazing strips the underlying grass roots, so that plants cannot easily recover from drought stress. Over an extended period, the original grasses gradually die out, creating extensive bare patches that secondary grass species can invade. At this stage, rodent infestations can play a critical role in converting dryland to wasteland.

Under normal circumstances, it is unusual for healthy wetland to be degraded directly to wasteland without going through the dryland stage. The only exception occurs when the ground is repeatedly and severely trampled by grazing stock (see Tane et al. 2016, Chap. 13). Physical (mechanical) damage can lead to rapid wetland deterioration, even if the water reserve would otherwise be sufficient to maintain the wetland. Trampling can destroy the protective sod layer much more quickly if the wetland is situated on a slope, considerably shortening the time needed to reach the wasteland stage of degradation.

In cases of severe external disturbance (e.g. widespread burrowing), wastelands may be converted to badlands if fertile surface soils are lost through wind and water erosion (Calzolari and Ungaro 1998; Howard 1997). Both wasteland and badland are of little value to animal husbandry. However, it is environmentally important to differentiate them and to prevent wasteland from progressing to the badland stage. Although wastelands may not be able to support yak, the remaining vegetative cover continues to protect the underlying soil. By comparison, badlands are mostly devoid of vegetation and so are vulnerable to soil erosion. Badland landscapes, covered by coarse sands and gravels, are commonly known as “*Heitutan*”, or black earth beach (see Li et al. 2016, Chap. 7). Li et al. (2014) demonstrate a continuum of transition states in the analysis of *Heitutan* degraded grasslands on the Qinghai–Tibet Plateau.

10.3.4 Degradation Risk Varies According to Local Factors

Whilst the water/moisture budget (Eq. 10.1) succinctly sums up the potential for wetland degradation, it fails to explain why some spots are degraded whilst others within the same region remain healthy. The severity of wetland degradation in a region is not spatially uniform because of variation in the factors that control the distribution of moisture at local scales: microclimate, topography, proximity to water sources, etc. (Yu et al. 2001), and degradation agents that represent external disturbances to wetland ecosystems. Although these factors do not directly trigger degradation, they govern the conditions that make wetlands more or less vulnerable to degradation processes. This vulnerability (or risk) can be expressed as a function of the four factors (Eq. 10.2).

$$\text{Degradation risk} = \text{f(micro - climate,topography,agents,proximity to water)} \tag{10.2}$$

This equation illustrates the risk of plateau wetland degradation in a general way. It does not claim to offer a predictive model. Indeed, the variables included in the equation can interact, so the equation is neither additive nor does it describe a linear relationship. Determination of the nature and the specific form of this function falls beyond the scope of this paper. Instead, the specific role of each variable in contributing to wetland degradation is explored below.

The four variables in Eq. 10.2 fall into two broad groups: natural and anthropogenic. Natural factors include climate change (e.g. reduced precipitation, global warming, increased evaporation, increased melting of snow/glaciers), topography and proximity to water sources. All these factors can reduce hydrological inputs to wetlands (Li et al. 2006). Anthropogenic factors include agents that reduce channel flow (e.g. dams) or reduce grass cover (e.g. overgrazing).

Microclimate variables encompass four subcomponents: temperature, evaporation, rainfall (snow or rain) and sunshine hours. Reduced precipitation and global warming have a mixed effect on wetland well-being. On the one hand, warming enhances evaporation, whilst on the other hand, it accelerates melting of snow and glaciers, and thawing of permafrost. This could result in drought stress on low-lying wetlands, but an enhanced hydrological recharge to upland wetlands. Both desiccation and evaporation contribute to wetland degradation, albeit with quite different mechanisms. Whilst desiccation (decreasing recharge) is associated with smaller inputs to the moisture/water balance, evaporation increases hydrological outputs from the wetland system (Eq. 10.1). Whilst sunshine hours mainly affect water/moisture evaporation, rainfall mainly affects hydrological recharge. The net effect of climate variables may vary locally, depending on the altitude or aspect of a wetland.

Topography has four subcomponents: elevation, slope gradient (steepness), slope shape and slope aspect. Elevation refers to the altitude at which wetlands are located. Elevation controls the redistribution of moisture on a slope as moisture always moves downslope under the effect of gravity. Elevation profoundly affects the vulnerability of wetlands to degradation, since wetlands at a lower elevation tend to receive larger water inputs and to have smaller water outputs than those at higher elevations. Thus, low-lying riverine and lacustrine wetlands are not as easily degraded as more elevated piedmont and terrace wetlands (Fig. 10.1). Higher altitudes also tend to have lower temperatures, with less evaporation and more precipitation.

Slope gradient affects the rate of flow: slow-moving water has more chances to enter the soil and move down the slope in subsurface seepage, whilst fast-moving water is more likely to move away as surface run-off, failing to replenish local wetlands. There is therefore an inverse relationship between slope gradient and the tendency towards degradation (Qiu et al. 2001).

Slope shape influences flow direction. Slopes that are concave from both planform and profile perspectives promote convergent flows, so water is stored locally in lower lying wetlands. Conversely, convex slopes promote divergent flows, limiting local recharge and so making these wetlands more vulnerable to degradation.

Aspect (orientation) affects the amount of solar radiation received on a slope. Its major influence on wetlands is via temperature, affecting evaporation rates as described above. In the northern hemisphere, south-facing slopes receive more solar radiation, so soil moisture is lost at a faster rate than from their north-facing counterparts.

Degradation agents include rodents, stock and humans, all of which can accelerate degradation. Unlike the previous factors considered, agents do not directly impact the water balance (Eq. (10.1)). Instead, agents exert an indirect impact on water balance by altering the surface structure of wetlands. Four types of rodents (small mammals), plateau pika (*Ochotona curzoniae*), plateau zokors (*Myospalax fontanierii*), plateau voles (*Pitymys irene*) and Himalayan marmots (*Marmota himalayana*) have damaged wetlands (Arthur et al. 2007). Pika damage the surface cover by digging holes on the ground after the wetland water/moisture drops to a certain threshold. Native grasses are suffocated to death after being covered by piles of loosened soils deposited next to burrow entrances. Pika can also cause the collapse of a grass hummock when adjacent burrows coalesce, so increasing the size of a bare patch. They also decrease vegetative cover by devouring nutritious grasses.

By comparison, large herds of yaks not only accelerate evaporation by decreasing grass cover, they also accelerate degradation through trampling. Trampling is especially damaging along the periphery of hummocks and may cause the collapse of the sod layer, thus expanding bare patches left behind by dehydration (Tane et al. 2016, Chap. 13).

The last type of degradation agent is humans. Although human activities in this region seldom damage alpine wetlands deliberately (cf., drainage of valley floor and basin fill wetlands described by Li et al. 2016, Chap. 9), indirect effects may impact negatively on wetland health. For example, abstraction of water reduces the quantity of water available for recharging low-lying riverine and lacustrine wetlands.

At the local scale, *proximity to water sources* controls the amount and frequency of wetland recharge. In general, wetlands located closer to water sources are replenished more frequently and more plentifully than are those further away. In other words, a longer distance to water represents a higher risk of degradation.

10.4 A Conceptual Model for Degradation Severity

The four stages of degradation are linked to the controls on degradation risk in a conceptual model shown in Fig. 10.6. This model is intended to be heuristic, providing a starting point for discussions and the development of hypotheses.

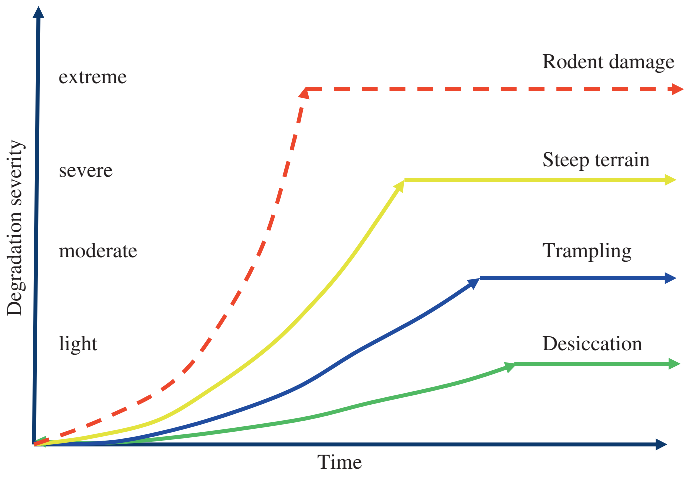

Fig. 10.6 Models of wetland degradation to four severity levels. This conceptualization illustrates how variables can interact to accelerate the pace and severity of degradation. Each of the degradation triggers can interact with any of the others, and thresholds between the various levels of degradation vary in different landscape settings

It is not intended to be a process model that can be parameterized to accurately reflect reality and predict outcomes in a particular location. Various levels of degradation severity expressed on the vertical axis interact over time (horizontal axis). Degradation resulting solely from environmental change (e.g. increased evaporation or decreased recharge associated with climate fluctuations) is relatively slight, occurring over an extended period of time (green curve). This type of degradation often occurs in riverine and valley wetlands within flat terrain. If such a wetland is also heavily trampled by stock, degradation is accelerated, and a moderate level of degradation may be reached over a shorter period (blue curve). Such degradation usually occurs in lacustrine wetlands, along lake shores. Lacustrine wetlands tend to be resilient to further degradation, since abundant moisture in the lake deters the invasion of drought-tolerant grass species. In most cases, the degradation of lacustrine wetlands is slight, only reaching moderate levels of severity when the surface is heavily trampled by stock. If wetlands are located on slopes, the time taken to deteriorate is often further accelerated, since bare patches are liable to expand faster than on flat terrain, as loosened soil is more quickly removed by wind or water (yellow curve). This situation is commonly associated with piedmont wetlands whose surface is much steeper than valley and riverine wetlands. Soil erosion can also be accelerated by the action of rodents, which can also drive a wetland to the extreme level of degradation (i.e. wasteland and/or badland). Since piedmont wetlands are those furthest from a water source, they are especially vulnerable to such extreme levels of degradation. Alpine wetlands are also highly vulnerable, due to their relative steepness. However, their high elevation is associated with greater precipitation, which makes them less vulnerable to desiccation.

In this conceptual model, degradation should be considered as the net effect of individual factors, not merely as a linear summation. The total damage is multiplied many times over if more than one factor drives the degradation process. Outcomes are dependent on the particular combination of the factors present at a particular location. For instance, pika cannot tolerate the low temperatures found at high altitudes, so they are only found at relatively low elevations. Their impact is lessened in flat areas and greater in steeper areas. Thus, their impact changes with local elevation and topography.

In summary, the conceptualization demonstrates that various drivers of degradation combine to accelerate both the rate and severity of degradation processes. More research is needed to better understand the relationships between drivers in different wetland types in various climatic settings. Particular concern should be given to identify and measure threshold conditions between different levels of severity and to identify indicators that such thresholds are being approached.

10.5 Field Assessment of Degradation Severity

10.5.1 Degradation Indicators

Wetland degradation can be diagnosed from primary and secondary symptoms. The primary symptom of degradation is a reduced water reserve. Wetland degradation starts with desiccation that causes a decrease in the water level and shrinkage in wetland extent. If desiccation persists, small puddles or pools of water within wetlands may dry up. This represents a definite sign of stress and is a precursor to potential degradation. The same degree of desiccation may not cause large water bodies (e.g. ponds and lakes) to dry up completely, leading only to a drop in water level. Secondary signs of degradation include enlargement of bare patches, the presence of secondary, drought-tolerant grass species and the presence of large rodent populations.

The severity of wetland degradation is most easily indicated by the percentage of grass cover within a sampled plot, surface hydrology, soil moisture content and the density of rodent burrows (Table 10.3). These factors are comprehensive, since they take into consideration biology (grass cover), hydrology (soil moisture content), soil condition and external disturbance (rodent burrows), all of which are core elements for assessing wetland ecological health (Fennessy et al. 2007). Collectively, they provide a quantitative measure on the continuum from full ecological integrity (i.e. intact wetland) to highly degraded (poor condition) variants. Importantly, measures are easy and quick to assess at a site and are replicable, thereby supporting objective and comparable analyses across different geographic areas and different types of wetland.

The use of *vegetation cover* expressed as a percentage is valid only when the wetland is of the same type. For instance, riverine wetlands are inherently less vulnerable to degradation than piedmont wetland owing to their larger water reserve,

Table 10.3 Indicators of plateau wetland degradation and criteria for grading degradation severity

Severity level	Vegetation		Hydrology		Soil erosion	Pest damage (rodent burrows/9 m^2)
	Cover (%)	Grass species	Surface water	Moisture content @10 cm (%)		
Intact	>90	Original	Ponds and pools	>50	Absent	<1
Slight	>80	Mostly original	Small pools	>40	Sod layer damaged	2–3
Moderate	≥50	Half original	Wet surface	≥25	Piles of loosened soil	4–5
Severe	<50	Mostly secondary	Dry surface	<25	>50 original soil gone	≥5

even though they have much less vegetative cover. In general, vegetative cover is related negatively to degradation intensity for the same type. The worse the degradation intensity, the lower the vegetative cover. Therefore, vegetative cover is not a perfect indicator of degradation intensity if it has a very low level (e.g. within the slight degradation level; Gao et al. 2013b) or it is not of the original native vegetation. In fact, vegetation cover can be rather high for severely degraded land if it is comprised of invasive, unpalatable species that are not grazed by stock. This deficiency can be overcome with the use of the proportion of unpalatable grasses (Gao and Zha 2010).

Hydrology encompasses two subvariables: surface water and soil moisture content. In the analysis here, emphasis is placed upon the two-dimensional area of surface water area, as it is almost impossible to estimate precisely the water volume. However, soil moisture can be easily measured at a certain depth beneath the surface. The reliability of soil moisture seems to be related to the degradation severity. However, it is not reliable beyond the moderate level of degradation, as beyond a certain level of surface moisture depletion there is little capacity for further change in moisture content (Gao et al. 2013b). This limitation of moisture content in indicating wetland degradation level can be avoided by measuring it at a depth closer to the surface, such as 10 cm. However, the closer the measurement to the surface, the more it is subject to fluctuations in climate condition. In order to generate reliable measurements, moisture has to be measured at the same spot repeatedly so as to eliminate temporal variations. Another problem with this indicator is that it remains unknown how the two subvariables should be combined to derive an index.

It is difficult to quantify the degree of *soil erosion* in the field. However, the amount of sod layer remaining and the extent of loose soil can be used as a surrogate measure. In reality, barren ground may simply appear after the evaporation of water, but this bareness does not imply degradation. The surface can only be degraded to a serious state when the bare ground is disturbed to such a degree that it contributes to sediment supply during rain or wind storms.

Although the presence of pika burrows indicates the presence of one form of *external disturbance* to the wetland system, the density of pika burrows is a problematic indicator in that they can be abandoned or deserted when little original vegetation remains at the affected site. The absence of suitable forage forces them to migrate elsewhere. Pika burrows will be eventually covered up by regenerated vegetation. Another reason for abandonment is flooding by water. The nonlinear relationship between burrow density and degradation intensity suggests that it is not a perfect indicator of degradation intensity (Gao et al. 2013b). Care needs to be excised in using this indicator by including only the active burrows in the assessment of degradation intensity.

10.6 Wetland Conservation and Rehabilitation

The transformation of marshy meadow to meadow and steppe meadow suggests that the warming and drying of climate is a major cause of wetland change (Pan et al. 2007). Climate warming has caused the wetland ecosystem to shift to bottomland ecosystem and even grassland (Xu et al. 2007). Atop this, human activities have exacerbated wetland loss (Li et al. 2016, Chap. 9; Tane et al. 2016, Chap. 13). In order to avoid the negative consequences of wetland degradation, it is very important to conserve existing wetlands and to restore degraded wetlands so as to improve their cooling and humidifying effects and establish a balanced ecosystem.

10.6.1 Rehabilitation Measures

A number of measures can be adopted to rehabilitate the degraded wetlands on the Plateau, ranging from biological and ecological to engineering. Biological measures aim at restoring the damaged vegetative cover through reduced grazing. In order for the swampy meadow to revert to its former healthy state and to be grazed sustainably, grazing intensity should be lessened via fence enclosure, at least initially, or through rotational (e.g. seasonal) grazing. Overgrazing should be controlled not only in the growing season when both water and energy are in bountiful supply (thereby encouraging production of fodder), but also in marginal seasons when grass roots just produce new sprouts. If the wetland has been degraded beyond the biotic recoverable threshold, human intervention (e.g. artificial seeding and revegetation) should be implemented to reduce soil erosion and land degradation. In addition, rodent predators may be introduced to maintain a high level of biodiversity (Xiang et al. 2009). Engineering measures can take the form of constructing shallow dams and trenches to retain water within the peatlands. Determination of the most appropriate restorative measure is dependent upon the causes of degradation. Restoration measures must target the root causes of wetland degradation.

10.6.2 Impediments to the Protection and Conservation of Plateau Wetlands

Conservation of plateau wetlands is significant not only to sustaining the local animal husbandry and the livelihood of local herdsmen, but also to maintaining a sound ecosystem and preventing soil erosion. However, successful conservation of the remaining wetlands faces a number of challenges in funding, land ownership and environmental awareness (Tian 2014). First of all, there is a lack of funding for all restoration work. Some wetlands facing the risk of degradation need to be fenced off from grazing whilst ditches have to be dammed to prevent water from being drained out of the wetlands. Both types of human intervention require enormous financial investment from the local government. Although the central government has set aside funds for such conservation efforts, they are not consistently allocated to local needs across provincial borders.

The second barrier is a lack of an ecological compensation mechanism. At present, most swampy meadows are subdivided among herdsmen who are at liberty to use them. In order to bring overgrazing under control, a mechanism needs to be established to compensate pastoralists for their reduced income caused by a lowered grazing intensity. Although governments have tried to reduce overgrazing by shifting some pastoral population away from grazing, the long-term sustainability of this strategy in reducing grazing intensity is uncertain as the newly settled herdsmen lack a steady source of income to sustain their livelihood.

Finally, lack of understanding of the functions and significance of plateau wetlands due to lack of environmental education has hindered society-wide recognition and consensus over the necessity and value of wetland conservation (Tian 2014). In some local areas, economic development through animal husbandry or mining has taken precedence over wetland protection and conservation.

10.6.3 Recovery Prospects

Prospects for recovery of degraded wetlands reflect the severity level of degradation. Full recovery is possible if the wetlands are degraded only seasonally or slightly (e.g. still within the biotic threshold of degradation). In this case, minimum investment or human invention is needed other than fencing off the wetlands for grazing until full recovery is achieved, or a reduction in grazing capacity through a reduction in the stocking level. The time required to recovery to the formal healthy state depends on external natural environments (e.g. climate change) and disturbance (e.g. grazing). If abundant rain water is available to recharge the wetlands, then only a short period may be required. However, it will take much longer for the wetland to recover fully if the vegetation composition has been altered by the invasion of secondary species after wetland has dried up. Modelling results suggest that completely desertified wetlands may require hundreds of years to recover fully, with the exact length of recovery depending on the intensity of external disturbances, such as grazing (Li 2012). This time frame can be shortened if mechanical means (e.g. artificial seeding) are implemented as part of the restoration efforts.

10.7 Conclusions

The restoration of alpine wetlands is crucial in the role they play in influencing the quantity and quality of downstream hydrological systems, supporting sustainable ecosystems, as well as buffering the effects of climate change (Quivira Coalition 2014). Capturing, slowing, spreading and infiltrating water as high up on the landscape as possible support efforts to disperse flow across wetland surfaces and recharge their shallow groundwater aquifers, thereby maintaining baseflows to downstream areas.

Wetlands in the Yellow River headwater region on the Qinghai–Tibet Plateau are distributed across a wide range of elevations and have varying proximity to river channels. Consequently, they exhibit a diverse range of forms and they have various types of vegetation associations. Based on their geomorphic and hydrological characteristics, they can be categorized into alpine, valley, piedmont, terrace, floodplain, riverine and lacustrine types. Over the last five decades, these wetlands have been degraded to varying severity levels. In the worst case, former swampy marshes have been degraded to barren sandy land. The risk of wetland degradation is derived from factors such as climate change, topography, degradation agents and proximity to water sources.

Four distinctive stages of degradation have been identified: intact wetland, dryland, wasteland and badland. A conceptual model illustrates that the joint effect of multiple triggers far exceeds that of the combined influence of individual factors. Thus, their overall effect is not simply additive but integrative and cumulative. Only certain joint contributors can result in particular types of degradation severity. These impacts can be assessed using three indicators: soil moisture, vegetative cover and density of pika burrows. Whilst useful in general, each indicator is not perfect, and care needs to be exercised in ensuring that exceptions to the norm are considered in any assessment. Of the various causes of wetland degradation, climate warming is recognized as important for the disappearance of small lakes and ponds, whilst overgrazing is the major factor causing the degradation of swampy meadow wetlands.

Differing measures are required to address underlying causes of wetland degradation in efforts to rehabilitate degraded wetlands. Combinations of biological, ecological and engineering measures are required. Biological and ecological approaches entail relatively low investment and may be effective at rehabilitating mildly degraded wetlands. However, expensive mechanical and engineering measures are required to restore heavily damaged wetlands. It may take centuries for the worst degraded wetlands to recover fully in the absence of excessive human disturbance.

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References

Arthur, A. D., Pech, R. P., Zhang, J., et al. (2007). *Grassland degradation on the Tibetan Plateau: The role of small mammals and methods of control*. Canberra: Australian Centre for International Agricultural Research.

Avis, C. A., Weaver, A. J., & Meissner, K. J. (2011). Reduction in areal extent of high-latitude wetlands in response to permafrost thaw. *Nature Geoscience, 4*, 444–448.

Bai, J., Lu, Q., Zhao, Q., et al. (2013). Effects of alpine wetland landscapes on regional climate on the Zoige Plateau of China. *Advances in Meteorology*. Article ID 972430, 7 pp.

Bai, J. H., Ouyang, H., Xiao, R., et al. (2010). Spatial variability of soil carbon, nitrogen, and phosphorus content and storage in an alpine wetland in the Qinghai-Tibet Plateau, China. *Australian Journal of Soil Research, 48*, 730–736.

Bai, J., Ouyang, H., Xu, H., et al. (2004). Advances in studies of wetlands in Qinghai-Tibet Plateau. *Progress in Geography, 23*, 1–9.

Brierley, G. J., Yu, G. A., & Li, Z. W. (2016). Geomorphic diversity of rivers in the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 59–78). Berlin: Springer.

Calzolari, C., & Ungaro, F. (1998). Geomorphic features of a badland (biancane) area (Central Italy): characterisation, distribution and quantitative spatial analysis. *Catena, 31*, 237–256.

Fang, S., Han, G., & Wang, Y. (2011). Climate change over the Qinghai-Tibet Plateau and its impacts on local agriculture and animal husbandry in the last 50 years. *Resources Science, 33*, 1969–1975.

Feng, Q. S., Shang, Z. H., Liang, T. G., et al. (2008). Remote sensing monitoring and dynamic change of marsh wetlands in Maqu County, the first turning area of Yellow River. *Wetland Science, 6*, 379–385.

Fennessy, M. S., Jacobs, A. D., & Kentula, M. E. (2007). An evaluation of rapid methods for assessing the ecological condition of wetlands. *Wetlands, 27*, 543–560.

Gao, J., Li, X. L., Brierley, G., et al. (2013a). Geomorphic-centered classification of wetlands on the Qinghai-Tibet Plateau, western China. *Journal of Mountain Science, 10*, 632–642.

Gao, J., Li, X., Cheung, A., et al. (2013b). Degradation of wetlands on the Qinghai-Tibet Plateau: A comparison of the effectiveness of three indicators. *Journal of Mountain Science, 10*, 658–667.

Gao, J. Q., Lv, X. G., & Liu, H. Y. (2003). Cold-humid effect of wetlands. *Rural Ecoenvironment, 19*, 18–21.

Gao, J., & Zha, Y. (2010). Monitoring of grassland degradation near Lake Qinghai, West China from satellite data. In G. Brierley, X. Li, & G. Chen (Eds.), *Landscape and environment science and management in the Sanjiangyuan Region* (pp. 166–173). Qinghai: Qinghai People's Publishing House.

He, C., & Zhao, K. (2000). Influence of human activities on the mire in Zoige Plateau and countermeasure. *Scientia Geographica Sinica, 20*, 444–449.

Howard, A. (1997). Badland morphology and evolution: Interpretation using a simulation model. *Earth Surface Processes and Landforms, 22*, 211–227.

Li, X. (2012). *The spatio-temporal dynamics of four plant-functional types (PFTs) in alpine meadow as affected by human disturbance*, Sanjiangyuan region, China. PhD thesis, University of Auckland, 213 pp.

Li, X., Brierley, G. J., Shi, D., et al. (2012). Ecological protection and restoration in Sanjiangyuan Natural Reserve, Qinghai Province, China. In D. Higgitt (Ed.), *Perspectives on environmental management and technology in Asian River Basins* (pp. 93–120). Netherlands: SpringerBriefs in Geography.

Li, L., Li, F., Guo, A., et al. (2006). Study on the climate change trend and its catastrophe over Sanjiangyuan Region in recent 43 Years. *Journal of Natural Resources, 21*, 79–85. (in Chinese with English abstract).

Li, X. L., Perry, G., & Brierley, G. J. (2016a). Grassland ecosystems of the Yellow River Source Zone: Degradation and restoration. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 137–166). Berlin: Springer.

Li, X. L., Perry, G. L. W., Brierley, G. J., et al. (2014). Quantitative assessment of degradation classifications for degraded alpine meadows (Heitutan), Sanjiangyuan, Western China. *Land Degradation & Development, 25*, 417–427.

Li, Z. W., Wang, Z. Y., Brierley, G., et al. (2015). Shrinkage of the Ruoergai Swamp and changes to landscape connectivity, Qinghai-Tibet Plateau. *Catena, 126*, 155–163.

Li, Z. W., Wang, Z. Y., & Pan, B. Z. (2016b). Wetland ecosystems of the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 183–208). Berlin: Springer.

Liu, H.-Y., & Bai, Y.-F. (2006). Changing process and mechanism of wetland resources in Ruoergai Plateau, China. *Journal of Natural Resources, 21*, 810–818.

Luo, L. (2005). Analysis of climatic background of wetlands degradation in the Qinghai-Xizang Plateau. *Wetland Science, 3*, 190–199.

Miehe, G., Miehe, S., Bach, K., et al. (2011). Plant communities of central Tibetan pastures in the alpine steppe/kobresia pygmaea ecotone. *Journal of Arid Environments, 75*, 711–723.

Pan, J. H., Wang, J., & Wang, J.-H. (2007). Dynamic change of frigid wetlands in Source Region of the Yangtze and Yellow Rivers. *Wetland Science, 5*, 298–304. (in Chinese).

Pan, X., Zhang, J., Luo, Z., et al. (2011). Natural wetland in China. *African Journal of Environmental Science and Technology, 5*, 45–55.

Qi, D. (2016). Fish of the Upper Yellow River. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 233–252). Berlin: Springer.

Qiu, Y., Fu, B., Wang, J., et al. (2001). Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. *Journal of Arid Environments, 49*, 723–750.

Quivira Coalition. (2014). *Characterization and restoration of slope Wetlands in New Mexico. A guide for understanding slope Wetlands, causes of degradation and treatment options.* New Mexico Environment Department Surface Water Quality Bureau, Wetlands Program.

Ran, Y. C., Xie, J. X., & Li, X. L. (2016). Socio-economic development and its effects on the ecological environment of the Yellow River Source Zone. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*, (pp. 331–351). Berlin: Springer.

SFA—State Forestry Administration. (2004). *First National Wetland Resources Survey*.

SFA—State Forestry Administration. (2014). *Outcomes of the Second National Wetland Resources Survey* (http://www.china.com.cn/zhibo/zhuanti/ch-xinwen/2014-01/13/content_31170329.htm)

Shen, W., Liu, D., Ji, D., et al. (2012). Dynamics and driving forces of the alpine wetlands in the Yarlung Zangbo River basin of Tibet, China. *World Academy of Science, Engineering and Technology*, *67*, 2012-07-22 (http://waset.org/publications/12588)

Sun, S. G., & Zhang, Z. W. (1987). Old channels of the Huanghe River on Ruoergai Plateau and its palaeogeographic significance. *Scientia Geographica Sinica, 7*, 266–272.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) Headwaters. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 275–330). Berlin: Springer.

Tian, K. (2014). *Plateau wetlands: Functions, values, and environmental deterioration*. Chinese Research Perspectives Online. Edited by: International Advisory Board Chinese Research Perspectives Online. Brill Online, 2014. Accessed 13 February 2014 (http://www.blonline.nl/entries/chinese-research-perspectives-online/plateau-wetlands-functions-values-and-environmental-deterioration-C9789004182417_011)

Tian, R., Cao, C.-X., Ma, G.-R., et al. (2011). Changes and driving factors of plateau wetlands in Maduo County. *Wetland Science, 9*, 61–68. (in Chinese).

Wang, G., Cheng, G., & Shen, Y. (2001). *Research on ecological environmental change in the source regions of Yangtze-Yellow Rivers and their integrated protection*. Lanzhou: Lanzhou University Press.

Wang, G., Li, Y., Wang, Y., et al. (2007). Typical alpine wetland system changes on the Qinghai-Tibet Plateau in recent 40 years. *Acta Geographica Sinica, 62*(5), 481–491.

Xiang, S., Guo, R., Wu, N., et al. (2009). Current status and future prospects of Zoige Marsh in Eastern Qinghai-Tibet Plateau. *Ecological Engineering, 35*, 553–562.

Xing, Y., Jiang, Q., Qiao, Z., et al. (2010). Analysis of the wetland environment change in Qinghai-Tibet Plateau using remote sensing. In *4th International Conference on Bioinformatics and Biomedical Engineering (iCBBE)*, Chengdu, 18–20 June 2010, doi:10.1109/ICBBE.2010.5515483

Xu, X., Liu, J., Shao, Q., et al. (2007). The dynamic changes of ecosystem spatial pattern and structure in the Three-River Headwaters region in Qinghai Province during recent 30 years. *Geographical Research, 27*, 829–838.

Yang, Y. (1999). Ecological environment deterioration, mire degeneration and their formation mechanism in the Zoige plateau. *Journal of Mountain Research, 17*, 318–323.

Yang, R.-M., An, R., Wang, H.-L., et al. (2013). Monitoring wetland changes on the source of the Three Rivers from 1990 to 2009, Qinghai, China. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 6*, 1817–1824.

Yong, G., Shi, C. C., & Pengfei, Q. (2003). Monitoring on desertification trends of the grassland and shrinking of the wetland in Ruoergai Plateau in North-west Sichuan by means of remote-sensing. *Journal of Mountain Science, 21*, 758–762.

Yu, Z., Carlson, T. N., Barron, E. J., et al. (2001). On evaluating the spatial-temporal variation of soil moisture in the Susquehanna River Basin. *Water Resources Research, 37*, 1313–1326.

Zhang, Y., Wang, G., & Wang, Y. (2011). Changes in alpine wetland ecosystems of the Qinghai-Tibetan plateau from 1967 to 2004. *Environmental Monitoring and Assessment, 180*, 189–199.

Zhou, H., Zhao, X., Tang, Y., et al. (2005). Alpine grassland degradation and its control in the source region of the Yangtze and Yellow Rivers, China. *Grassland Science, 51*, 191–203.

Chapter 11
Fish of the Upper Yellow River

Delin Qi

Abstract The native fish species of the Upper Yellow River are dominated by schizothoracine fishes of the Cyprinidae (carp family) and nemacheiline fishes of the Cobitidae (loach family). These species have adapted and evolved over millions of years to the highland environment. They play significant roles in the trophic web of freshwater communities. This chapter presents an overview of fish from the Upper Yellow River. The chapter is structured as follows. First, the chapter summarizes the fish diversity and distribution patterns in the Yellow River Source Zone. Second, the fish biology, including growth and body weight, reproduction and morphological adaptations related to feeding habits, is outlined. Third, a summary is provided of the evolutionary history of major fish species and populations, related to tectonic uplift and changes in the configuration of lakes and drainage networks. Fourth, the present conservation status of native fish in the region is described, highlighting the number of endangered species and the main factors associated with the decline of fish diversity and numbers. Finally, management and conservation initiatives are discussed, outlining future prospects for conservation, population recovery and basic biology of native fish in the region.

Keywords Native fish · Schizothoracine fishes · Diversity · Biology · Evolution · Phylogeography · Conservation

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11.1 Introduction

As elsewhere on the Qinghai–Tibet Plateau, the aquatic ecosystems of the Upper Yellow River support distinctive fish communities that have adapted and evolved over millions of years to the high altitudes, harsh climate and relative isolation of this region. Habitats shaped by factors such as the flow and sediment regime of rivers, vegetation associations, water quality and aquatic biogeochemistry have evolved over time in response to tectonic uplift, as headward migration of knickpoints and channel incision brought about the integration of the drainage network to its present configuration (Brierley et al. 2016b, Chap. 3). Over the course of time, mutual interactions among abiotic and biotic processes have fashioned particular patterns of habitat availability and viability occupied by native fish species, many of which are not found elsewhere.

This chapter presents an overview of fish diversity and its origins in the Yellow River Source Zone, together with an account of contemporary pressures on native fish populations and initiatives for their conservation. The chapter is structured as follows. First, a summary of fish diversity and distribution patterns is provided (Sect. 11.2). This is followed by an account of fish biology in the region, including growth and body weight, reproduction and morphological adaptations related to feeding habits (Sect. 11.3). In Sect. 11.4, the evolution history of various fish species and populations is related to the history of tectonic uplift and changes in the configuration of lakes and drainage networks. Section 11.5 describes the present conservation status of native fish in the Upper Yellow River, highlighting cultural associations to fish, concerns for endangered species and threats to fish diversity and numbers. Finally, management and conservation initiatives are discussed in Sect. 11.6, which concludes with a consideration of future prospects.

11.2 Fishes Endemic to the Upper Yellow River

The native fish species of the Upper Yellow River are dominated by schizothoracine fishes of the Cyprinidae (carp family) and nemacheiline fishes of the Cobitidae (loach family). To date, 23 species have been described (Wu and Wu 1992; Chen and Cao 2000; Tang et al. 2005; Fig. 11.1):

- Cyprinidae (carp family)
  - 6 species from the subfamily Schizothoracinae: *Gymnodiptychus pachycheilus*, *Gymnocypris eckloni*, *Gymnocypris scolistomus*, *Schizopygopsis pylzovi*, *Chuanchia labiosa* and *Platypharodon extremus*
  - 2 species from the subfamily Gobioninae: *Acanthogobio guentheri* and *Gobio huanghensis*
  - 1 species from the subfamily Leuciscinae: *Leuciscus chuanchicus*

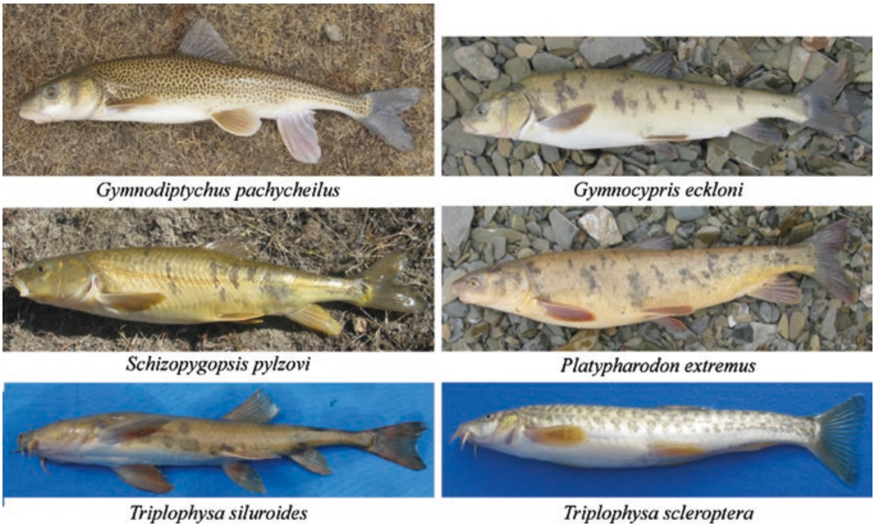

Fig. 11.1 Examples of endemic fish species from the Upper Yellow River

- Cobitidae (loach family)
  - 12 species from the subfamily Nemacheilinae: *Triplophysa longianguis, Triplophysa pseudoscleroptera, Triplophysa scleroptera, Triplophysa stoliczkae, Triplophysa pappenheimi, Triplophysa siluroides, Triplophysa robusta, Triplophysa leptosoma, Triplophysa orientalis, Triplophysa microps, Triplophysa alticeps and Triplophysa obtusirostra*
  - 1 species from the subfamily Cobitinae: *Cobitis granoei*
- Siluridae (catfish family)
  - 1 species from the Siluridae family: *Silurus lanzhouensis*

11.3 Biological Features and Adaptations of Fishes from the Upper Yellow River

Native fishes from the Yellow River Source Zone have evolved a range of morphological and physiological adaptations to their cold and hypoxic environment, including slow growth, reproductive strategies and feeding mechanisms suited to their food sources.

11.3.1 Growth and Body Weight

The high altitude and cold weather of the Upper Yellow River appear to slow down the growth rates of native fishes. Reported assessments of the time taken to attain a body weight of 0.5 kg include more than seven years for *Platypharodon extremus*, eight years for *Gymnodiptychus pachycheilus* and nine years for *Gymnocypris eckloni* (Tsao and Wu 1962; Chen et al. 2002). The slow growth of these fishes makes them especially vulnerable to local extinctions following population crashes, since it can take considerable time to restore populations to their original sizes (Wu and Wu 1992; Qi et al. 2006a, 2012).

11.3.2 Reproduction

During the spawning period, the native fishes in the Upper Yellow River show obvious differences between male and female. For the schizothoracine fishes, the last simple ray of the dorsal fin of male fish changes to two strong spiny fins and the “pearl star” on the pelvic fin becomes obvious. For the genus *Triplophysa*, the pectoral fins of male thicken (Wu and Wu 1992).

The spawning period of native fishes generally takes place from April to July, but differs by species and with altitude, typically extending from June to July at elevations above 4000 m, from May to June at elevations between 3000 and 4000 m and from April to May at elevations lower than 3000 m (Wu and Wu 1992).

For the schizothoracine fishes, males become mature after three years, attaining a standard length of 120 mm. Females become mature after four years and have a standard length of 150 mm. Egg size does not significantly change with standard length, but it increases with the age of fishes. The individual absolute fecundity varies from 2282 to 65,340 eggs for *Gymnocypris eckloni*, from 4347 to 35,162 eggs for *Platypharodon extremus* and from 6490 to 12,882 eggs for *Schizopygopsis pylzovi*. For the genus *Triplophysa*, the individual absolute fecundity varies from 1500 to 2000 eggs (Wu and Wu 1992).

11.3.3 Feeding Habits and Adaptations

Food resources for the native fishes of the Upper Yellow River include zooplankton, plankton, zoobenthos, periphytic algae and aquatic plants. Functional groups of fish can be identified according to their food preferences and the adaptations they have evolved for gathering a particular type of food (Wu and Wu 1992; Qi et al. 2012):

1. *Scrapers*, such as *Schizopygopsis pylzovi*, *Platypharodon extremus*, *Triplophysa stoliczkae*, *Triplophysa pseudoscleroptera,* have a sharp outer horny sheath on the lower jaw, with an inferior or subinferior mouth, spoon-shaped teeth and intermediate pharyngeal bones. They live in fast flowing currents and feed primarily by scraping food from solid substrates such as periphytic algae and diatoms growing on stones, as well as on a small quantity of benthic invertebrates and organic debris.

2. *Filter feeders*, such as *Gymnocypris eckloni* and *Gymnocypris scolistomus,* have a terminal mouth and well-developed filtering apparatus consisting of gill rakers, gill arches and the palatal organ. However, they lack the horny sheath on the lower jaw of scrapers. These fishes mainly live on plankton and benthic aquatic insects, including some aquatic plants and algae.
3. *Benthic invertebrate feeders* such as *Chuanchia labiosa*, *Triplophysa microps* and *Triplophysa longianguis* have a blunt outer horny sheath on the lower jaw and a terminal mouth which allows them to crush and scrape invertebrates and algae found on the river bed.
4. *Carnivorous feeders*, such as *Silurus lanzhouensis* and *Triplophysa siluroides,* have terminal mouths with undershot jaws and fine teeth that allow them to feed on juvenile freshwater fishes and some benthic aquatic insects.

11.4 Phylogenetics and Biogeography

11.4.1 Ecological Adaptation and Speciation

The discovery of the ecological and evolutionary forces responsible for population divergence and adaptation has long been a major objective of evolutionary biology. Local adaptation driven by differing ecological conditions often results in the adaptive phenotypic and genetic divergence of geographically isolated populations and may drive the formation of new taxa (Collin and Fumagalli 2011; Kawecki and Ebert 2004; Kirkpatrick and Barto 2006; Rice 1987; Rowe et al. 2011).

As noted above, various feeding mechanisms have evolved in fish of the Upper Yellow River to adapt to different food sources. Similar local adaptations in response to changing ecological conditions often result in genetic differentiation and adaptive phenotypic divergence. For example, the number of gill rakers is associated with the manner of food acquisition, and it has been suggested that variations in gill raker number may be at least partially influenced by natural selection. Zhang et al. (2013) studied a *Gymnocypris* species complex consisting of three morphs distributed across four bodies of water (the Yellow River, Lake Qinghai, the Ganzi River and Lake Keluke) in the north-east of the Qinghai–Tibet Plateau. The complex includes three members: *Gymnocypris eckloni eckloni*, distributed in the upper reaches of the Yellow River, *Gymnocypris przewalskii przewalskii* from Lake Qinghai and *Gymnocypris przewalskii ganzihonensis* in the Ganzi River. The results suggest that disruptive natural selection due to divergent habitats and dietary preferences is likely the driving force behind the formation of new morphs, and that similarities between phenotypes may be attributable to the similarities between forms of niche tracking associated with food acquisition.

The main cause of divergence in sympatric populations is natural selection through ecological specialization in local environments (Barluenga and Meyer 2004; Barluenga et al. 2006; Gavrilets et al. 2007; Schliewen et al. 2001). The morphological characteristics of two sympatric fish species, such as the shape of the mouth and lower jaw, are usually related to the types of food consumed by the different taxa (Cao et al. 1981; Tsao and Wu 1962). Zhao et al. (2009) investigated two subspecies (*Gymnocypris e. eckloni* and *G. e. scoliostomus*) of the schizothoracine *Gymnocypris* fish species complex from a small glacier lake (Sunmucuo Lake) in the upper reaches of the Yellow River. They suggested that ecological disruptive selection based on morphological traits (i.e. mouth cleft characters) and food utilization may be a mechanism for the incipient speciation of two sympatric populations within the lake. Their study provides the first genetic evidence for sympatric speciation in the schizothoracine fish from the Upper Yellow River.

At larger spatial and temporal scales, relationships between the contemporary distribution of fish populations, fish speciation events and geological history help to explain the co-evolution of landscapes and the biota they support.

11.4.2 Relationships Between Fish Speciation and the Geological Evolution of the Upper Yellow River

Since the early 1980s, the biogeography of fishes endemic to the Qinghai–Tibet Plateau has been studied by relating the geographical distributions of each species to morphological and anatomical differences between the species. Cao et al. (1981) first suggested that the subfamily Schizothoracinae could be divided into three groups that correspond to three phases of uplift of the plateau, based on an evolutionary sequence of the degeneration of body scales and reduction in numbers of both pharyngeal teeth and barbells. Each group is hypothesized to have evolved in different phases of uplift of the plateau, with step-by-step adaptations to the new, higher altitude resulting from each uplift phase. The three groups are given below:

- *Primitive*, consisting of the genera *Racoma*, *Schizothorax* and *Aspiorhynchus*
- *Specialized,* including *Ptychobarbus*, *Gymnodiptychus* and *Diptychus*
- *Highly specialized,* including the remaining five genera (*Gymncypris*, *Oxygymncypris*, *Schizophygopsis*, *Chuanchia* and *Platypharodon*).

The primitive schizothoracine fishes are not found in the Upper Yellow River, but are present in all the other main rivers of the plateau (Fig. 11.2). All six schizothoracine genera found in the Upper Yellow River fall into the specialized and highly specialized groups, suggesting that the origins of the Schizothoracinae fishes of the Upper Yellow are relatively recent. This suggestion was later confirmed by a cladistic analyses based on morphological comparison with putative ancestors (Wu 1984; Wu and Wu 1992).

In recent years, investigations using molecular techniques have provided further evidence that the evolution timeline of native fishes in the Upper Yellow River is strongly related to the geological evolution of the region. This reflects uplift and

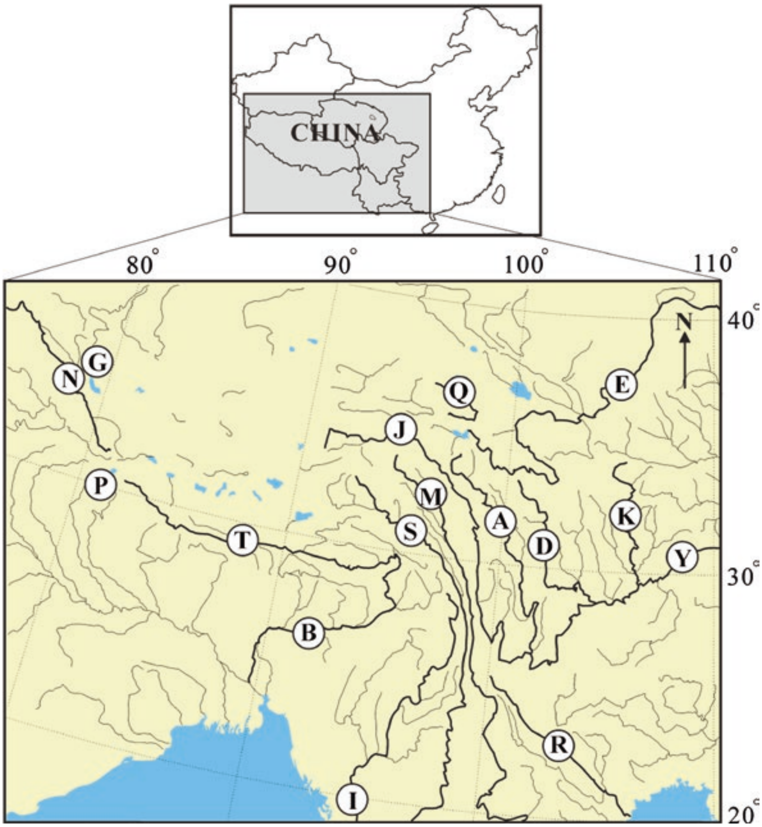

Fig. 11.2 Rivers of the Qinghai–Tibet Plateau have distinct fish communities. In contrast to the other primary rivers in the region, the Upper Yellow River does not have the primitive schizothoracine fishes that are found in the Yangtze, Mekong, Salween, Irrawaddy, Tsangpo and Indus rivers. The letters in circles refer to the following: *A* Yalung River; *B* Brahmaputra River; *D* Dadu River; *E* Yellow River; *G* Bangongco Lake; *I* Indus River; *J* Jinsha River; *K* Kialing River; *M* Mekong River; *P* Mapangyongco Lake; *Q* Qiadam Basin; *R* Red River; *S* Salween River; *T* Tsangpo River; *Y* Yangtze River

integration of the drainage network and associated separation from adjacent areas such as inflowing drainage systems in the Qaidam Basin, the outflowing drainage system of the Yangtze River and isolated lakes such as Qinghai Lake and Tuosuo Lake (Fig. 11.3; Duan et al. 2009; He et al. 2004; He and Chen 2007; Qi et al. 2006a, b, 2007a, b, 2012, 2013; Zhao et al. 2005, 2009). Furthermore, phylogenetic techniques enable the divergence of different evolutionary lines to be dated, suggesting timelines for geological events that can potentially be corroborated by geological evidence.

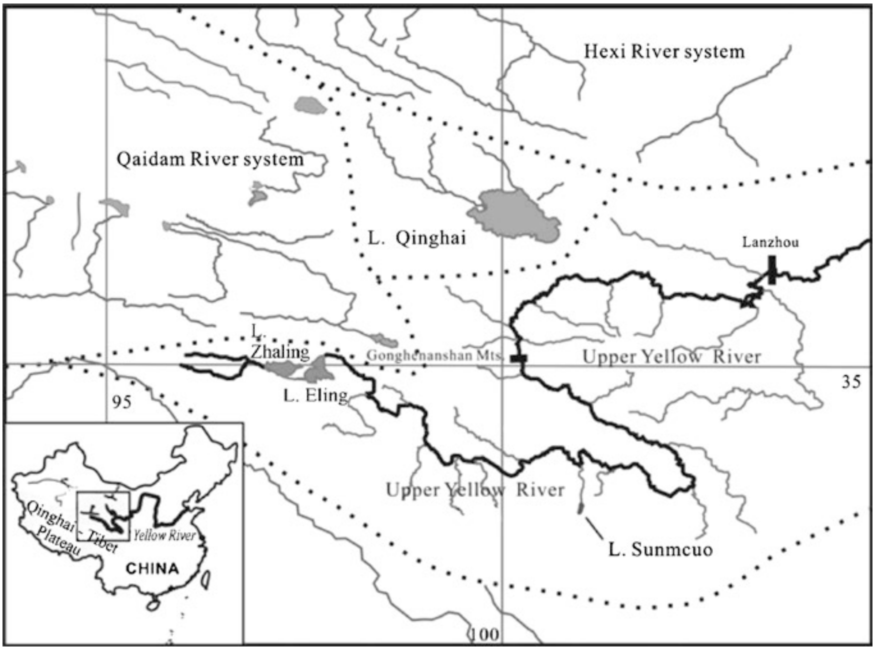

Fig. 11.3 River and lake networks along the Upper Yellow River for which distinctive fish populations have emerged over time (adapted from Zhao et al. 2009). As the river adopted its present course, incising back into the plateau and associated basin fills, it is separated from adjacent systems, isolating fish populations that has previously been connected and able to interbreed (see also Fig. 11.4)

Several hypotheses linking phylogenetic traits and biogeography are outlined below.

(i). **The recent evolution of native fish in the Upper Yellow River is relatively late, consistent with the recent evolution and formation of the Upper Yellow River relative to other river and lake systems in the region** (Figs. 11.2 and 11.3). As the Yellow River adopted its present course, it incised back into the plateau and associated basin fills and became separated from adjacent systems that contained populations of primitive schizothoracine.

The contemporary development of the Upper Yellow River began some 1.6 million years ago, when the Yellow River adopted its present course in response to a series of tectonic events and river captures (Li et al. 1996; Brierley et al. 2016a, Chap. 1). Based on the phylogenetics and biogeography of schizothoracine fishes and tectonic data, He and Chen (2007) suggested that the ancestral headwaters of the Yellow River flowed along the present Zoigê Basin and out into a tributary of the Yangtze River in the Sichuan Basin, while the headwaters of the Yellow River were captured by the inland rivers of the Qaidam Basin. These relationships are shown in Fig. 11.4.

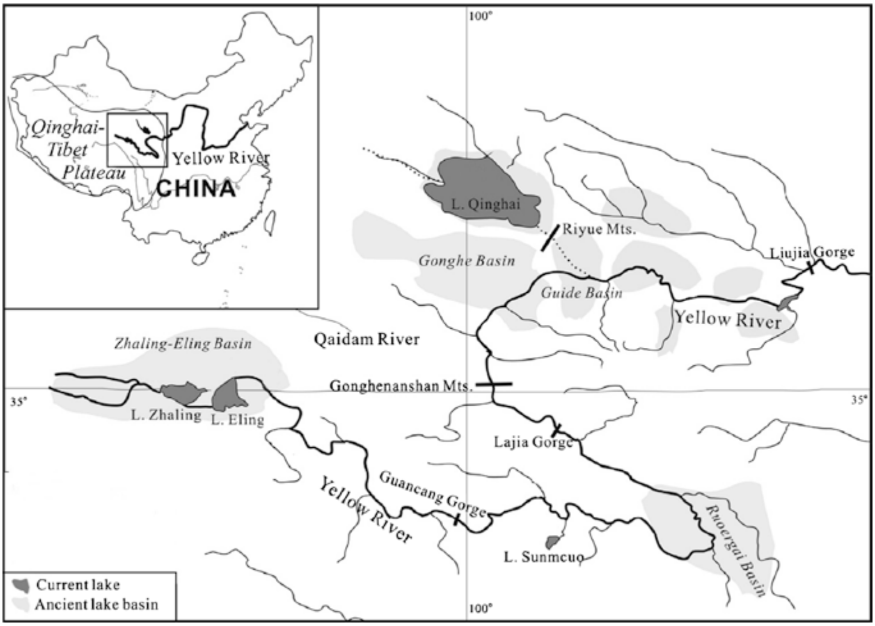

Fig. 11.4 Former inland draining basins of the Upper Yellow River that became integrated as the river incised and cut back into the plateau associated with uplift events, thereby creating the present integrated drainage network (adapted from Duan et al. 2009)

(ii). **The presence of both specialized and highly specialized schizothoracine fishes in both the Yellow and Yangtze Rivers suggests past connections between these basins**. Molecular estimates of divergence times reveal that the major cladogenetic events of the specialized and highly specialized schizothoracine fishes occurred largely during the Late Pliocene and Pleistocene (about 3.6 million years ago). This timing is consistent with geological evidence for rapid uplift phases of the Qinghai–Tibet Plateau at this time (He et al. 2004; He and Chen 2007). The planation surface formed in the Middle–Late Pliocene disintegrated and the major drainage basins in the plateau formed in succession, including the western drainages (Salween–Mekong River), the central drainages (inland lakes in northern Tibet, the Tsangpo Salween and southern Tibet) and the drainages of the eastern Tibetan Plateau (Hexi Corridor, Qaidam Basin, the Upper Yellow River and Yangtze River) (Fig. 11.4).

However, temporary river connections during Pleistocene glacial–interglacial cycles and complications associated with headward erosion by rivers may have allowed exchange between the specialized and highly specialized schizothoracine fishes in different drainages on the eastern plateau until around 1.1–0.7 million years ago. Indeed, tectonic studies have demonstrated connections between various basins in the eastern plateau at this time, including connections between the Upper Yangtze, Yellow and inland rivers in the Qaidam Basin.

(iii). **Temporary connections between the Qaidam Basin and the Yellow River have been inferred from investigations of population evolution and dispersal of *Schizopygopsis pylzovi***. The nested clade phylogeographical analysis of *Schizopygopsis pylzovi* based on mtDNA data suggests that historical tectonic events associated with phases of uplift of the Qinghai–Tibet Plateau influenced the contemporary geographical and population structuring of *Schizopygopsis pylzovi* (Qi et al. 2007a). The geographical connections of the haplotypes of *Schizopygopsis pylzovi* distributed in the Qaidam Basin (i.e. Germu River and Tuosuo Lake), the Zhaling Lake and the Yellow River suggest there were temporary connections among these rivers and lakes in the past. In fact, the tectonic events that occurred during the Kunlun–Huanghe Movement (Middle Pleistocene) resulted in a large eastward outflow drainage system in the Qaidam Basin, which connected the Germu River and Tuosuo Lake in the Qaidam Basin with Tuosuo Lake, Zhaling Lake and Yellow River (Li and Ying 1998; Li et al. 2000a).

(iv). **The evolutionary pattern for *Gymnocypris przewalskii* and *Gymnocypris eckloni* supports recent separation of Qinghai Lake from the Upper Yellow River**. *Gymnocypris eckloni* is distributed in the Upper Yellow River, while *Gymnocypris przewalskii* inhabits Qinghai Lake. Previous morphological studies indicated a very close relationship between *Gymnocypris przewalskii* and *Gymnocypris eckloni*. This supports the hypothesis that Qinghai Lake was once connected to the Upper Yellow River (Zhu and Wu 1975). Using mtDNA data, Zhao et al. (2005) conducted a molecular phylogenetic analysis for *Gymnocypris* in Qinghai Lake and adjacent drainages including the Upper Yellow River. The results showed that *Gymnocypris eckloni* from the Upper Yellow River might have two different origins, of which one shows very close relationship with *Gymnocypris przewalskii* from Qinghai Lake, supporting the hypothesis that relatively recent tectonics separated Qinghai Lake from the Upper Yellow River.

(v). **A series of large, ancient lake basins might have acted as fish evolutionary reservoirs prior to their capture by the Yellow River some 0.03 million years ago** (see Fig. 11.4). Stratigraphic evidence shows that around 1.2 million years ago the ancient Yellow River originated at the north-eastern edge of the Tibetan Plateau (Li et al. 2001). Originally, two ancient lake basins, Lake Qinghai Basin and Guide Basin, were linked to each other (Li et al. 2001), and Lake Qinghai may have been the headwater of the ancient Yellow River (Chen 1988). The "Gonghe Movement" event of the Tibetan Plateau in the Late Pleistocene (about 0.15 million years ago) led to the Yellow River capturing the Gonghe Basin and the uplift of the Riyue Mountains, which separated Lake Qinghai from the Upper Yellow River (Zhang et al. 2003). About 0.03 million years ago, the Yellow River started cutting through the South Gonghe Mountains and more recently captured the Ruoergai Basin and Zhaling–Eling Basin, reaching upwards to the present headwaters (Zhang et al. 2003).

Duan et al. (2009) conducted a study on the comparative phylogeography of the Yellow River schizothoracine fishes (including all of the six species that inhabit the Upper Yellow River) based on the sequences of mitochondrial cytochrome *b* gene (Cyt *b*) and a control region. They calibrated a divergence time of the mtDNA lineages within the *Gymnocypri* species complex around 0.23 million years ago. This suggests that the genetic differentiation within the Yellow River *Gymnocypris eckloni* could have existed far before the time when Lake Qinghai was separated from the Yellow River (about 0.15 million years ago). On the other hand, all *Gymnocypris coliostomus* individuals endemic to Lake Sunmucuo only occur in one lineage of the *Gymnocypris* complex, and the estimated divergence times within this complex (0.23 and 0.30 million years ago) are also long before the capture event of the Yellow River (about 0.03 million years ago) (see, Figs. 11.3 and 11.4). They therefore suggest that these large, ancient lake basins might have acted as fish evolutionary reservoirs, serving as barriers to gene flow for the Yellow River schizothoracine fishes, followed by a later coalescence as the Yellow River captured these ancient basins.

(vi). **The low genetic diversity of native fish resource in the Upper Yellow River suggests evolutionary bottlenecks associated with tectonic movements and paleoenvironmental fluctuations**. In general, high levels of genetic variability in a given population are achieved from large populations that are stable for long periods of time. When a population goes through a severe bottleneck, random genetic drift is likely to induce a massive loss of genetic variability. Most of the native fishes in the Upper Yellow River exhibit a relatively low level of haplotype and nucleotide diversity compared with other cyprinid fishes, suggesting the existence of historical genetic bottlenecks (Zhao et al. 2005; Qi et al. 2007a; Qi 2009). Based on Cyt *b* sequences, Zhao et al. (2005) investigated the genetic diversity of the *Gymncypris eckloni* population. The result showed that the haplotype diversity (h) and nucleotide diversity (π) were 0.87 and 0.0048, respectively. A similar result was obtained by Qi (2009) ($h = 0.75$–0.89 l; $\pi = 0.0026$–0.0048). Other studies with different species also showed relatively low genetic diversity: *Schizopygopsis pylzovi* ($h = 0.83$–0.98, $\pi = 0.0013$–0.0032) (Qi et al. 2007a), *Platypharodon extremus* (Chao and Yang 2008), *Triplophysa siluroides* ($h = 0.50$, $\pi = 0.0008$) (Chao et al. 2011) and *Gymnodiptychus pachycheilus* ($h = 0.84$, $\pi = 0.0054$) (Sun et al. 2012). However, Sun et al. (2012) showed that *Platypharodon extremus* exhibited relatively high haplotype diversity (0.99–1.00) and nucleotide diversity (0.0107–0.0158) compared with other native fishes in the Upper Yellow River. Thus, further studies are needed to investigate the genetic diversity of *Platypharodon extremus* and to explain this apparent anomaly.

(vii). **Genetic similarities and differences between populations of the same species can be related to the reconfiguration of the Upper Yellow River during the Pleistocene**. Zhao et al. (2005) investigated the genetic structure of populations of *Gymncypris eckloni* from the Upper Yellow River based on

Cyt b sequences. Their findings suggested three population groups related to separate reaches between Guancang and Lajia gorges. However, only slight genetic differentiation with no significant geographical structure was observed in *Schizopygopsis pylzovi* from this area (Qi et al. 2007a; Duan et al. 2009). It has been suggested that the weaker subdivision in *S. pylzovi* may be associated with its superior dispersal ability compared to *G. eckloni* (Duan et al. 2009), since species with high dispersal potential generally lack sharp geographical differentiation (Roman and Palumbi 2004; Ritz et al. 2008). *S. pylzovi* has the widest distribution of all endemic fishes in the Upper Yellow River (Tsao and Wu 1962), dominating the headwaters of all tributaries, including many torrential mountain streams, and also occurring in large rivers and lakes (Wu and Wu 1992). In contrast, *G. eckloni* is mainly confined to wide valleys and deep lakes, suggesting a relatively sedentary habit (Tsao and Wu 1962).

Headwater taxa are potentially those most vulnerable to genetic divergence following river capture (Koblmüller et al. 2008), so distinct populations of *S. pylzovi* might be expected. One explanation for this seeming anomaly is that population isolations may have occurred too recently for divergent populations of *S. pylzovi* to establish. Duan et al. (2009) offered an alternative explanation, inferring that although ancient lake basin boundaries might have generated distinct populations of *S. pylzovi*, their high dispersal ability may have facilitated substantial later intermixing. A third hypothesis is offered by Qi et al. (2007a), who showed that *S. pylzovi* underwent a sudden population expansion around 0.11 million years ago, after the large tectonic event of the Gonghe Movement (about 0.15 million years ago). This movement transformed river configurations in the north-west plateau (Li and Ying 1998; Zhu et al. 2003), maybe facilitating contiguous range expansion of *S. pylzovi* populations beyond their previously established habitats.

The lack of geographical structure within *Platypharodon extremus* and *Gymnodiptychus pachycheilus* populations in the Upper Yellow River can also be related to the capture of the ancient lakes by the incising Upper Yellow River. The *Platypharodon* is a monotypic genus endemic to the Yellow River, most abundant in Zhaling and Eling lakes. Population numbers decrease from the upper towards the middle reaches (Duan et al. 2009), and it is seemingly absent from the lower reaches and downstream from Lake Sunmucuo (Wu and Wu 1992). This is consistent with a stepping-stone colonization, which suggests a recent dispersal from the upper reaches to the middle reaches.

There is evidence that Zhaling and Eling lakes once comprised a single water body, the "Zhaling-Eling Basin" (Fig. 11.4), separating into two lakes at the time of the Yellow River capture during the Late Pleistocene, around 0.03 million years ago (Zhang et al. 2003). The population expansion of *P. extremus*is estimated to have occurred around 0.086 million years ago, before the separation of the lakes. Duan et al. (2009) therefore suggest that speciation and a rapid radiation event of *P. extremus* occurred before the capture event of the Yellow River and was maintained in the new configuration of the uppermost reaches of the Yellow River.

(viii). **The genetic structure of native fish populations suggests Pleistocene glacial refugia in the ancient lakes of the Upper Yellow River**. It appears that the Yellow River schizothoracine fishes have passed through recent demographic expansions at several locations after the genetic bottleneck associated with the separation of the lakes in the Late Pleistocene (Duan et al. 2009). Analyses of Fu's Fs and unimodal mismatch distributions of the frequencies of pairwise differences based on cytochrome *b* haplotypes of schizothoracine fishes coupled with the star-like phylogenies indicated that further population expansions of the schizothoracine fishes in the Upper Yellow River occurred at about 0.132–0.062 million years ago (Duan et al. 2009). This timing is likely related to climatic shifts of the Late Pleistocene, which are likely related to the large uplift events of the Qinghai–Tibet Plateau. The largest phase of glacial expansion atop the plateau occurred during the Middle Pleistocene (0.5 million years ago), while glacial retreat has occurred since 0.17 million years ago (Shi 2002; Zheng et al. 2002). The recent rapid population increases of the Yellow River schizothoracine fishes occurred in the period following the maximum glacial extent. Thus, Duan et al. (2009) suggested that the ancient lake basins (e.g. Zhaling–Eling Basin) in the Upper Yellow River acted as a Pleistocene glacial refugia for the schizothoracine fishes.

11.5 Threats to Native Fish in the Upper Yellow River

Populations of native fish in the Upper Yellow River have declined dramatically in recent decades (Qi et al. 2006b, 2007a; Yue and Chen 1998). This decline has been attributed to a number of factors, including overfishing, environmental changes, habitat destruction and alteration, changes in reproductive habitat and introduction of exotic competitors and diseases (Wu and Wu 1992; Qi et al. 2007a). Native fish of this region are particularly vulnerable to local extinctions, as their low reproductive rate and the long time it takes them to reach maturity mean that declining populations take a long time to recover (Wu and Wu 1992; Qi et al. 2006a, 2012).

11.5.1 The Conservation Status of Native Fish in the Upper Yellow River

Before the 1960s, fish in this area were preserved due to religious sentiments. Eating fish is abhorrent to most Tibetans, since according to Tibetan Buddhism fish embody the dragon god. Furthermore, Tibetans are reluctant to fish or otherwise disturb lakes reflecting their belief that water is sacred and that fish protect the water. Other reasons why Tibetans do not eat fish include: (1) they wish to take as few lives as possible and thus prefer to eat yak, as one individual can feed many mouths; (2) "water burial", in which corpses are disposed of in rivers, is common and certain fish feed on the dead bodies; (3) they have a fear of getting fish bones stuck in their throats; and (4) they believe that fish do not have tongues and therefore cannot gossip (Tibetans detest gossip and reward fish by not eating them) (Jacobsen et al. 2013).

However, in recent years, emigration from inland areas and lifestyle changes has resulted in the growth of fishing, particularly targeting the schizothoracine fishes endemic to the Upper Yellow River.

Over the last 50 years, the population of native fish in the Upper Yellow River has declined dramatically and their distribution has been drastically reduced in area (Yue and Chen 1998; Qi et al. 2006b, 2007a). Three species (*Chuanchia labiosa*, *Platypharodon extremus* and *Triplophysa siuroides*) were listed as endangered in 1998 by the National Environmental Protection Agency and Endangered Species Scientific Commission (Yue and Chen 1998). In 2004, two endangered and seven vulnerable species in the Upper Yellow River were listed in the "China Species Red List" (Wang and Xie 2004). The endangered species are: *Gymnodiptychus pachycheilus* and *Silurus lanzhouensis,* while *Leuciscus chuanchicus*, *Acanthogobio guentheri, Gobio huanghensis*, *Gymnocypris scolistomus*, *Chuanchia labiosa*, *Platypharodon extremus and Triplophysa siuroides* are all listed as vulnerable. Various factors associated with this decline are discussed below.

11.5.2 Commercial Fishing

Overfishing is one of the major factors responsible for the decline in native fish stocks. Since the late 1950s, schizothoracine fishes have been exploited for food. By 1960, over 26,000 tonnes of fish were caught in Qinghai Province. Between 1960 and 1962, in Zhaling River, the catch for *Gymnocypris eckloni* alone reached 1.115 million kg. After 1962, fishing activities were stopped for about fifteen years, but they started again in 1976, with much declined catches. From 1978 to 1987, over 15,000 tonnes of schizothoracine fish were taken from Zhaling Lake and Eling Lake (Wu and Wu 1992). Despite government regulations and the current severe limitations on commercial fishing, past fishing and continuing illegal fishing have undoubtedly contributed to the declining stocks of *Gymnocypris eckloni*, *Chuanchia labiosa*, *Platypharodon extremus* and *Triplophysa siluroides* (Tang et al. 2006).

11.5.3 Environmental Changes

With global warming and consequent reduced snow cover in the Bayan Har and Buqing mountains, run-off contributions to the Duoqu, Maqu and Shunaqu rivers have decreased. Indeed, these three tributaries of the Yellow River have dried up in recent years, causing a fall in the water level of Zhaling and Eling lakes. Furthermore, the flow between Zhaling and Eling lakes has also dried up on occasion, with significant impacts on native fish populations.

11.5.4 Habitat Destruction and Change

Fish habitat includes both physical factors (e.g. temperature, water depth, velocity, bed types, vegetation cover) and chemical factors (e.g. pH, dissolved levels of oxygen, mineral content, and other substances) that fish need to thrive. Fish often require several habitat types at different life stages (e.g. spawning, juvenile development). Loss or change to any of these habitats induces population decline or even the local extinction of native fish species. At the same time, other species that are more tolerant of habitat changes may replace the native fishes.

Threats to native fish habitat include the construction of dams and hydroelectric power stations, environmental pollution, environmental degradation and land degradation (Tang et al. 2006; Shen et al. 2014).

The construction of a dam or hydroelectric power station on a river can block fish passage, affecting foraging migration, overwintering and spawning of native fishes, and thus contribute to the decline of a species. The government has authorized the construction of 28 hydroelectric power stations in the mainstream of the Upper Yellow River over the last 40 years, and most of them have been completed (Tang et al. 2006). In the main tributaries of the Upper Yellow River (e.g. Datong River, Qushian River, Gequ River, Yao River), more than 20 hydroelectric power stations have been authorized and many of them have already been designed and constructed.

Overgrazing in catchments of the Upper Yellow River has accelerated soil erosion, resulting in increased run-off of sediment and silt into water bodies (see Hu et al. 2016, Chap. 5; Li et al. 2016, Chap. 7; Tane et al. 2016, Chap. 13). Soil erosion has also led to changes in stream bank structure, affecting stream flows and increasing stream temperatures (Li et al. 2000b; Ren 2002). All these factors change fish habitat, with significant negative effects upon fish life cycles and population numbers (Tang et al. 2006).

11.5.5 Exotic Competitors and Diseases

The introduction of exotic fish has taken place for many reasons, including aquaculture, past releases to boost commercial fishing stocks and by accident. Some species have been released by local people for religious reasons. These introductions have resulted in significant changes to the native fish communities of the Upper Yellow River.

Table 11.1 Non-native fish species in the Upper Yellow River

Species	Family	Date of introduction	Purpose of introduction
Oncorhynchus mykiss	Salmonidae	1990s	Aquaculture (farm escape)
Coregonus peled	Salmonidae	2010s	Aquaculture (farm escape)
Coregonus muksum	Salmonidae	2010s	
Hypomesus olidus	Osmeridae	1990s	Aquaculture (farm escape)
Protosalanx hyalocranius	Salangidae	1990s	Aquaculture (farm escape)
Ctenopharyngodon idellus	Cyprinidae	1960s	Aquaculture (farm escape)
Hypophthalmichthys molitrix	Cyprinidae	1960s	Aquaculture (farm escape)
Rhodeus sinensis	Cyprinidae	2010s	Aquaculture (farm escape)
Pseudorasbora parva	Cyprinidae	1960s	Accidental
Cyprinus carpio	Cyprinidae	1960s	Aquaculture (farm escape)
Carassius auratus	Cyprinidae	1960s	Aquaculture (farm escape) and release
Misgurnus anguillicaudatus	Cobitidae	1960s	Accidental

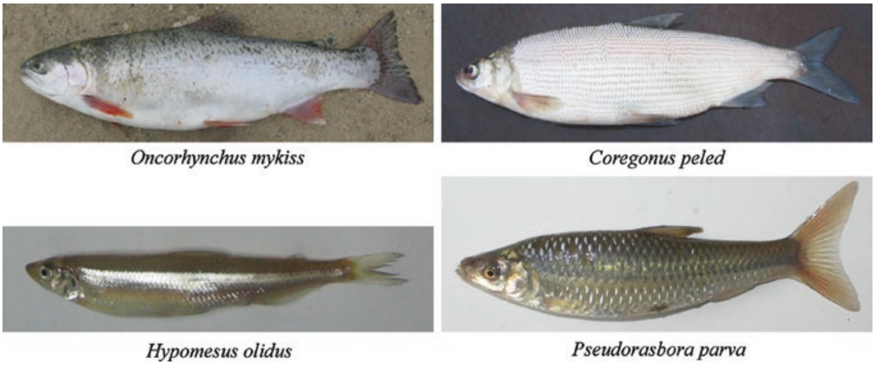

Fig. 11.5 Some non-native fishes found in the Upper Yellow River

Introduced exotic fish negatively impact upon the survival and genetic integrity of native fishes through competition, predation, the introduction of disease parasites and habitat alteration. So far, 12 non-native fish species have been identified in the Upper Yellow River and the Huangshui River (a tributary of the Yellow River near Xining; Table 11.1 and Fig. 11.5). Some of these species are known to prey on eggs and larvae of native fishes (e.g. rainbow trout) while others potentially compete with native fish for food. Competition between native and exotic fishes is certain to occur to some degree, but there is little quantitative information as yet. Furthermore, it is highly likely that exotic species are more tolerant to environmental changes than are the native fish of the region.

11.6 Management and Conservation of Native Fishes

In view of the ecological importance and the threatened status of many native fishes in the Upper Yellow River, several restoration initiatives have been established by the government in Qinghai Province. The first is to establish national conservation zones for native fishes. The first National Endemic Fish Conservation Zone for the Upper Yellow River was established in 2007 (Shen et al. 2014). The National Aquatic Germplasm Resources Conservation Zone for Zhaling–Eling Lake and the National Endemic Fish Conservation Zone for Gequ River were subsequently established in 2008 and 2011, respectively. To date, six national conservation zones related to native fishes in the Upper Yellow River have been established, aiming to promote the recovery of native fish populations (Shen et al. 2014).

The second initiative is the establishment of a research programme on the artificial breeding, release and proliferation of native fishes. This research, jointly sponsored by the national Ministry of Agriculture and by local government, has made great strides in artificially hatching, rearing and releasing native fishes in the Upper Yellow River, including *Gymnocypris eckloni*, *Schizopygopsis pylzovi* and *Platypharodon extremus*. Two stations for native fish proliferation and release have been constructed in the Upper Yellow River, at Jishixia and Suzhi.

By the end of 2014, more than 5.5 million artificially cultured fries had been released into the Upper Yellow River (Shen et al. 2014). Although this has a positive role in resource recovery of native fishes, it is difficult to quantitatively evaluate the effect of these releases on native populations (e.g. Su et al. 2015). Further studies are required to assess outcomes, including the adaptation and survival rates of artificially cultured fries, the effects of artificially cultured fries on wild population and the extent of population recovery.

The third major conservation initiative is the monitoring of the freshwater environment of the Upper Yellow River and environmental assessment for large-scale dams and hydroelectric projects. The local government has been monitoring the freshwater environment of the Upper Yellow River since 2004, establishing 44 monitoring sites, covering almost all the catchments of the Upper Yellow River (Shen et al. 2014). The monitoring data help the fishery administrators and local government officials to understand the present status of the eco-environment and aquatic organisms of the Upper Yellow River, supporting the development and implementation of effective measures to protect native fish resources, such as the establishment of rearing and release stations.

Further research is required on the conservation, population recovery and basic biology of native fish in the source zone of the Yellow River, including local surveys of their migration, feeding, breeding behaviour and spawning grounds and investigations into their adaptations to the cold and hypoxic environment of the plateau. In addition, further research is needed to improve captive breeding and broodstock maintenance techniques for endangered native fish species, together with critical evaluation of the effects of artificially released cultured fries on the population recovery of native fishes (e.g. Su et al. 2015). The research findings can then be integrated into practical plans for conservation and population recovery that can be implemented by the fishery administrators and the local government departments.

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References

Barluenga, M., & Meyer, A. (2004). The Midas cichlid species complex: Incipient sympatric speciation in Nicaraguan cichlid fishes? *Molecular Ecology, 13*, 2061–2076.

Barluenga, M., Stölting, K. N., Salzburger, W., et al. (2006). Sympatric speciation in Nicaraguan crater lake cichlids. *Nature, 439*, 719–723.

Brierley, G. J, Li, X., Cullum, C., et al. (2016a). Introduction: Landscape and ecosystem diversity in the Yellow River Source Zone. In G. J. Brierley., X. Li., C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*, (pp. 1–34). Berlin: Springer.

Brierley, G. J., Yu, G. A., & Li, Z. W. (2016b). Geomorphic diversity of rivers in the Upper Yellow river basin. In In G. J. Brierley., X. Li., C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*, (pp. 59–78). Berlin: Springer.

Cao, W. X., Chen, Y. Y., Wu, Y. F., et al. (1981). Origin and evolution of schizothoracine fishes in relation to the upheaval of the Xizang Plateau. In Tibetan Expedition of the Chinese Academy of Science (Ed) *Studies on the period, amplitude and type of the uplift of the Qinghai–Xizang Plateau* (pp. 118–130). Beijing: Science Press.

Chao, Y., Shen, Z. X., Wang, G. J., et al. (2011). Genetic diversity and divergence of *Triplophysa siluroides* between populations from the Datong River and the Yellow River. *Journal of Anhui Agriculture Science, 39*, 14139–14140.

Chao, Y., & Yang, C. (2008). Sequence characteristics of mitochondrial DNA cytochrome b and genetic diversity of *Platypharodon extremus*. *Journal of Qinghai University (Nature Science), 26*, 62–65.

Chen, Z. M. (1988). A preliminary analysis of paleo-limnology and its environment at the upper reaches of the Huanghe River. In: *Proceedings of the Third Chinese Oceanological and Limnological Science Conference*. Beijing: Science Press.

Chen, Y. F., & Cao, W. X. (2000). Schizothoracinae. In P. Q. Yue (Ed.), *The fauna of animal in China—Teleostei, Cyprinidae* (pp. 273–388). Beijing: Science Press.

Chen, Y. F., He, D. K., Cao, W. X., et al. (2002). Growth of Selincuo schizothoracini (*Gymnocypris selincuoensis*) in Selincuo Lake Tibeten Platean. *Acta Zoologica Sinica, 48*, 667–675.

Collin, H., & Fumagalli, L. (2011). Evidence for morphological and adaptive genetic divergence between lake and stream habitats in European minnows (*Phoxinusphoxinus*, *Cyprinidae*). *Molecular Ecology, 20*, 4490–4502.

Duan, Z. Y., Zhao, K., Peng, Z. G., et al. (2009). Comparative phylogeography of the Yellow River schizothoracine fishes (I): Vicariance, expansion, and recent coalescence in response to the Quaternary environmental upheaval in the Tibetan Plateau. *Molecular Phylogenetics and Evolution, 53*, 1025–1031.

Gavrilets, S., Vose, A., Barluenga, M., et al. (2007). Case studies and mathematical models of ecological speciation. 1. Cichlids in a crater lake. *Molecular Ecology, 16*, 2893–2909.

He, D. K., & Chen, Y. F. (2007). Molecular phylogeny and biogeography of the highly specialized grade schizothoracine fishes (*Teleostei: Cyprinidae*) inferred from cytochrome b sequences. *Chinese Science Bulletin, 52*, 777–788.

He, D., Chen, Y., Chen, Y., et al. (2004). Molecular phylogeny of the specialized schizothoracine fishes (Teleostei: Cyprinidae), with their implications for the uplift of the Qinghai-Tibetan Plateau. *Chinese Science Bulletin, 49*, 39–48.

Hu, X. S., Brierley, G. J., Cullum, C., et al. (2016). Hillslope stability in the Yellow River source region. In G. J. Brierley., X. Li., C. Cullum., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*, (pp. 101–115). Berlin: Springer.

Jacobsen, D., Laursen, S. K., Hamerlik, L., et al. (2013). Sacred fish: On beliefs, fieldwork, and freshwater food webs in Tibet. *Frontiers in Ecology and the Environment, 11*, 50–51.

Kawecki, T. J., & Ebert, D. (2004). Conceptual issues in local adaptation. *Ecological Letters, 7*, 1225–1241.

Kirkpatrick, M., & Barton, N. (2006). Chromosome inversions, local adaptation and speciation. *Genetics, 173*, 419–434.

Koblmüller, S., Schliewen, U. K., Duftner, N., et al. (2008). Age and spread of the haplochromine cichlid fishes in Africa. *Molecular Phylogenetics and Evolution, 49*, 153–169.

Li, C. A., & Ying, H. F. (1998). Tectonic uplift, water system response and environment evolvement in the eastern part of the Kunlun Mountains. *Science—Journal of China University of Geosciences, 23*, 456–459.

Li, C. A., Ying, H. F., & Yu, Q. W. (2000a). Evolution of drainage systems and its developing trend in connection with tectonic uplift of Eastern Kunlun Mt. *Chinese Science Bulletin, 45*, 1904–1908.

Li, J. J., Fang, X. M., Ma, H. Z., et al. (1996). Geomorphological and environment evolution in upper reaches of Yellow River during the late Cenozoic. *Science in China Series D (Earth Sciences), 39*, 380–390.

Li, J. J., Fang, X. M., Pan, B. T., et al. (2001). Late cenozoic intensive uplift of Qinghai-Xizang Plateau and its impacts on environments in surrounding area. *Quaternary Sciences, 21*, 381–391.

Li, L., Zhang, G. S., Wang, Q. C., et al. (2000b). Study on evapotranspiration and its impact factors over Yellow River upper stream area. *Advance in Earth Science, 15*, 256–259.

Li, X. L., Perry, G., & Brierley, G. J. (2016). Grassland ecosystems of the Yellow River Source Zone: Degradation and restoration. In G. J. Brierley., X. Li., C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*, (pp. 137–166). Berlin: Springer.

Qi, D. L. (2009). Genetic variation and diversity of *Gymncypris eckloni* in the Upper Yellow River inferred from mitochondrial cytochrome b gene. *Zoological Research, 30*, 255–261.

Qi, D. L., Chao, Y., Guo, S. C., et al. (2012). Convergent, parallel and correlated evolution of trophic morphologies in the subfamily Schizothoracinae from the Qinghai-Tibetan Plateau. *PLoS ONE, 7*(3), e34070. doi:10.1371/journal.pone.0034070.

Qi, D. L., Chao, Y., Zhao, L. Y., et al. (2013). Complete mitochondrial genomes of two relatively closed species from Gymnocypris (Cypriniformes: Cyprinidae): Genome characterization and phylogenetic considerations. *Mitochondrial DNA, 24*, 260–262.

Qi, D. L., Guo, S. C., Tang, W. J., et al. (2007a). Mitochrondrial DNA phylogeny of two morphologically enigmatic fishes in the subfamily Schizothoracinae (*Teleostei: Cyprinidae*) in the Qinghai-Tibetan Plateau. *J Fish Biol, 70*, 60–74.

Qi, D. L., Guo, S. C., & Zhao, X. Q. (2006a). Molecular systematics of two enigmatic fish in the genus *Schizopygopsis* in the Qinghai-Tibetan Plateau. *Acta Zoologica Sinica, 52*, 1058–1066.

Qi, D. L., Guo, S. C., Zhao, X. Q., et al. (2007b). Genetic diversity and historical population structure of *Schizopygopsispylzovi* (*Teleostei: Cyprinidae*) in the Qinghai-Tibetan Plateau. *Freshwater Biology, 52*, 1090–1104.

Qi, D. L., Li, T. P., Zhao, X. Q., et al. (2006b). Mitochondrial cytochrome b sequence variation and phylogenetics of the highly specialized schizothoracine fishes (*Teleostei: Cyprinidae*) in the Qinghai-Tibetan Plateau. *Biochemical Genetics, 44*, 270–285.

Ren, C. Y. (2002). Origin and control of desertification in Maqu County. *Northwest Water Power, 1*, 10–12.

Rice, W. R. (1987). Speciation via habitat specialization: The evolution of reproductive isolation as a correlated character. *Evolutionary Ecology, 1*, 301–314.

Ritz, M. S., Millar, C., Miller, G. D., et al. (2008). Phylogeography of the southern skua complex-rapid colonization of the southern hemisphere during a glacial period and reticulate evolution. *Molecular Phylogenetics and Evolution, 49*, 292–303.

Roman, J., & Palumbi, S. R. (2004). A global invader at home: population structure of the green crab, Carcinusmaenas, in Europe. *Molecular Ecology, 13*, 2891–2898.

Rowe, K. C., Aplin, K. P., Baverstock, P. R., et al. (2011). Recent and rapid speciation with limited morphological disparity in the genus Rattus. *Systematic Biology, 60*, 188–203.

Schliewen, U., Rassmann, K., Markmann, M., et al. (2001). Genetic and ecological divergence of a monophyletic cichlid species pair under fully sympatric conditions in Lake Ejagham Cameroon. *Molecular Ecology, 10*, 1471–1488.

Shen, Z. X., Wang, G. J., Li, K. M., et al. (2014). The situation and protection measures of fish resources in upstream of Longyang valley of the Yellow River. *Journal of Hydroecology, 35*, 70–76.

Shi, Y. F. (2002). Characteristics of late Quaternary monsoonal glaciation on the Tibetan plateau and in East Asia. *Quaternary International*, *97*, 79–91.

Su, J., Ji, W., Zhang, Y., et al. (2015). Genetic diversity and demographic history of the endangered and endemic fish (*Platypharodon extremus*): Implications for stock enhancement in Qinghai Tibetan Plateau. *Environmental Biology of Fishes, 3*, 763–774.

Sun, J. H., Zhang, Y. P., Lou, Z. Y., et al. (2012). Genetic structure of *Gymnodiptychus pachycheilus* from the upper reaches of the Yellow River as inferred from mtDNA control region. *Acta Ecologica Sinica, 32*, 4191–4198.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) headwaters. In G. J. Brierley., X. Li., Cullum, C. et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*, (pp. 275–330). Berlin: Springer.

Tang, W. J., Shen, Z. X., & Jian, S. L. (2006). Conservation strategies of rare and endangered native fishes in the Upper Yellow River. *Reservoir Fisheries, 26*, 57–60.

Tang, W. J., Wang, M., & Li, K. M. (2005). Indigenous fish in Qinghai Province. *Chinese Journal of Fisheries, 18*, 13–17.

Tsao, W. S., & Wu, H. W. (1962). An investigation of the fish biology and fishery problems in Ganze-Apa region of western Szechwan province. *Acta Hydrobiolica Sinica, 2*, 79–110.

Wang, S., & Xie, Y. (2004). *China species red list*. Beijing: China Higher Education Press.

Wu, Y. F. (1984). Systematics and taxonomy of the Schizothoracine fish in China. *Acta Biologica Plateau Sinica, 3*, 119–139.

Wu, Y. F., & Wu, C. Z. (Eds.). (1992). *The fishes of the Qinghai—Xizang plateau*. Chengdu: Sichuan Science and Technology Press.

Yue, P. Q., & Chen, Y. Y. (1998). Pisces. In S. Wang (Ed.), *China red data book of endangered animals*. Beijing: Science Press.

Zhang, R., Peng, Z., Li, G., et al. (2013). Ongoing speciation in the Tibetan Plateau Gymnocypris species complex. *PLoS ONE, 8*(8), e71331. doi:10.1371/journal.pone.0071331.

Zhang, Z. Y., Yu, Q. W., Zhang, K. X., et al. (2003). Geomorphological evolution of Quaternary River from Upper Yellow River and geomorphological evolution investigation for 1:250,000 scale geological mapping in Qinghai-Tibet plateau. *Earth Science—Journal of China University of Geosciences, 28*, 621–633.

Zhao, K., Duan, Z. Y., Peng, Z. G., et al. (2009). The youngest split in sympatric schizothoracine fish (Cyprinidae) is shaped by ecological adaptations in a Tibetan Plateau glacier lake. *Molecular Ecology, 18*, 3616–3628.

Zhao, K., Li, J. B., Yang, G. S., et al. (2005). Molecular phylogenetics of *Gymnocypris* (*Teleostei: Cyprinidae*) in Lake Qinghai and adjacent drainages. *Chinese Science Bulletin, 50*, 1325–1333.

Zheng, B. X., Xu, Q. Q., & Shen, Y.P. (2002). The relationship between climate change and Quaternary glacial cycles on the Qinghai-Tibetan plateau: review and speculation. *Quaternary International*, *97*, 93–101.

Zhu, S. Q., & Wu, Y. F. (1975). The study on ichthyofauna of Lake Qinghai Lake. In *Ichthyofauna of Lake Qinghai and biology of Gymnoypris przewalskii (Cyprinidae)*. Beijing: Science Press.

Zhu, X. M., Kang, A., Han, D.X., et al. (2003). Relation among quaternary environmental evolution, tectonic deformation in the Qiadam basin and uplifting of the Qinghai -Tibet Plateau. *Chinese Journal of Geology*, *38*, 413–424.

Chapter 12
Climate, Vegetation and Human Land-Use Interactions on the Qinghai–Tibet Plateau Through the Holocene

Meiqin Han, Gary John Brierley, Carola Cullum and Xilai Li

Abstract The Qinghai–Tibet Plateau is renowned for its geomorphologic diversity and high sensitivity to climatic changes and human disturbance. These relationships vary markedly across the region, shaped by factors such as the elevation, vegetation cover, water distribution, climate variability and the history of human settlement and land use. This chapter presents an overview of Holocene environmental evolution and human settlement history across the region, based on an assessment of the key literature on palaeoenvironmental conditions (e.g. glacial records, lacustrine strata, river deposits, aeolian (sand dune) histories) and analyses of Palaeolithic and Neolithic relics. A summary of climate–vegetation–human activities, relationships, interactions and evolution is provided. Climate changes are shown to be key drivers of regional variability in vegetation and hydrological patterns. It is very likely that long-term grazing activities have brought about a pronounced transition to grazing-adapted ecosystems in many grassland areas across the region. An overview of the human settlement history includes assessment of Dadiwan, Yangshao, Majiayao and Qijia cultures, and their associated agriculture (grazing) economies.

Keywords Qinghai–Tibet Plateau · Holocene · Palaeoclimate · Palaeoenvironmental conditions · Vegetation cover · Vegetation evolution · Human settlement · Human activities · Grazing-adapted ecosystems

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12.1 Introduction

Across the world a delicate balance is played out between environmental capacity to support human activities, the consumption of natural resources, the provision of ecosystem services and the human adaptation to environmental conditions. This balance must be successfully negotiated in the quest for survival, especially under extreme conditions such as those found on the Qinghai–Tibet Plateau. Harmonious relationships and the quest for sustainability take very different forms in different places. They reflect human history, as people have evolved and adapted to recurrently cope with variability and conflict. Much may be learnt from past experiences. Indeed, the imprint of history provides the context for contemporary choices. Flexibility and resilience are required to cope with new situations and circumstances. Whatever form these adjustments may take, it is now acknowledged that wilderness is dead across our planet (Wohl 2013), and we now live within a no-analogue state (Hobbs et al. 2009; Williams and Jackson 2007). In the Anthropocene, human activities are the dominant forces shaping our world.

It is fascinating to consider how these issues are played out in the most challenging, extreme and marginal environments of the world. Such is the case atop the Qinghai–Tibet Plateau, where remarkable adaptations have been required in response to altitudinal, climatic and environmental conditions. Indeed, recent research points to genetic adaptations from a Denisovan gene pool that supports human adjustments to oxygen-depleted high-altitude conditions (Huerta-Sánchez et al. 2014; Keim 2014). Despite the fascinating stories that can doubtless be told, our understanding of long-term (post-glacial) environmental changes and human adaptations on the Qinghai–Tibet Plateau remains in its infancy. Here, we convey a sketch of recently derived understandings, recognizing explicitly that far more complete and intriguing analyses are likely to emerge in the future years.

Pollen analysis indicates considerable climate changes during the Holocene (the last 12,000 years), associated with tectonic uplift of the plateau and global shifts in atmospheric patterns. These adjustments have led to considerable changes in vegetation. However, not all the vegetation changes covary with the patterns of climate change. Anomalies are particularly evident in areas of human habitation, suggesting that humans have been responsible for some modification of vegetation patterns. Thus, the vegetation seen today is a result not only of contemporary and historical landforms and climate, but also of the history of human activity.

This chapter presents a geographic overview of post-glacial climatic and environmental conditions across the Qinghai–Tibet Plateau and their interactions with human activities. Many of the contemporary grassland areas of the plateau were once quite heavily forested. It seems very likely that humans were responsible for deforestation and that domesticated yaks have grazed the lands for thousands of years (i.e. these are now grazing-adapted ecosystems; see Li et al. 2016, Chap. 7; Tane et al. 2016, Chap. 13). Thus, both the humans and the vegetation have adapted to the climate and environment, shaping the landscapes and ecosystems of this region.

We start this chapter with a summary of the contemporary climate and vegetation distribution across the plateau. We then assess the post-glacial vegetation history through a regional assessment of selected pollen records. This work is complemented by an appraisal of human occupation sites that provide insights into long-term land-use changes in the region. Finally, this overview is synthesized to provide an assessment of prospective future socio-cultural adaptations in this area.

12.2 Contemporary Climate and Vegetation Across the Qinghai–Tibet Plateau

Considerable climate gradients influence both horizontal and vertical vegetation patterns across the Qinghai–Tibet Plateau (Fig. 12.1). Elevation- and monsoon-driven climates induce transitions from the colder and drier deserts of the north-west to the wetter and warmer forested areas of the south-east (Tang et al. 2000; see McGregor 2016, Chap. 2 for further detail). Altitudinal gradients from the world's highest peaks to relatively low-lying (though still very high) plains control the distribution of plants at multiple scales.

Moving successively from south-eastern areas of the plateau to the west, forest vegetation is replaced by alpine shrub/alpine meadow, alpine grassland/temperate alpine grassland and alpine desert/montane desert (Wu 1980; Zhang 1978):

- In the south-east, the terrain is slightly lower (3000–4000 m), with a warm and humid climate that supports dense forests.
- From the eastern plateau to western Sichuan, and from southern Qinghai Province to the eastern region of northern Tibet (where the terrain is generally 4000–4500 m), the climate is cold and humid and is unsuited to tree growth. As a result, these areas are characterized by alpine meadow and shrubs.
- To the north and west of the region, in the source area of the Yangtze River and the hinterland of the Qinghai–Tibet Plateau, the terrain has an average elevation of 4500–5000 m and is characterized by alpine meadows and alpine desert steppe vegetation.
- In southern Tibet, lower elevation valleys (<4400 m) have a cooler and relatively dry climate that supports warm temperate grasslands and arid deciduous shrub vegetation. In contrast, elevations above 4400 m are characterized by alpine meadows and shrubs.
- In the lake basin areas of the farthest north-west of the Qinghai–Tibet Plateau, at an average altitude of more than 5000 m between the Karakulun and Kunlun mountains, the climate is extremely cold and dry, with large areas of permafrost and arid desert vegetation.
- To the west, the Ali region has a slightly lower altitude (4200–4500 m), the climate is relatively warm but very dry, and mountain temperate desert or steppe desert vegetation has developed.

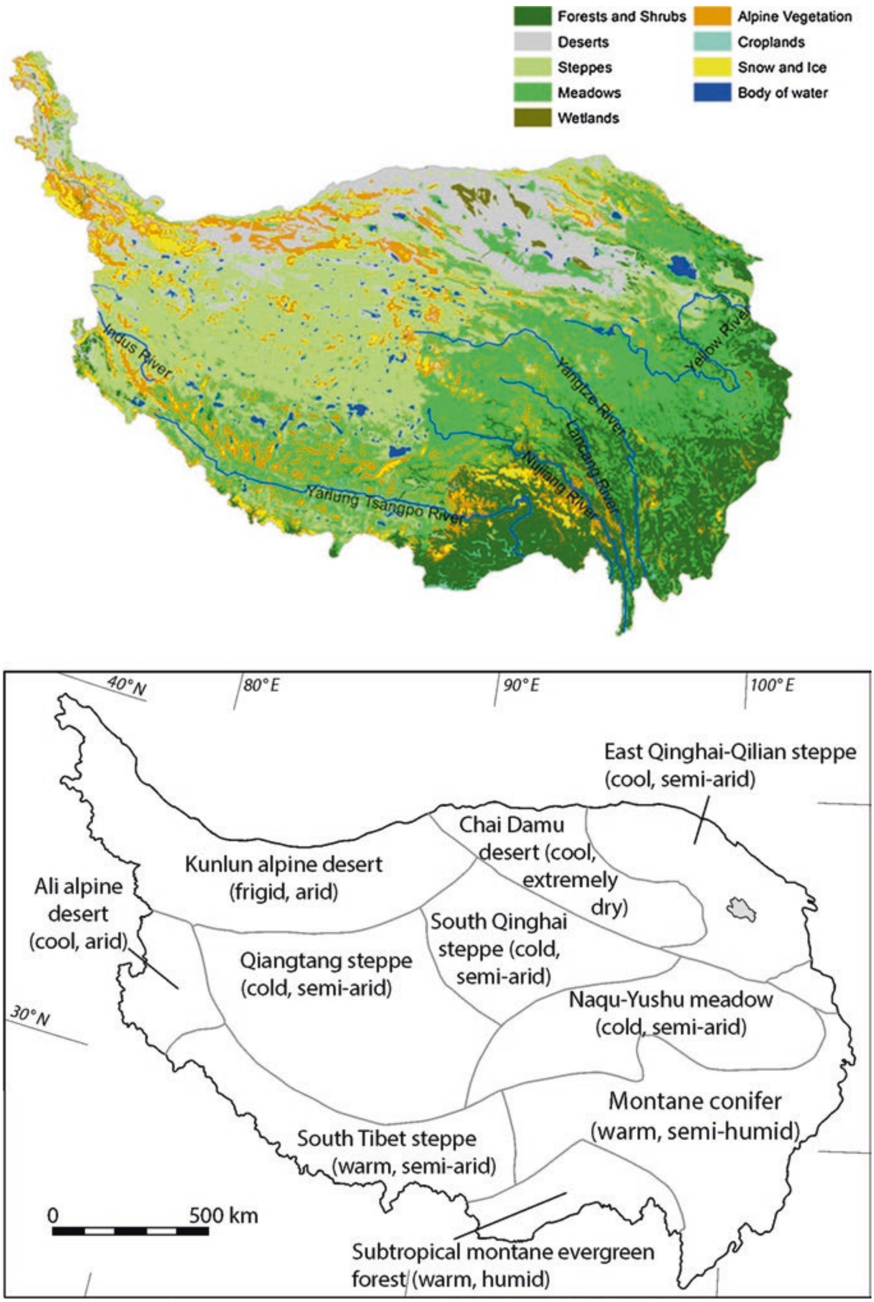

Fig. 12.1 Vegetation and climate gradients across the Qinghai–Tibet Plateau. Altitudinal climate gradients are seen both on individual hillslopes and between the mountainous areas and the plateau. Vegetation distribution of the Qinghai–Tibet Plateau. (Adapted from Chen et al. (2013) and Wang et al. (2015))

Vertical distribution characteristics complicate this simplified zonation:

- In *central* areas of the plateau, there is a relatively simple vertical structure, with mountain forest in the valleys, alpine meadows and alpine cushion-shaped shrub vegetation on the lower slopes and sparse subalpine vegetation below permanent snow on the highest slopes. These structural relationships vary with aspect (see Tane et al. 2016, Chap. 13). In the subalpine coniferous tree zone, for example, cedar trees are found on shady hillslopes and cypress trees on sunny slopes. In alpine shrub meadow zones, alpine shrubs are found on shady hillslopes but alpine meadows on sunny slopes.
- From the *south-east margin to the central area,* the vertical vegetation structures are simpler with less pronounced aspect-induced differences. For example, in the Changtang highland, there are only three types of structures: alpine grassland, sparse vegetation and permanent snow, with similar plant communities on shady and sunny hillslopes.

Vertical transitions in vegetation cover tend to occur at higher elevations moving from the south-east to the north-west. For example, in the forests of the Hengduan Mountains, alpine meadows are found up to 4800 m, while in the north-east area around Maduo, they exist up to 5000 m. Similarly, alpine grasslands extend up to 4600 m in southern Tibet, but only to 5000 m in the central area (Wu 1980; Zhang et al. 2014).

In summary, as altitude and relative relief gradually increase from the south-east to the north-west of the plateau, differences in vegetation type reflect climate changes from warm and wet to cold and dry, changing from evergreen broad-leaved forest/boreal coniferous forest to alpine shrub/alpine meadow, alpine steppe (temperate grasslands in low-altitude valleys) and finally to alpine desert (temperate mountain desert in arid valleys with lower elevations).

These spatial relationships have varied markedly in the post-glacial period as vegetation has responded to quite dramatic climate shifts, as well as to human activities.

12.3 Glacial History in the Qinghai–Tibet Plateau

The oxygen isotope record extracted from the Guliya ice core on the north-west plateau indicates that severe climate changes have taken place over the last 125,000 years, with several millennia-scale oscillations between warm and cold periods (Yao 1999, 2000):

- An extensive system of interconnected lakes, with an estimated area of 360,000 km^2 and a total volume of about 53×10^8 km^3, was evident from around 65–53 to 40–30/35 thousand years ago. Rapid uplift of the plateau and cooler climate conditions around 30,000 years ago were coincident with rapid drainage of these lakes. The Upper Yellow River adopted its contemporary course at this time, flowing through the Gonghe Basin to the Huanghai Sea, reforming the lake and river systems at the margins of the plateau, with extensive transfer of cold water to the Indian Ocean and the western Pacific Ocean (Brierley et al. 2016a, b, Chaps. 1 and 3; Zheng et al. 2006). Around the same time, extensive salt bed development was initiated at Qaidam Lake, where a large number of organisms became extinct, indicating transition to dry and cold climatic conditions (Fan et al. 2012; Jing and Sun 2001).

- During the Last Glacial Maximum (about 32–16,000 years ago), temperatures were around 7 °C colder than present on the Tibetan Plateau, while precipitation was only 30–70 % of present (Shi et al. 1997).
- Around 30–23,000 years ago was an even colder period, with temperatures roughly 10 °C lower than present (Yao 2000).
- From 25–15,000 years ago, a large part of south-eastern Tibet, including Zoige, Qaidam and Kekexili, was characterized by desert grassland, with cold and dry climate conditions and annual temperatures 6 °C lower than present. At this time, the forests in the Qinghai Lake area were replaced by grassland vegetation (Tang et al. 1998).
- Despite several cold events, temperatures have gradually increased in the last 15,000 years, becoming notably warmer after about 10,500 years ago (Yao 2000).

12.4 Climate and Vegetation History Through the Holocene

More detailed climate and vegetation history is available for the Holocene (from about 11,700 years ago to the present day). Holocene paleoclimatic fluctuations on the Qinghai–Tibet Plateau are broadly consistent with the global glacial/interglacial sequence of events, as evidenced by pollen records across many different parts of the plateau. In the following section, regional differences are appraised through records from the research sites shown in Fig. 12.2.

12.4.1 Eastern Plateau: Ruoergai Plateau, Gonghe Basin and Qinghai Lake

In the southern part of the eastern plateau, vegetation has changed from forests to alpine meadows as temperatures have decreased through the Holocene. In contrast, in the semi-arid areas to the north, vegetation has shifted from forests to temperate steppe, driven largely by changes in precipitation (Zhao et al. 2011a, b).

In the southern area, atop the Ruoergai Plateau in Sichuan Province, analysis of tree pollen and peat properties suggests that forest conditions were evident from 12–11,000 years ago, with spruce, fir (15 %) and birch (10 %) prominent

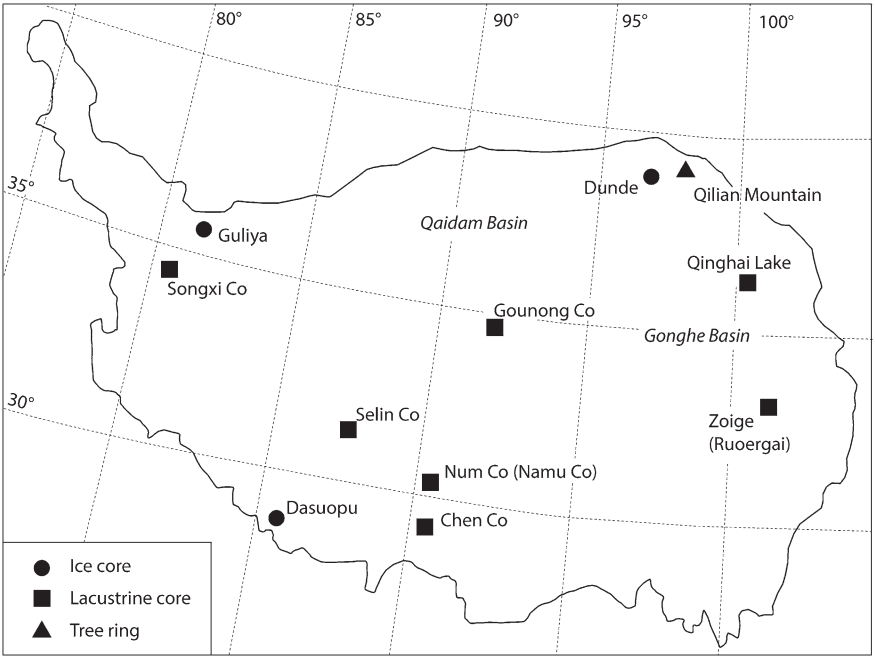

Fig. 12.2 Main sites used to reconstruct regional variability in past climates atop the Qinghai–Tibet Plateau (modified from Li et al. 2012). Note that Song(mu)xi Lake and Sumxi Lake are different names for the same feature

(Wang et al. 1993). In this area, the warmest period in the Holocene (known as the 'climate optimum') occurred around 6.5–4.7 thousand years ago. Since then, forests have declined, giving way to alpine meadows. This decline corresponds with increases in clastic sediment input and in peat decomposition, suggesting a drying and cooling trend that may be associated with weakening monsoon intensity and decreasing summer insolation (Zhao et al. 2011a, b).

Pollen records from Qinghai Lake reveal that 15,200 years ago the climate was cold and dry. The Holocene climate optimum occurred at around 6700 years ago in this area (Liu et al. 2002). In the Early Holocene, the salinity of Qinghai Lake water was higher than that at present, reaching its highest value around 8400 years ago. From 7.7–5.1 thousand years ago, the salt content decreased greatly, but increased again from 3200 years ago to present. High lake levels, up to 17.5 m higher than the present lake level, occurred at 6.4, 5 and 3.5 thousand years ago. The frequent fluctuations of lake level suggest phases of climatic instability (Pengxi et al. 1994).

Further north, in the Gonghe Basin, tree pollen was replaced by shrub and herbaceous pollen from 12.3–11.3 thousand years ago, indicating a grassland desert landscape associated with a stable cold climate in the Early Holocene

(Cheng et al. 2013). Although the effective humidity started to increase about 11.3–9.7 thousand years ago, grassland remained, evidenced by the high herbaceous and shrub pollen content associated with this period. The ratio between Chenopodiaceae and Artemisia pollen (the A/C ratio is a useful indicator of humidity) continued to increase from 9.7–8.9 thousand years ago, indicating further increases in temperature and effective humidity. However, after about 8.9–6.8 thousand years ago, the overall concentration of pollen increased considerably, as did the proportion of pollen from tree species (predominantly spruce and pine). From 6.8–5.0 thousand years ago (the climatic optimum), the tree pollen further increased to levels equal to herbaceous pollen. The trend reversed from 5.0–3.4 thousand years ago, when a cooling period is suggested by decreasing proportion of tree pollen and increasing herbaceous and shrub pollen. The cooling continued from 3.4–1.0 thousand years ago, as herbaceous and shrub pollen continued to increase, with Chenopodiaceae, Artemisia and other grasses and sedges becoming dominant and tree pollen (mainly pine) falling to a low percentage of the total. The progressive decline in trees then continued, reaching the lowest proportion of all pollen by 1000 years ago, by which time the area had become temperate steppe (Cheng et al. 2013).

12.4.2 Southern Plateau: Chen, Nariyong and Peiku Lakes in Southern Tibet

In the south, vegetation has changed from sparse steppe shrubland some 11.0–8.0 thousand years ago, through a warm, semi-humid period with spruce, fir and some deciduous trees (8.0–3.0 thousand years ago). Current conditions are cool and semi-arid, with forest and shrub vegetation.

Analysis of the pollen record from Nariyong and Chen lakes in southern Tibet by Huang et al. (1995) suggests widespread sparse shrub steppe in this region from 11–8.0 thousand years ago. Herbaceous pollen occupies 70–80 % of the total record, with some spruce and fir indicating of cool, semi-arid high-mountain climate conditions. Vegetation thrived from 8.0–3.0 thousand years ago, with increases in tree pollen, including deciduous species such as oak, birch, Rosaceae and Azalea. At this time, herbaceous vegetation comprises 30–70 % of the record, with Artemisia, Asteraceae, Gramineae, Thalictrum and legumes indicating a forest shrub meadow landscape and a warm, semi-humid climate. Similar records are evident from the Peiku Lake area (Tang and Shen 1996; Huang 2000), where an apparent rise of birch, oak, cedar and hemlock is indicative of increasing humidity and temperature relative to the previous phases. From 3000 years ago to present, the proportion of woody plant pollen decreases from 30–34 % to under 20 %. Shrub vegetation dominates, with herbaceous plants making up 73–89 % of the pollen record. This is indicative of a transition to cooler, semi-arid climate conditions.

12.4.3 Western Plateau: Sumxi Lake and Bangong Lake

Pollen records from the western plateau indicate fluctuations through the Holocene from cold and dry conditions to a wetter period where grasses flourished, followed by increasing dryness and a reversion to steppe.

Analysis of pollen records from Sumxi Lake indicates cold and dry conditions around 10.5–9.9 thousand years ago. From 7.7–4.3 thousand years ago, more humid climate conditions and grasslands prevailed, indicated by the high Artemisia/Chenopodiaceae ratio. The wettest periods were between 8.0–7.7 and 7.5–6.0 thousand years ago, when the highest lake level was recorded. From 5.5–4.3 thousand years ago, the Artemisia/Chenopodiaceae ratio gradually declines while the proportions of Ephedra and tree pollen increase. The presence of Ephedra indicates a transition towards drier conditions in this period. From 43,000 years ago to present, decreases in the ratio of Artemisia/Chenopodiaceae alongside changes in the oxygen isotope record (reduced $\delta^{18}O$) and decreases in carbon content suggest a continuation of the trend towards drier conditions (van Campo and Gasse 1993).

Pollen concentrations in the Bangong Lake, some 170 km to the south-east of Sumxi Lake, show that from 9.9 to 9.6 thousand years ago, the region had a dry climate with very sparse vegetation and the lake area was occupied by a slightly saline marsh, rich in charophytes. An extremely abrupt environmental change from arid to wet conditions is recorded at around 9.6 thousand years ago, when steppe vegetation rapidly established over the region. A freshwater, oligotrophic, planktonic diatom flora developed in the lake, implying a sudden influx of dilute, nutrient poor water. From 9.6 to 6.3 thousand years ago, this rapidly flowing, freshwater lake persisted, as shown by the diatom flora and the stable isotope record. The lowest $\delta^{18}O$ values, regarded as reflecting minimum water residence time in the lake and maximum monsoon rainfall, are observed between 9.0 and 8.7 thousand years ago, and between 7.5–7.2 and 6.3 thousand years ago. From 5.7 to 3.8 thousand years ago, steppe and alpine meadow cover regressed in two steps, at around 5.5 and 3.9 thousand years ago. Influxes of detrital material increased in response to the lowering of the lake level. From 3.8–3.2 thousand years ago, relatively low $\delta^{18}O$ content suggests that the core site was directly subject to a river influence, likely a deltaic zone during a phase of very low water level. Ephedra pollen, characteristic of desert environments, makes up >10 % of the pollen record, indicating that this was an arid episode.

12.4.4 Central Plateau: Kekexili Kusai and Selin Lakes

In the Early Holocene, the central part of the plateau was cold and dry, with sparse vegetation. The warmest period occurred 9.6–6 thousand years ago, when there was a transition to alpine steppe and a few trees. Over the last 3000 years, the area has become drier, windier and colder. Trees have been lost and the vegetation is now sparse steppe.

Sun et al. (1993) document findings from a pollen record from the Selin Lake region. Sparse vegetation cover is indicated from the Early Holocene (11.0–9.6 thousand years ago), reflecting a cold and dry climate. A transition to alpine steppe occurred by the Mid-Holocene (9.6–6 thousand years ago), with warmer conditions, rising lake levels and swamp development adjacent to lakes from 8.5–7.5 thousand years ago. There is evidence for forest expansion in nearby areas. Although herbaceous pollen dominates the record from 6.0–3.8 thousand years ago (81 %, with sedges and Artemisia prominent), tree pollen is also found (13–28 %). Trees increase from 3.8–2.4 thousand years ago, dominated by spruce. A marked drop in pine pollen is evident from 1.2–0.7 thousand years ago, with a corresponding increase in herbaceous pollens from sedges, Chenopodiaceae and Ranunculaceae, but a decrease in Artemisia. This is indicative of drier and colder conditions during which tree cover decreased and swamps expanded around the lake. There is evidence for three-hundred-year-scale drought events in the central plateau, around 5.8–4.9, 4.4–3.9 and 2.8 thousand years ago (Tang et al. 2009).

Wu et al. (2007) concluded that solar insolation exerted a dominant influence upon Holocene climatic changes on the central plateau. The $\delta^{18}O$ record indicates a gradually cooling trend since the climatic optimum of the Early Holocene. A prominent drought in the Mid-Holocene (around 4.7 thousand years ago) was marked by very high concentrations of dust and soluble aerosols (other than nitrates). Calcium concentrations have increased since 3500 years ago, while dust and $\delta^{18}O$, and ion species, have all decreased gradually, signalling the onset of more arid and possibly windier conditions (Thompson et al. 2006). Analysis of mineral assemblages from Kekexili Kusai Lake indicates that the climate was relatively warm from 3.7–2.5 thousand years ago, with a gradual cooling trend from 2.5–2.15 thousand years ago followed by much more rapid cooling from 2.15 thousand years ago to present. Over the same period, humidity in the area decreased, salinity of the lake increased, and aeolian activity strengthened.

12.4.5 Northern Plateau: Yellow River Source Zone

Lacustrine strata deposited atop glacial moraines in the Yellow River source region indicate rapid glacial retreat in response to the transition from cold–dry to warm–wet conditions in the early post-glacial period. Fluctuations between these phases have occurred to the present day, with cold–dry periods characterized by desert steppe vegetation and alpine steppe and alpine meadow occurring during warmer, more humid periods.

Expansions in forest vegetation cover, high lake levels and high rates of soil development indicate that peak warm and humid conditions were experienced around 7–6 thousand years ago (Shi et al. 1997). The record from 7.5–5.8 thousand years ago has the highest pollen concentration, with high proportions of sedges and a low magnesium/calcium coefficient. This indicates that during this Holocene climatic optimum, conditions were relatively humid, with temperatures 4 °C higher than present. From 5.8–4.5 thousand years ago, the temperature fell and drier climate conditions prevailed. For instance, ice core studies from the Qilian Mountains indicate cold and dry conditions from 6.0–5.0 thousand years ago, but sporadic short-term temperature fluctuations are also evident (Yao et al. 2001). A warmer and more humid phase from 4.5–3.5 thousand years ago was characterized by temperature and humidity conditions that were slightly lower than the early period. The end of this period is demarcated by a rapid decrease in the proportion of tree pollen from 3500 years ago, with some distinct cooling phases (Shi et al. 1997; Zhang and Zhang 1995). Research at Eling Lake shows that around 1900 years ago, this region was relatively warm and humid, but between 1.9 and 1.6 thousand years ago, the climate became cold and arid, so that the vegetation changed to desert steppe. Since 16,000 years ago, the climate has been getting warmer and more humid again, with the vegetation changing to alpine steppe and alpine meadow, dominated by Cyperaceae, Brassicaceae and Artemisia.

12.4.6 Summary Overview of Regional Variability in Vegetation History Across the Qinghai–Tibet Plateau

Holocene pollen records vary markedly across the Qinghai–Tibet Plateau. Whereas evergreen conifers once occupied the south-east, little tree pollen is seen in records from northern areas (Tang and Shen 1996). In large part, this reflects the gradual weakening of summer monsoon precipitation from the south-east to the north-west. In general terms, conditions were cold and arid in the Early Holocene (12–9 thousand years ago), with the warmest and most humid conditions occurring around 8–6 thousand years ago. This climatic optimum for vegetation produced the highest biomass, as indicated by the highest pollen concentrations in lacustrine cores. The proportion of trees increased in all areas, with vegetation cover increasing, so that steppe turned to meadows and meadows turned to shrublands. The timing of this climatic optimum varied across the plateau. At Sumxi Lake, in the south, this environmental optimum occurred from 7.5–5.5 thousand years ago (Gasse et al. 1996), whereas at Ruoergai, in the north-east, it occurred from 8.2–6.4 thousand years ago (Wang et al. 2006). Shen and Tang (1995) postulate high water levels at Qinghai Lake from 7.4–6.0 thousand years ago. These various records suggest that the Holocene climatic optimum period occurred across the whole plateau, but lasted longer in the Zoige Basin and Qinghai Lake area (Shen and Tang 1995; Wang and Fan 1987; Zhu et al. 1994).

Since the Mid-Holocene, there has been a long-term trend towards drier and cooler climes across the whole plateau, likely linked to a weakening of the monsoons and decreasing summer insolation (Zhao et al. 2011a, b). A cold and arid event occurred at about 3500 years ago in many areas. Impacts of other Holocene climatic events such as the 8.2 thousand years ago cooling event, the Medieval Warm Period, the Little Ice Age and the twentieth-century warming trend have varied in space and time across the plateau (e.g. Duan et al. 2012; Yang et al. 2009).

12.5 The Long-Term History of Human Activities on the Qinghai–Tibet Plateau

There is a very patchy and incomplete record of archaeological sites and analyses across the Qinghai–Tibet Plateau. As a result, great reliance is made upon inferential reasoning in scoping phases and patterns of human land use and adaptation across the region.

The Qinghai–Tibet Plateau is inhospitable to human settlement because of low oxygen conditions (hypoxia), cold climate and scarce resources. At 4000 m elevation, each breath contains only about 60 % of the oxygen inhaled at sea level (Beall 2007). These extreme conditions have limited population migration, the exploitation of natural resources and technological developments—from the earliest times to the present day (Gao et al. 2008).

12.5.1 Human Adaptation to High-Altitude Conditions

Tibetans exhibit many biological features in common with other high-altitude mammalian species (such as antelopes), including the absence of chronic mountain sickness, thin-walled pulmonary vascular structure and high blood flow (Monge and Leon-Velarde 1991). These phenotypes are highly correlated with physiological responses to low oxygen concentration, which facilitate more efficient oxygen utilization. Evidence from the studies of Y chromosome suggested that Tibetans, together with the Yi people, were descendants of Tibeto-Burmans who diverged from ancient settlers of East Asia. Since the Himalayas present a strong barrier to gene flow from the south into the Tibetan Plateau, the valleys of the Hengduan Mountain range (to the west of the plateau) may have been a major migration route (Wang et al. 2011). Gayden et al. (2007) support the hypothesis that the Tibetan gene pool reflects significant contributions from East and/or Southeast Asia. Qian et al. (2000) concluded that Tibetan Y chromosomes may have been derived from two different gene pools in Central and East Asia.

Skoglund and Jakobsson (2011) found a genetic link between Tibetans with the Denisovan hominids that spread from eastern Eurasia through southern China to Southeast Asia and Melanesia. Huerta-Sánchez et al. (2014) found that a highly unusual haplotype structure could only be explained by introgression of DNA from Denisovan or Denisovan-related individuals into humans. This selected haplotype is only found in Denisovans and in Tibetans, and has very low frequency among Han Chinese. They concluded that this haplotype was introduced into humans before the separation of Han and Tibetan populations, and was then subject to selection in Tibetans after the Qinghai–Tibet Plateau was colonized, resulting in the distinctive Tibetan adaptation to high altitudes.

Archaeological evidence suggests that migration of the archaic human population to the Qinghai–Tibet Plateau occurred from the north-eastern margin of the plateau (Deng et al. 2004). It is suggested that people settled at lower altitudes in the north-east and gradually moved south and west as warmer climates allowed them to settle at higher altitudes (Gayden et al. 2007; Madsen et al. 2006).

12.5.2 Human Colonization of the Qinghai–Tibet Plateau

A widely accepted colonization model for the Qinghai–Tibet Plateau differentiates between three elevation areas:

1. The low-elevation source areas of the northern plateau below 3000 m, which consist primarily of Gansu Province, the Inner Mongolian Region and Xinjiang Uygur Autonomous Region.
2. An intermediate area between 3000 and 4000 m, including the large internal lake basins of Qinghai Province.
3. An extreme elevation step above 4000 m that includes portions of Qinghai Province and most of the Tibetan Autonomous Region (Brantingham et al. 2001, 2007; Brantingham and Xing 2006; Madsen et al. 2006).

Variations in the climate of this area are largely controlled by spatial and temporal variations in the strength of the Southeast Asian summer monsoon (McGregor 2016, Chap. 2). As described in the previous section, climate and environmental changes in the middle- and high-elevation steps of the plateau parallels those in the surrounding low-elevation areas, alternating between cooler–drier and warmer–wetter periods, albeit with different starting points in each area (Brantingham and Xing 2006). Climate factors exerted a critical influence upon human colonization on the plateau (Brantingham et al. 2003; Chongyi et al. 2013; Hou et al. 2010). Prior to the Holocene, human activities were directly influenced by climatic fluctuations. Following the Holocene climatic optimum, the marked increase in the number of occupation sites indicates the blossoming of various cultures. Demographic pressure was a prime motivation for the Neolithic expansion (Davison et al. 2006). For example, the introduction of agriculture brought about significant population expansion in the north-eastern margin of the plateau, as evidenced at sites associated with the Dadiwan culture (5.8–5.4 thousand years ago).

The ‘three-phase’ model for human settlement on the plateau relates to changes in climate on each elevation step:

1. Initial stage occupation of lower elevations from 40–25 thousand years ago by highly mobile foragers collecting key resources. At this time, temperature was 2–4 °C higher and precipitation was 40–100 % higher than today (Liu et al. 1998; Shi and Liu 1999). Qinghai Lake appeared to be warm and wet, with high water levels and mixed forests occurring on the surrounding landscapes (Fan et al. 2012; Yao 2000; Zhou et al. 2003).
2. Immediately prior to and after the Last Glacial Maximum (25–10 thousand years ago), foragers ventured out from permanent home bases along the lower elevation margins of the plateau to occupy temporary, short-term, special-purpose foraging sites on the middle and upper steps of the plateau.
3. Increasing temperatures and decreasing effective moisture after the Last Glacial Maximum encouraged full-scale, year-round occupation of the upper regions of the plateau by Early Neolithic pastoralists (Fan et al. 2012). Although changing climatic conditions favored archaic population migration on the plateau, demographic pressure is also considered to be a prime driver of the Neolithic expansion (Lee 1997). For example, low-level agricultural activities at sites associated with the Dadiwan culture (5.8–5.4 thousand years ago) transitioned into intensive agricultural activities focused around large, complex permanent settlements associated with Yangshao (6.9–5.3 thousand years ago) and Majiayao (5.3–4.2 thousand years ago) civilizations. The subsequent rapid transition from warm–semi-arid to warm–arid conditions around 4/3.5 thousand years ago may have driven a reduction in the total number and distribution of agricultural settlements over the western Loess Plateau. Nomadic pastoralism appears to have become a viable alternative to rain-fed agriculture sometime during the Qijia cultural stage (around 4.3–3.9 thousand years ago) (Brantingham et al. 2013).

Several sources of evidence suggest that the plateau was initially populated by migrations from northern China. Grey green quartz stone tools found horizontally stratified between two well-preserved beach ridges at Lenghu on the northern margin of the Qaidam Basin (2804 m, around 37 thousand years ago, see Fig. 12.3) are typologically indistinguishable both from the Levallois-like blade technology seen at Shuidonggou site in northern China and from other Early Upper Palaeolithic occurrences (around 30,000 years ago) in the low-elevation source area of the plateau (Brantingham et al. 2001). Furthermore, the stone assemblages (quartzite cores, flakes, choppers, scrapers, end scrapers, rock drills and carvers) found at the Lesser Qaidam site (3170 m, 30 thousand years ago) are also typical of the traditional stone technology of northern China (Gao et al. 2008; Zhang 1990).

Hearths near Qinghai Lake provide evidence for the second stage of settlement. Dating from around 12–14,000 years ago, the archaeological evidence suggests single, short-term visits by small foraging parties, since there is evidence of cooking animals, but no evidence of preparing agricultural foodstuffs (Brantingham and Xing 2006; Gao et al. 2008; Madsen et al. 2006). Heimahe (Black Horse

Fig. 12.3 Location of major Palaeolithic sites in the north-eastern part of the Qinghai–Tibet Plateau. *1* Lenghu; *2* Lesser Qaidam; *3* Heimahe; *4* Jiangxigou; *5* Gouhou reservoir; *6* Loula reservoir; *7* Xiadawu (Xidatan); *8* Donggeicuona Lake (after Gao et al. 2008; Yi et al. 2011)

River; 3120 m; Gao et al. 2008) and Jiangxigou (3330 m; Madsen et al. 2006) are located along streams that fed into the southern margin of Qinghai Lake. A single hearth at Heimahe reflects occupation around 12.94–13.1 thousand years ago. Artefacts providing indicators of land-use activities include many bifacial thinning flakes, a quartzite core, two microblade fragments, a bifacially worked slate scraper, a ground stone cobble and fragmentary bone splinters. Most of the bone splinters appear to be from a medium-sized mammal, while others are from a mid-sized ungulate, possibly a gazelle (Brantingham and Xing 2006; Gao et al. 2008; Madsen et al. 2006). All bones have been broken and shattered for marrow extraction and possibly for degreasing. No evidence of seed processing or geophyte use has been found—ground stone seems to represent tool production rather than food processing. Two granite cobbles and two pieces of microdebitage related to microblade production were also recovered from two stratigraphically separate hearths at Jiangxigou (Madsen et al. 2006). Charcoal from the lower and upper hearths dates from 14.2–14.92 and 14.16–14.83 thousand years ago, respectively. Lithic collections from Jiangxigou and Heimahe are virtually identical, both in terms of the technology they imply and in the consistent small size of the specimens.

Charcoal, ash, burned bone fragments and lithic collections (mainly quartz, including blade, shatter and microblade fragments) were excavated from a hearth near the Loula reservoir (3395 m, around 13 thousand years ago; Yi et al. 2011). At Gouhou (3056 m; Gao et al. 2008), charcoal, ash and cobble with limited microblade specimens comprised primarily of quartz and chert suggest that the site was used for short-term food processing. Abundant stone cores, microstone

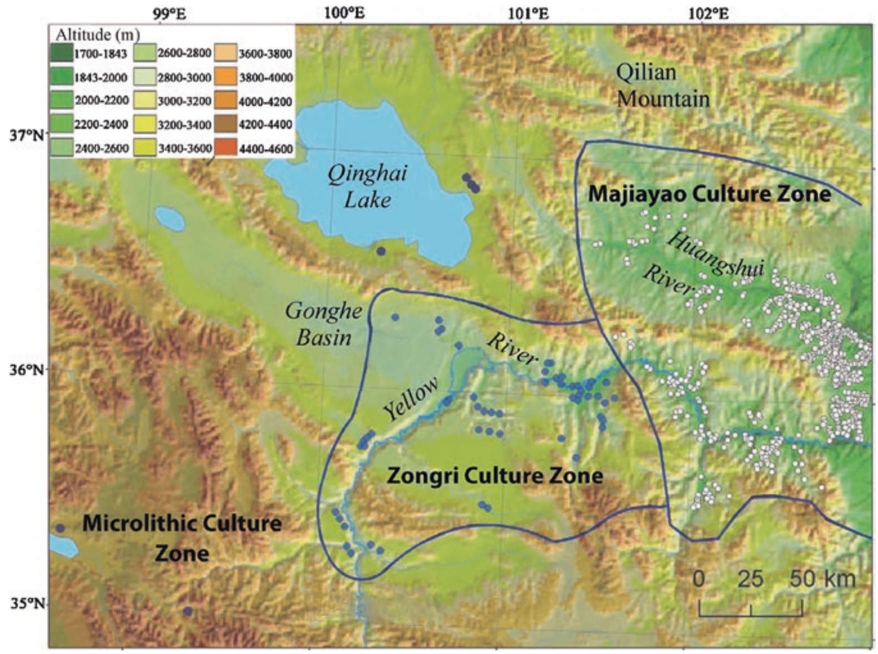

Fig. 12.4 Archaeological sites and the distribution of prehistoric cultures in the north-east of the Qinghai–Tibet Plateau (modified from Chongyi et al. 2013)

cores, scrapers and flakes found in the terraces of Donggeicuona Lake in Maqin County (4106 m) indicate that archaic populations settled in this area according to fluctuations of the lake shorelines (Yi et al. 2011).

Sites associated with the third stage of settlement in the Neolithic and Bronze ages suggest several distinctive cultural zones in the Upper Yellow River (Fig. 12.4; An et al. 2006; Duan 2002; Hou et al. 2010; Lang 1992; Zhang et al. 2010). The Zongri cultural zone encompasses archaeological sites from the Dadiwan culture (7.80–7.35 thousand years ago), while the Yangshao culture dates from 6.8–4.9 thousand years ago, the Majiayao culture from 5.3–4.2 thousand years ago, and the Qijia culture from 4.3–3.9 thousand years ago.

A diverse array of raw materials and technologies has come from an archaeological site atop a terrace of the Kunlun River at Xidatan (4300 m, 9.2–6.4 thousand years ago; Brantingham et al. 2007). Cores, flakes and retouched tools document use of the site by highly mobile foraging groups, who may have engaged in seasonal foraging rounds that carried them onto and off the high-elevation plateau. Raw materials include quartzite, jasper, mudstone, obsidian, vein quartz and metamorphic rocks. The presence of obsidian at site JXG 2 (indicated on Fig. 12.4) suggests stone transport over distances up to 1000 km through the Kunlun Mountain Pass between the middle- and high-elevation steps of the plateau by approximately 8000 years ago (Brantingham et al. 2013). This pass likely served as a major corridor for human population movements onto the high plateau.

Early evidence of agriculture and animal domestication comes from Jiangxigou (3312 m), where microlithic artefacts including blades and bladelets date from 9.3–5 thousand years ago. Microlithic industries are represented by abundant microblades and blade fragments, microblade cores and core fragments, and four crested bladelets. The end-hafted blade points are very similar to those found at the Changtang sites on the high central Qinghai–Tibet Plateau (Brantingham et al. 2001). Many bone and teeth fragments of small- and medium-sized mammals suggest that they may have been processed for grease or marrow extraction. Species include sheep (most likely the bharal or Himalayan blue sheep, *Pseudois nayaur*, but possibly domestic sheep, *Ovis aries*), Tibetan gazelle (*Procapra picticaudata*), and a small deer (Rhode et al. 2007a, b). It is uncertain whether these mammals were domesticated. Chongyi et al. (2013) suggested that relatively high pollen content of Poaceae and its attendant weedy plants from 9–6 thousand years ago might relate to human activities. The proportion of Poaceae reached its highest level between 6.7 and 4.0 thousand years ago—a period associated with multiple pottery shards that are also likely to be associated with farming activities.

An isolated hearth at Heimahe (3202 m, 8.54–8.37 thousand years ago; Rhode et al. 2007a, b) contains highly fractured bone fragments from a medium-sized mammal (possibly a gazelle) likely indicate marrow extraction. Poplar wood charcoal and small, carbonized lumps of composite organic material identified as herbivore dung indicate the use of yak dung as fuel. It is likely that dried herbivore dung was used as a fuel by archaic people during much of the period of occupation of the plateau, even during periods when woody fuel was more plentiful in the area (Brantingham and Xing 2006; Rhode et al. 2007a, b). The hypothesis is consistent with the pollen records analysis from Tibet (Miehe et al. 2009). Indeed, yak dung is still used as fuel over much of the now largely treeless pasture lands on the plateau.

Dadiwan sites at Shaoan village (Qingan County, Gansu Province) contain evidence of rain-fed agricultural cultivation and animal domestication (1500 m; 7.8–7.3 thousand years ago; Zhang et al. 2010). Four stages of human activities in the area have been proposed, reflecting transitions from a primitive hunter-gatherer economy through phases of advanced hunter-gatherer activities and a primitive crop cultivation economy to a mature agricultural economy (Zhang et al. 2010). For example, the first period of Dadiwan culture was characterized by broomcorn, suggesting primary, rain-fed agriculture, whereas the emergence of millet in subsequent periods associated with Yangshao culture is indicative of a later stage of agricultural development (An et al. 2006; Liu et al. 2004).

12.6 Discussion

Both vegetation and human settlements on the Qinghai–Tibet Plateau have evolved against a backdrop of changing climates. The largely treeless landscape around Qinghai Lake today probably results from regional-scale climate changes inducing forest decline, which in turn may have initiated changes in the type and intensity of human activities (Herzschuh et al. 2005). However, the relative roles of climatic and human factors as drivers of changing vegetation patterns remain contentious, with some researchers contending that low population densities could not trigger the extensive vegetation shifts seen across the region (Chen et al. 2013; Herzschuh et al. 2005; Ji et al. 2005; Tang et al. 2009). Clearly, much more research is required to provide additional insights. However, one thing is sure: Humans were not passive, but acted as agents of change to at least some degree. Pastoralists took advantage of the Mid-Holocene climatic optimum to migrate onto higher lands, clearing forests through the use of fire (Miehe et al. 2009; Ren 2000, 2007). Furthermore, the dominant grass species now seen on the plateau are highly adapted to grazing, having evolved over the thousands of years that these pastures have been grazed by domesticated animals (Miehe et al. 2008a, b; Wischnewski et al. 2014). In many ways, the quest to separate human and 'natural' changes is futile—mutual adjustments are inevitable, since we are part of nature.

Our histories fashion who we are, our socio-cultural associations and how we live with this planet. The choices we make indicate the importance we give to concerns for equity, justice and sustainability and the prospects for those who follow. They reflect our choices and rights for self-determination, alongside political, institutional and governance framings that determine how these rights are expressed. Respect for our ancestors must be viewed alongside concerns for the future generations. Inevitably, these issues are played out in very different ways in different areas. Societal interactions are far from static. They reflect interactions among differing cultural groups, values and lifestyles. In an emergent world in which it is increasingly recognized that we live in a 'no-analogue state' where novel ecosystems are inevitable, it remains to be seen how traditional cultures will be sustained into the future. Although traditional ways of living cannot be frozen in time to form a 'museum', historically framed visions offer vital perspectives for scoping potential futures and reflections upon our personal and societal choices (see Brierley et al. 2016c, Chap. 15).

The landscapes and ecosystems of the Upper Yellow River present challenging sets of constraints upon human interactions and prospects for the development. A suite of culturally framed adaptations to these constraints has enabled distinctive and diverse societies to emerge, survive and thrive in this area over many thousands of years. Doubtless future generations will also rise to their challenges, surviving and thriving through harmonious relationships with nature.

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References

An, C. B., Wang, L., Ji, D. X., et al. (2006). Temporal-spatial change of Neolithic culture and its potential driving forces in Ganqing area. *Quaternary Research, 26*, 923–927.

Beall, C. M. (2007). Two routes to functional adaptation: Tibetan and Andean high-altitude natives. *Proceedings of the National Academy of Sciences, 104*(1), 8655–8660.

Brantingham, P. J., Gao, X., Olsen, J. W., et al. (2007). A short chronology for the peopling of the Tibetan Plateau. *Developments in Quaternary Sciences, 9*, 129–150.

Brantingham, P. J., Ma, H., Olsen, J. W., et al. (2003). Speculation on the timing and nature of Late Pleistocene hunter-gatherer colonization of the Tibetan Plateau. *Chinese Science Bulletin, 48*, 1510–1516.

Brantingham, P. J., Olsen, J. W., & Schaller, G. B. (2001). Lithic assemblages from the Chang Tang region, Northern Tibet. *Antiquity, 75*, 319–327.

Brantingham, P. J., & Xing, G. (2006). Peopling of the northern Tibetan Plateau. *World Archaeology, 38*, 387–414.

Brantingham, P. J., Xing, G., Madsen, D. B., et al. (2013). Late occupation of the high-elevation Northern Tibetan Plateau based on cosmogenic, luminescence, and radiocarbon Ages. *Geoarchaeology, 28*, 413–431.

Brierley, G. J., Cullum, C., Li, X. L., et al. (2016a). Conclusion: Environmental futures of the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 353–370).Berlin: Springer.

Brierley, G. J., Li, X., Cullum, C., et al. (2016b). Introduction: Landscape and ecosystem diversity in the Yellow River Source Zone. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 1–34). Berlin: Springer.

Brierley, G. J., Yu, G. A., & Li, Z. W. (2016c). Geomorphic diversity of rivers in the Upper Yellow River Basin. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 59–78). Berlin: Springer.

Chen, H., Zhu, Q., Peng, C., et al. (2013). The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau. *Global Change Biology, 19*, 2940–2955.

Cheng, B., Chen, F., & Zhang, J. (2013). Palaeovegetational and palaeoenvironmental changes since the last deglacial in Gonghe Basin, northeast Tibetan Plateau. *Journal of Geographical Sciences, 23*, 136–146.

Chongyi, E., Hou, G. L., Sun, Y. J., et al. (2013). Human activities and environmental change in Holocene in the northeastern margin of Qinghai-Tibet Plateau: A case study of JXG2 relic site in Qinghai Lake. *Acta Geographica Sinica, 68*, 380–388.

Davison, K., Dolukhanov, P., Sarson, G. R., et al. (2006). The role of waterways in the spread of the Neolithic. *Journal of Archaeological Science, 33*, 641–652.

Deng, W., Shi, B., He, X., et al. (2004). Evolution and migration history of the Chinese population inferred from Chinese Y-chromosome evidence. *Journal of Human Genetics, 49*, 339–348.

Duan, J. (2002). *Gansu and Qinghai Prehistoric Archeology*. Heritage Press.

Duan, K. Q., Yao, T. D., Wang, N. L., et al. (2012). The unstable Holocene climatic change recorded in an ice core from the central Tibetan Plateau. *Scientia Sinica (Terrae), 42*, 1441–1449.

Fan, Q., Ma, H., & Hou, G. (2012). Late Pleistocene lake and glaciation evolution on the northeastern Qinghai-Tibetan Plateau: A review. *Environmental Earth Sciences, 66*, 625–634.

Gao, X., Zhou, Z. Y., & Guan, Y. (2008). Human cultural remains and adaptation strategies in the Tibetan Plateau margin region in the late Pleistocene. *Quaternary Sciences, 28*, 969–977.

Gasse, F., Fontes, J. C., van Campo, E., et al. (1996). Holocene environmental changes in Bangong Co basin (Western Tibet). Part 4: Discussion and conclusions. *Palaeogeography, Palaeoclimatology, Palaeoecology, 120*, 79–92.

Gayden, T., Cadenas, A. M., Regueiro, M., et al. (2007). The Himalayas as a directional barrier to gene flow. *The American Journal of Human Genetics, 80*, 884–894.

Herzschuh, U., Zhang, C., Mischke, S., et al. (2005). A late Quaternary lake record from the Qilian Mountains (NW China): Evolution of the primary production and the water depth reconstructed from macrofossil, pollen, biomarker, and isotope data. *Global and Planetary Change, 46*, 361–379.

Hobbs, R. J., Higgs, E., & Harris, J. A. (2009). Novel ecosystems: Implications for conservation and restoration. *Trends in Ecology & Evolution, 24*, 599–605.

Hou, G. L., Xu, C. J., & Fan, Q. S. (2010). Three expansions of prehistoric humans towards northeast margin of Tibetan Plateau and environmental change. *Acta Geographica Sinica, 65*, 65–71.

Huang, F. (2000). Vegetation and climate between 13 thousand years ago to 5 thousand years ago in Peiku Co, Tibet. *Acta Palaeontologica Sinica, 39*, 441–448.

Huang, C., van Campo, E., & Li, S. (1995). Holocene environmental changes of western and northern Qinghai-Xizang Plateau based on pollen analysis. *Acta Micropalaeontologica Sinica, 13*, 423–432.

Huerta-Sánchez, E., Jin, X., Bianba, Z., et al. (2014). Altitude adaptation in Tibetans caused by introgression of Denisovan-like DNA. *Nature, 512*(7513), 194–197.

Ji, D. X., Chen, F. H., Bettinger, R. L., et al. (2005). Human response to the last glacial maximum: Evidence from North China. *Acta Anthropologica Sinica, 24*, 270–282.

Jing, C. M., & Sun, N. D. (2001). Climatic evolution recorded by Ostracoda in Dabusun Lake in Qaidam basin during the past 30 ka years. *Marine Geology & Quaternary Geology, 21*, 55–58.

Keim, B. (2014). *Tibetans can thank ancient humans for gene that lets them live the high life*. National Geographic. Source: news.nationalgeographic.com/news/2014/07/140702 (viewed: 05.04.2015).

Lang, S. D. (1992). *Gansu prehistory research and development*. Northwest History, 2.

Lee, R.B. (1997). What hunters do for a living, or, how to make out on scarce resources. In: Gowdy, J. (Ed.). *Limited wants, unlimited means: A reader on hunter-gatherer economics and the environment*. Island Press. pp. 43-64.

Li, X. L., Perry, G., & Brierley, G. J. (2016). Grassland ecosystems of the Yellow River Source Zone: Degradation and restoration. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 137–166). Berlin: Springer.

Li, S. J., Chen, W., Jiang, Y. J. et al. (2012) Geological records for Holocene climatic and environmental changes derived from glacial, periglacial and lake sediments on Qinghai-Tibetan Plateau. *Quaternary Science, 32*(1): 151–157.

Liu, C. J., Kong, Z. C., & Lang, S. D. (2004). Plant relics of the crops of different cultural period at Dadiwan site in Qinan, Gansu. *Central Plains Heritage, 4*, 26–30.

Liu, X., Shen, J., Wang, S., et al. (2002). A 16000-year pollen record of Qinghai Lake and its paleoclimate and paleoenvironment. *Chinese Science Bulletin, 47*, 1931–1936.

Liu, K. B., Yao, Z., & Thompson, L. G. (1998). A pollen record of Holocene climatic changes from the Dunde ice cap, Qinghai-Tibetan Plateau. *Geology, 26*, 135–138.

Madsen, D. B., Haizhou, M., Brantingham, P. J., et al. (2006). The late Upper Paleolithic occupation of the northern Tibetan Plateau margin. *Journal of Archaeological Science, 33*, 1433–1444.

McGregor, G. R. (2016). Climate variability and change in the Sanjiangyuan region. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 35–58). Berlin: Springer.

Miehe, G., Kaiser, K., Co, S., et al. (2008a). Geo-ecological transect studies in northeast Tibet (Qinghai, China) reveal human-made mid-Holocene environmental changes in the upper Yellow River catchment changing forest to grassland. *Erdkunde, 2008*, 187–199.

Miehe, G., Miehe, S., Kaiser, K., et al. (2009). How old is pastoralism in Tibet? An ecological approach to the making of a Tibetan landscape. *Palaeogeography, Palaeoclimatology, Palaeoecology, 276*, 130–147.

Miehe, G., Miehe, S., Will, M., et al. (2008b). An inventory of forest relicts in the pastures of Southern Tibet (Xizang AR, China). *Plant Ecology, 194*, 157–177.

Monge, C., & Leon-Velarde, F. (1991). Physiological adaptation to high altitude: Oxygen transport in mammals and birds. *Physiological Reviews, 71*, 1135–1172.

Pengxi, Z., Baozhen, Z., Haijun, Q. G. L., et al. (1994). The study of paleoclimatic parameter of Qinghai Lake since Holocene. *Quaternary Sciences, 3*, 225–238.

Qian, Y., Qian, B., Su, B., et al. (2000). Multiple origins of Tibetan Y chromosomes. *Human Genetics, 106*, 453–454.

Ren, G. (2000). Decline of the mid- to late Holocene forests in China: Climatic change or human impact? *Journal of Quaternary Science, 15*, 273–281.

Ren, G. (2007). Changes in forest cover in China during the Holocene. *Vegetation History and Archaeobotany, 16*, 119–126.

Rhode, D., Haiying, Z., Madsen, D. B., et al. (2007a). Epipaleolithic/early Neolithic settlements at Qinghai Lake, Western China. *Journal of Archaeological Science, 34*, 600–612.

Rhode, D., Madsen, D. B., Brantingham, P. J., et al. (2007b). Yaks, yak dung, and prehistoric human habitation of the Tibetan Plateau. *Developments in Quaternary Sciences, 9*, 205–224.

Shen, C., & Tang, L. (1995). Pollen evidence of changing Holocene monsoon on Qinghai-Xizang Plateau. *Acta Micropalaeontologica Sinica, 13*, 433–436.

Shi, Y. F., & Liu, X. D. (1999). Relationship between strong summer monsoon and Precession cycle in 40–30 ka in Qinghai-Tibetan Plateau. *Chinese Science Bulletin, 44*, 1475–1480.

Shi, Y. F., Zheng, B. X., & Yao, T. D. (1997). Glacier and the environment of Qinghai-Tibet Plateau during the last glaciation maximum. *Journal of Glaciology and Geocryology, 19*, 97–113.

Skoglund, P., & Jakobsson, M. (2011). Archaic human ancestry in East Asia. *Proceedings of the National Academy of Sciences, 108*, 18301–18306.

Sun, X. J., Du, N. Q., Chen, Y. S., et al. (1993). Holocene palynological records in Lake Selinco, northern Xizang. *Acta Botanica Sinica, 35*, 943–950.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) Headwaters. In G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 275–330). Berlin: Springer.

Tang, L. Y., & Shen, C. M. (1996). Holocene pollen records in Qinghai-Tibetan Plateau. *Acta Micropaleontologica Sinica, 13*, 407–422.

Tang, L. Y., Shen, C. M., Kong, Z. C., et al. (1998). Pollen evidence of climate during the last glacial maximum in Eastern Tibetan Plateau. *Journal of Glaciology and Geocryology, 2*, 133–140.

Tang, L. Y., Shen, C. M., Li, C. H., et al. (2009). Pollen-inferred vegetation and environmental changes in the central Tibetan Plateau since 8200 yr BP. *Science in China Series D: Earth Sciences, 52*, 1104–1114.

Tang, L. Y., Shen, C., Liu, K., et al. (2000). Changes in South Asian monsoon: New high-resolution paleoclimatic records from Tibet, China. *Chinese Science Bulletin, 45*, 87–91.

Thompson, L. G., Yao, T., Davis, M. E., et al. (2006). Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau. *Annals of Glaciology, 43*, 61–69.

van Campo, E., & Gasse, F. (1993). Pollen-and diatom-inferred climatic and hydrological changes in Sumxi Co Basin (Western Tibet) since 13,000 yr BP. *Quaternary Research, 39*, 300–313.

Wang, F. B., & Fan, C. Y. (1987). Climatic changes in the Qinghai-Xizang (Tibet) region of China during the Holocene. *Quaternary Research, 28*, 50–60.

Wang, F. B., Yan, G., & Lin, H. (1993). Preliminary study in Ruoergai Plateau peat δ~(13) C. *Chinese Science Bulletin, 38*, 65–67.

Wang, B., Zhang, Y. B., Zhang, F., et al. (2011). On the origin of Tibetans and their genetic basis in adapting high-altitude environments. *PLoS ONE, 6*(2), e17002. doi:10.1371/journal.pone.0017002

Wang, C., Guo, H., Zhang, L. et al. (2015). Assessing phenological change and climatic control of alpine grasslands in the Tibetan Plateau with MODIS time series. *International Journal of Biometeorology, 59*, 11–23.

Wang, Y., Zhao, Z. Z., Qiao, Y. S., et al. (2006). Paleoclimatic and paleoenvironmental evolution since the last glacial epoch as recorded by sporopollen from the Hongyuan peat section on the Zoige Plateau, northern Sichuan, China. *Geological Bulletin of China, 25*, 827–832.

Williams, J. W., & Jackson, S. T. (2007). Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment, 5*, 475–482.

Wischnewski, J., Herzschuh, U., Rühland, K. M., et al. (2014). Recent ecological responses to climate variability and human impacts in the Nianbaoyeze Mountains (eastern Tibetan Plateau) inferred from pollen, diatom and tree-ring data. *Journal of Paleolimnology, 51*, 287–302.

Wohl, E. (2013). Wilderness is dead: Whither critical zone studies and geomorphology in the Anthropocene? *Anthropocene, 2*, 4–15.

Wu, Z. Y. (1980). *Vegetation of China* (pp. 1023–1035). Beijing: Science Press.

Wu, Y. H., Li, S. J., & Wang, S. M. (2007). Lake sediment geochemical records indicate Holocene climate change in central Qinghai-Tibetan Plateau. *Science China Press (D), 37*, 1185–1191.

Yang, B., Bräuning, A., Liu, J., et al. (2009). Temperature changes on the Tibetan Plateau during the past 600 years inferred from ice cores and tree rings. *Global and Planetary Change, 69*, 71–78.

Yao, T. D. (1999). Abrupt climate change of Qinghai-Tibet Plateau in the last glaciation, comparative study of Guliya ice core and Greenland GRIP ice core. *Science China Press (D), 29*, 175–184.

Yao, T. D. (2000). Oxygen isotope stratigraphy of the Guliya ice core. *Quaternary Research, 20*, 165–170.

Yao, T. D., Yang, M. X., & Kang, X. C. (2001). Comparative study of the climate changes in the past 2000 years by using ice core and tree ring records. *Quaternary Sciences, 21*, 514–519.

Yi, M. J., Gao, X., Zhang, X. L., et al. (2011). Qinghai-Tibetan Plateau marginal areas prehistoric sites in 2009 Excavation Survey Report. *Acta Anthropologica Sinica, 2*, 124–136.

Zhang, X. S. (1978). Vegetation of the Tibetan plateau. *Bulletin of Botany, 20*, 140–149.

Zhang, S. S. (1990). Paleolithic industry regional progressive and cultural communication in northern China. *Acta Anthropologica Sinica, 9*, 322–333.

Zhang, D. J., Chen, F. H., & Bettinger, R. L. (2010). The archaeological record and origins of rainfed agriculture since 60 kaBP in Dadiwan relics, Gansu. *Science China Press, 55*, 887–894.

Zhang, L., Guo, H., Wang, C., et al. (2014). The long-term trends (1982–2006) in vegetation greenness of the alpine ecosystem in the Qinghai-Tibetan Plateau. *Environmental Earth Sciences, 72*, 1827–1841.

Zhang, Y. F., & Zhang, J. P. (1995). Holocene paleoclimate evolution of the Yellow River source region of Earth Science. *China University of Geosciences, 20*, 445–449.

Zhao, D., Wu, S., Yin, Y., et al. (2011a). Vegetation distribution on Tibetan Plateau under climate change scenario. *Regional Environmental Change, 11*, 905–915.

Zhao, Y., Yu, Z., & Zhao, W. (2011b). Holocene vegetation and climate histories in the eastern Tibetan Plateau: controls by insolation-driven temperature or monsoon-derived precipitation changes? *Quaternary Science Reviews, 30*, 1173–1184.

Zheng, J. P., Yuan, H. R., Zhao, X. T., et al. (2006). Quaternary great lake period and paleoclimate in Qinghai-Tibetan Plateau. *Acta Geologica Sinica, 79*, 169–180.

Zhou, D. J., Horse, H. Z., & Tan, H. B. (2003). Human activity and the northern part of Qinghai lake evolution since the late Pleistocene. *Salt Lake Research, 11*, 8–13.

Zhu, Y. Z., Bell, J. H., & Lee, W. S. (1994). *New tectonic movement and evolution of salt lake in Qaidam basin*. Geology Press.

Chapter 13
Ecogenesis of the Huang He Headwaters

Haikai Tane, Xilai Li and Gang Chen

Abstract The Huang He headwaters (33–36°N) occupy stepped suites of intermontane basins between 3000 and 6000 m asl separated by rugged gorges, hills and high mountains. Located in Qinghai's Sanjiangyuan region, the headwater's heterogeneous climate ecotypes reflect diverse habitat-meteorological relationships, producing boreal and temperate forests, subalpine shrublands, heathlands and meadows, alpine meadows and nival screefields. This chapter applies transdisciplinary research methods and complex open system geoscientific methods to assess the polygenetic origins and adaptive evolution of ecosystems in the headwaters region. Reconnaissance surveys included benchmark audits of rangeland valleys, undertaken over five years in all seasons. Appraisals of ecological dynamics and adaptive coevolution of rangeland ecosystems over Palaeolithic–Mesolithic–Neolithic times demonstrate how widespread deforestation and drainage of wetlands for pastoral grazing induced the emergence of "golf course" grasslands. Unintended consequences arising from traditional pastoral cultures included widespread soil erosion, subsequently leading to severe salinity and flash flooding, and ending in extreme pastoral desertification. The long-term ecological and socio-economic consequences of these watershed calamities on downstream communities are succinctly acknowledged by the renowned epithet for the Huang He as *China's Sorrow*. As access to safe drinking water declines, and casualties mount

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from watershed dysfunctions, remedying ecological degradation of the headwaters region is an urgent priority for China. The challenges are not insurmountable, but the choices are few. While engineering and conservation measures may alleviate some symptoms, restoring ecological functionality of the Huang He watershed and its essential life support systems requires ecological strategies for reviving watershed systems, while providing sustainable alternatives to pastoral grazing.

Keywords Watershed ecology · Cultural ecography · Resource economics · Grazing impacts · Rangeland salinity · Pastoral desertification

13.1 Introduction

Human-induced desertification is more often than not paramount in countries reliant on pastoral agricultures, aggravating climate change beyond normal levels (UNEP 2010). United Nations agencies have identified desertification as a key driver of global conflict and instability, food and water insecurity and entrenched poverty. UN Secretary-General Ban Ki Moon (2011, 2014) has called for urgent action to support communities in crisis. In his address to the United Nations Convention to Combat Desertification in Buenos Aires, Argentina, on 28 September 2009, he commented "*Desertification and land degradation destabilize societies, entrench poverty and exacerbate climate change*".

This chapter outlines a range of ecological indicators revealing a history of incremental human impacts throughout the Qinghai–Tibet rangelands, leading to soil desiccation, watershed salinity and pastoral desertification. It outlines methods for auditing watersheds for compliance with United Nations Agenda 21 (UN A21): the internationally agreed principles for integrating sustainable development and environmental protection. Our conclusions contain recommendations for adapting to climate change, reversing desertification and reviving sick streams, rivers and lakes. We note that experience in China and elsewhere shows that reversing processes of ecological degradation requires engaging communities in participatory watershed programmes for sustainable development of watershed ecosystems.

The study is conducted from the transdisciplinary perspectives of watershed ecography, cultural ecology and resource economics. Our prognoses and interpretations are based on extensive field surveys conducted from 2010 to 2014. Our research reveals how ecogenesis of watershed habitats and their communities in the Huang He (Yellow River) headwaters region has involved a raft of atmospheric, terrestrial and ecological processes that are continuously interacting and adapting in space and time. In these dynamic circumstances, the origins and evolution of watershed habitats and their communities are profoundly polygenetic. When conditions and time permitted, co-evolution entailed complex processes of adaptive ecosynthesis. More often, however, these processes were so badly disrupted by human activities that whole ecosystems have degraded and collapsed in a calamity of erosion, salinity and pastoral desertification.

This chapter begins with the premise that rangeland watersheds are complex open systems uniting dynamic living communities in ways that are inherently unpredictable. Because everything in a watershed is connected functionally by living communities through energetic processes, ecological food chains and complex spatial relationships, closed system methods are scientifically invalid as a platform to study rangeland watersheds. Complex open system geosciences are required to (a) understand the ecogenesis of dynamic living communities, (b) diagnose the ecological status of habitats, communities and ecosystems and (c) provide strategies and solutions for restoring the Huang He headwaters region.

13.2 Concerns for the Health of the Upper Yellow River and Its Rangelands

The Qinghai–Tibet rangelands are high-altitude regions traversed by the tallest mountain ranges on the planet and dissected by some of the largest rivers. Because these mountain rangelands are the birth place of Asia's most important river systems, they are known as the *Reservoir of Asia.* Though geographic extremes are characteristic features, these are not isolated or remote regions, for the Qinghai–Tibet rangelands are the crossroads of Asia with a cultural heritage of human occupation extending back to the last Ice Age.

The Huang He is known as the *Mother River of China* ~ reflecting its geographic location and cultural importance in the northern heartland of Chinese culture. With a history of repeated episodic floods, the Huang He has become better known by another epithet ~ *China's Sorrow*. There is a tragic irony underlying the dual epithets, one that demands attention from communities living along and depending on the River. For the Huang He is not happy nor healthy: China's Mother River is no longer capable of serving key ecological or hydrological functions required of living rivers. Even in her remote headwaters regions, essential life support systems are succumbing to human-induced salinity and pastoral desertification. The warning signs are widespread. Unless unsustainable land use activities are curtailed, she could die.

To explore how this situation arose and to better understand human cultural impacts, in our chapter we investigate the origins and evolution of watershed habitats and ecosystems in the Huang He headwaters (Fig. 13.1). The focus is on how habitats and ecosystems have adapted to and evolved with human activities since people settled the region during the last Ice Age. Our chapter is presented in three parts from the combined perspectives of (a) watershed ecography, (b) cultural ecology and (c) resource economics. For the most part, our chapter summarises rangeland research revealing how Tibetan, Mongolian and Islamic pastoral cultures inhabiting the headwaters region have transformed their mountain rangelands and disrupted watershed ecosystems in critical ways that aggravated droughts and floods, and induced pastoral desertification.

Fig. 13.1 The Huang He headwaters region lies mainly between 3000 and 5000 m asl. The region has an altitude range from over 6000 m (Maqen Kangri 6282 m) to below 3000 m (Longyangxia Reservoir lies at an elevation of 2600 m asl). The heterogeneity of the region's terrain includes deep river gorges, high rugged mountains, close knit hills and valleys and wide open intermontane basins. Given the region's long history of human occupation, the cultural landscapes of the region are comprised on polygenetic habitats and communities reflecting many millennia of human impacts shown on the satellite image (*left*), the headwaters region has lost so much of its forest and woodland communities that it is commonly described as a region of natural grasslands. The region is highlighted on the physiographic map (*right*)

13.3 Approach and Methods

> The critical thing to remember about watershed systems is that the rivers, the hill-slopes, the mountain-tops, and the flood formed bottom-lands, are really all part of one watershed system.
>
> All are integrated with each other (Curry 1976).

The approach, methods and perspectives of complex open system geosciences are integrative, synthetic and geospatial. While intractable mathematics can represent energy flows and chaotic behaviour, the geospatial approach is more widely comprehended. This entails gradually piecing together watershed habitats and their communities with their meteorological energies. It integrates the cultural heritage and histories of human activities and assesses their cumulative resource impacts and interrelationships. Through this, a comprehensive, unified assessment is possible, revealing the underlying ecographic patterns and ecological processes that drive dynamic ecogenesis.

Complex open systems scientific methods were introduced to the West by the transdisciplinary team which developed the Atom Bomb in the mid-1940s. The methods were later developed for more peaceful purposes by Russian Nobel Prize winner Ilya Progogine, his German contemporary Ferdinand von Bertalanffy, and subsequently by North American resource ecologists Clive Holling and Carl Walters (Tane 2009). These principles contrast starkly with the analytical and statistical methods and perspectives of closed system sciences applied by Newton, Darwin and eighteenth-to-nineteenth-century physical sciences, where time is assumed to be fixed and constant in order to allow linear cause-and-effect logical analysis. Closed system assumptions are strictly invalid when studying complex open systems with dynamic living communities such as watershed ecosystems. Alpha-numeric closed system sciences are unable to reveal the complex spatial relationships, feedback links and resilience thresholds that impact upon habitat conditions and the collapse of ecosystems.

In healthy functional ecosystems, suites of habitats are characterised by synergistic ecostructures. Elsewhere, when human activities and their impacts diminish vegetation cover and degrade soils, they disrupt ecological processes and the heat/water balance of watersheds. Spatial discontinuities, time lags and energy fluxes impact upon their dynamic behaviour. By allowing solar radiation at ground level to reach critical levels, sunburn, soil erosion and salinity inevitably lead to human-induced desertification (Tane et al. 2014).

To help clarify our scientific perspective, the literature review of the Qinghai–Tibet Plateau by Harris (2010) is considered to reflect an Anglo-American perspective of pastoral rangelands that applies closed system scientific thinking. While Harris provides a useful critique of pastoral rangeland research, we consider his review to be flawed by mistaken assumptions and significant omissions, thereby generating unreliable and misleading conclusions.

Transdisciplinary geosciences are gradually revealing how the complex processes of ecogenesis in the Huang He headwaters region have been driven mainly by anthropocentric processes. Since Harris published his critical review, widespread desertification in the Qinghai–Tibet rangelands has been referred to as a global calamity by Tibetan religious leaders and UN agencies. The desertification dilemma is no longer doubted, though the reasons for its occurrence continue to be debated.

For clarity, an overview of open system scientific methods applied in this study is outlined below. A summary of the steps entailed in such analyses is presented in Table 13.1 to distinguish the methodology employed from the closed system science approach of Harris (2010) and others seeking scientific explanations in terms of linear causality.

13.3.1 Scientific Methodology

The scientific methodology used in this study was developed over 30 years (1973–2003) in transdisciplinary studies of rangeland watersheds in North America, Australia, New Zealand, India and China. Referred to as *Eco*^{3} *Sustainability Audits* (Tane 2009; Tane et al. 2014), this method is employed for assessing watersheds for compliance with international law for sustainable development and environmental protection (UN Agenda 21). *Eco*^{3} *Sustainability Audits* integrate watershed ecography, cultural ecology and resource economics in strategic steps and sequences that feed back on each other. The sequence of steps cannot be altered or reversed without compromising scientific validity (Tane and Nanninga 1992, 1995).

Table 13.1 Heuristic modelling of rangeland ecosystems

Stage 1
1. An open invitation to conduct field-based open systems research from a host agency was necessary to provide a suitable foundation for managing the research programme and undertaking the field studies. In this case, Qinghai University research leaders invited the lead author to conduct a reconnaissance watershed audit of the Huang He headwaters.
2. The next step involved extensive reconnaissance surveys and field studies over five years encompassing all four seasons. This involved traversing the headwaters region repeatedly to observe, read and record the cultural ecography, watershed ecology and resource economies of the region (Fig. 13.2). The transdisciplinary method employed was empirical, practical and applied. An overview of the rangeland geography, cultural ecography and watershed ecology was compiled from field surveys before undertaking any desktop studies.
3. The third step was comparative research of the geographic, ecological and meteorological conditions to construct a suite of geospatial models representing potential watershed ecosystems. Visits to village communities, sacred sites and religious temples were important in establishing the cultural framework for setting the cultural ecography parameters. A visit to Kumbum Lamasery near Xining provided a very useful introduction to cultural parameters. Repeated visits to archaeological archives and museums were important. Attending cultural celebrations like public festivals and traditional Tibetan family weddings was also rewarding for developing the ecographic framework.
Stage 2
4. Desktop research reviewing the literature and scoping research followed after the first stage was completed.
5. To reconcile assumptions and conflicting scientific opinions, the second-stage field work incorporated mountain traverses, valley transects and specific site inspections to produce topographic catenas of habitats and their communities, to generate analogue models of watershed ecosystems and to establish benchmarks for ongoing monitoring purposes.
6. The sixth step was to formulate specific topics for presentation and reporting, making preliminary presentations to colleagues and postgraduate students; and preparing short essays on specific themes.
Stage 3
7. Addressing challenges, disagreements and disputes. This required additional desk top research on topics that remained equivocal.
8. Clarifying and resolving the situation empirically was the business end of the project. Further field work was required to address and resolve several issues.
9. Preparing the field report and manuscript with references. This was supported by a three-way review by professional peers, academic referees and community representatives.

Note The three steps were repeated several times before resolving issues with the highest uncertainties. Readers will note that the progression of stages reverses the order normally used by closed system scientists, who generally begin with a hypothesis, complete desk top research; and engage in statistical sampling to test their hypothesis. Field work is usually undertaken after the hypothesis is formulated and desktop research completed. While this approach is suitable for analysing closed systems like machines, linear cause-and-effect analyses are scientifically invalid methods when studying complex open systems incorporating dynamic living communities

The scientific methodology involved transdisciplinary teams engaging in repeated field surveys using skills and technologies developed for complex open system geosciences. For best results, superior field-based skills are required in surveying and mapping habitat/regolith relationships, followed by the application of geospatial technologies to model ecosystems and their meteorological processes.

The approach follows international land evaluation methodologies developed by UNESCO from the 1960 to 1990s for international watershed programmes (Holling 1978; Tane 2009) and refined for China's situation in audits of Lake Poyang (Tane and Yu 2002) and reforested watersheds on the Loess Plateau (Tane et al. 2014).

To avoid scientific bias and prejudicial perceptions, academic hypotheses and theories (along with existing alpha-numeric knowledge) are sidelined until after primary field work is completed. This enables a clear, open mind capable of strategically observing and assessing watersheds ecographically, ecologically and economically. Contemplative observation and recording (Wilhelm 1962; Watts 1972) is followed by heuristic, learning-by-doing experiments to observe, see and read terrains without mental filters or preconceptions (Walters and Holling 1990).

13.3.2 Geographic Scales for Studying Watershed Ecosystems

The lack of accurate, up-to-date true image mapping made it necessary to undertake extensive field investigations (9 field trips over 5 years) to collect sufficient information to complete this review. Figure 13.2 shows the routes taken. Transects and traverses were carried out at strategic locations and repeated several times at key sites.

Satellite imagery was helpful in gaining a geographic overview. However, the available satellite imagery lacked the scale, accuracy and image resolution necessary to identify and map habitats reliably. Scale issues are critical when mapping habitats and classifying landforms and terrains in mountain rangelands and river floodplains (Tane and Nanninga 1992, 1995).

Continental scale mapping (>1:1,000,000) gives the impression the headwaters region is part of an extensive high country plateau with low relief. Although continental scale studies (>1:500,000–1:1,000,000) provide broad impressions, they cannot capture or represent watershed communities or their habitats reliably. For a century or more, the Sanjiangyuan region combining the headwaters of the Huang He, Yangtze and Mekong rivers has been described as part of the Qinghai–Tibet Plateau. This assessment is induced by using inappropriate cartographic scale maps. At geographic scales used for landform studies (1:100,000–1:250,000), the impression of plateau landforms disappears and diverse suites of mountain rangeland, river valley and intermontane basin landforms are revealed.

Nor is it possible to extrapolate reliably by sampling local sites. Microstudies (<1:1000) reveal details of local idiosyncrasies. However, because rangeland watersheds are dynamic open systems with highly variable meteorological conditions and spatial heterogeneity, results from microstudies cannot be extrapolated to larger geographic areas such as river floodplains, mountain watersheds or rangeland regions. The complex meteorological conditions, diverse geomorphologies and heterogeneity of habitats and ecosystems make such predictions unreliable.

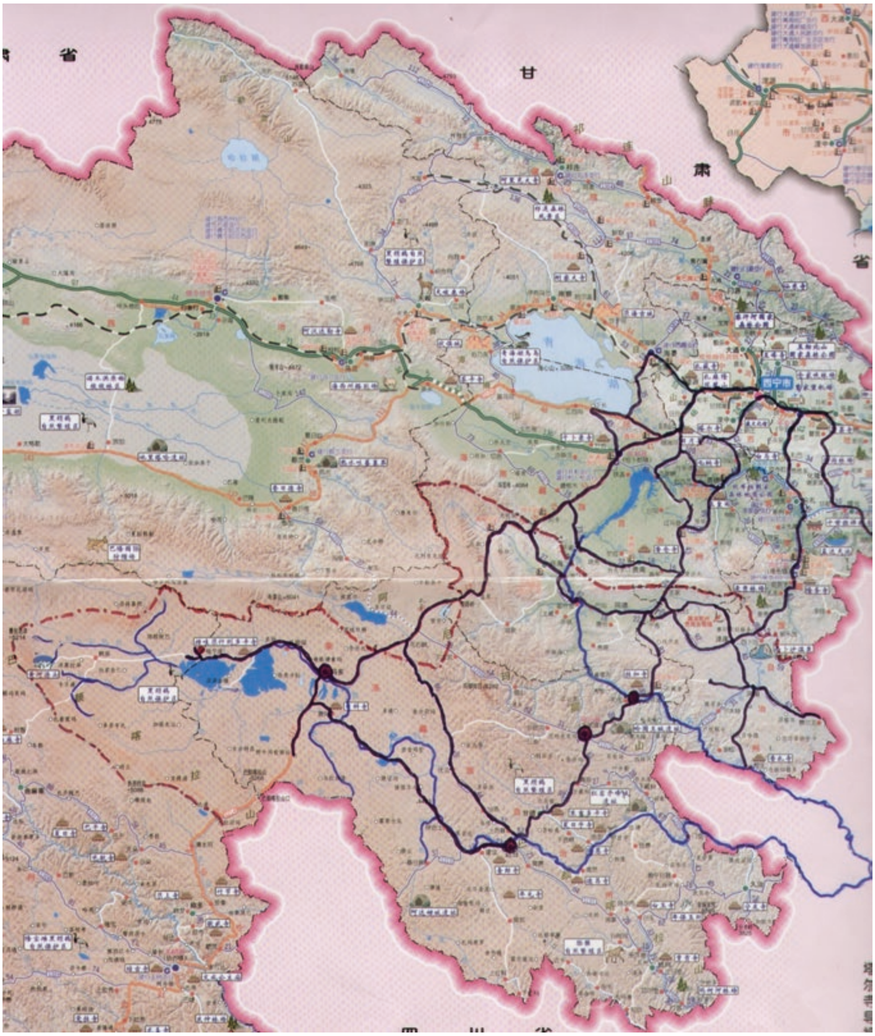


Fig. 13.2 Field work routes and site locations. Extensive field surveys and site observations undertaken with an open contemplative mind, and conducted over several years through all four seasons, were required

Field studies of watershed habitats and ecosystems are typically carried out at cartographic map scales from 1:5,000 to 1:20,000 in order to achieve final mapping scales from 1:25,000 to 1:100,000. At 1:100,000 scales or greater, the minimum map unit (>10 ha) does not allow for accurate or reliable mapping of critical riparian ecotones and the edge habitats that play such an important part in watershed ecosystems. Often just a few metres wide, riparian ecotones and their terraqueous ecostructures play crucial roles in the overall performance of watershed ecosystems (Naiman and Descamps 1990; Tane 2009; Tane et al. 2014; Tane and Williams 1999).

13.4 Part 1: Watershed Ecography

Asia's *Rangeland Reservoirs* include the headwaters of the Huang He, Yangtze, Mekong, Salween, Irrawaddy, Brahmaputra, Ganges and Indus rivers. These rangeland watersheds sustain hundreds of millions of people from diverse ethnicities. Political boundaries that separate the region into several countries result in fragmented governance of critical watershed systems.

The north-eastern sector is the Sanjiangyuan region in Qinghai Province. It contains the headwaters of the Huang He, Yangtze and Mekong rivers. To understand how Tibetans (and much later the Mongolians and Muslims) with their domestic herds of hardy ungulates impacted on the Huang He headwaters requires understanding the origins and evolutions of watershed habitats and ecosystems. We begin by examining the watershed ecography (Bardon 1991; Sveiby and Skuthorpe 2006; Tane 2009; Tane and Nanninga 1992) and ecographic relationships with ecological energetics and microclimate ecotypes in the headwaters region.

13.4.1 Watershed Ecography of the Headwaters Region

The headwaters of the Huang He lie in central Asia between 33 and 36°N where solar radiation levels are very high, well above minimum levels for cultivating crops. Elevated to 3000–6000 m asl, the climate and conditions of the headwaters region are much cooler and more challenging than their lowland-latitude equivalents. In these high-mountain districts, ecosystems forged by cultural activities and human impacts over millennia may seem improbable. However, a raft of evidence is revealing Mesolithic pastoral nomads settled the region during post-glacial warming from as early as 10,000 years ago onwards (Kaiser et al. 2007; Aldenderfer et al. 2011; Miehe et al. 2014; Han et al. 2016, Chap. 12). By 8800 years BP when warmer conditions made the climate even more suitable for human settlement, substantial tracts of cool temperate woodlands and forests growing on warmer hillslopes and in mountain thermal belts were being cleared by Tibetan settlers (Miehe et al. 2008, 2009, 2014).

While such high-altitude habitats may appear only marginally suitable for human occupation, Tibetan settlements were consolidated by cultivating barley and domesticating yak, among other hard-hoofed animals (horses, ponies, sheep and goats). The yak is arguably the toughest, most versatile grazing ungulate globally. Yak can graze at elevations above 5000 m asl, well into alpine zones. They are good swimmers capable of crossing rapids, icy rivers and lakes. They also have the climbing agility of mountain goats. The yak is the totemic animal of Tibetan culture. Together with barley, they form their basic resource economy (Fig. 13.3).

The rangelands of the Huang He headwaters descend towards the east and north in stepped suites of open intermontane basins separated by steep mountain ranges, dissected by stream valleys and river gorges (Weiner et al. 2003/06, refer Brierley

Fig. 13.3 Grazing livestock combined with growing barley are the economic base of Tibetan farming systems

et al. 2016b, Chap. 3). Emerging from discharge springs and small streams on the footslopes of Yagradadze Mountain (5214 m asl) and Bayan Har Mountains (5266 m asl), their spring-fed streams unite to form a multitude of ponds and streams in the open-basin terrains between the ranges. By the time they reach Zhaling Lake, the streams have grown into a small river forging a curvilinear network of anabranches and distributary swales within an episodic floodplain reflecting glacial outwash origins.

After passing through two large sediment retention basins occupied by Zhaling and Eling lakes (4200 m asl), the course of the river is diverted southwards by a mountain block downstream of Maduo (Golog Zangzuzie Hizou). The river then travels in an easterly direction parallel to the Anyémaqén Range, exiting into Sichuan and Gansu provinces, before the river cuts through the ranges and heads back north into Qinghai to enter Longyangxia Reservoir. In its wandering course, the Huang He displays wide-ranging geomorphologies reflecting diverse geology and hydrography.

13.4.2 *Rangeland Meteorology and Microclimatic Considerations*

Meteorological processes prevailing on the Qinghai–Tibet rangelands influence weather conditions across much of Asia (Zou et al. 2014). Solar radiation and summer heating of the Qinghai–Tibet rangelands generate high-pressure systems that draw in warm moist air flows from the Indian Ocean (Weiner et al. 2003/06, refer McGregor 2016, Chap. 2). The reliability of the monsoon rains ensures food security for much of Asia. It comes at a huge cost including episodic and periodic floods. Unsurprisingly, climatic conditions and their underlying meteorological processes have played a major role in the ecogenesis of Qinghai–Tibet's mountain rangelands (Ruijun 2006). Major drivers of regional climatic conditions, meteorological processes and climatic conditions also affect local microclimates.

Each summer warm moist air masses flowing in from the Indian Ocean are pushed high into colder atmospheric realms by central Asia's mountain rangelands, generating orographic rainfall measured in metres. Located on the lee side of parallel mountain ranges, the Huang He headwaters occupy rain shadow areas receiving residual rains from the monsoons, sometimes as little as 300–400 mm per year. Annual rainfall is quite variable; indeed, average rainfall is an unreliable ecological indicator of moisture availability and ecosystem potential in most mountain rangelands.

Another feature of the monsoons has far-reaching implications. Warm moist air taken up from the Indian Ocean also contains small amounts of sea salt. In wetter Asian climates, dissolved sea salts falling with rain are progressively diluted and leached out, without creating a serious problem. However, in low-rainfall districts like the Huang He headwaters, the situation is very different. Dissolved salts leach through the soils, accumulating in senescent clay layers. Salts are safely stored so long as they are retained within these clay layers. In drier intermontane climates subjected to soil erosion and pastoral desertification, however, huge loads of salts may be released as soils are eroded, exposing subsoil layers that become desiccated and dry out. Leaching of salts creates salinity hazards. With advancing pastoral desertification, tonnes of salt are flushed out of the cracked and desiccated clays, making soils and water supplies salty and unsuited for human consumption and most farming purposes. Severe dryland and stream salinity may ensue (Tane 1996; Tane and Andrews 1998).

At local scales, co-evolving mosaics of microclimates are so complex and divergent that normal climate measures like average rainfall and temperatures become unreliable indicators of habitat conditions or ecosystem potential. Making the situation even more complex and uncertain, human-induced changes to the heat/water balance at local and regional scales mean that each watershed habitat has unique microclimate attributes.

As a rule of thumb, watershed ecologists mapping habitats and their vegetation communities in mountain rangelands consider plants to obtain one-third of their moisture requirements from measurable precipitation, one-third from the direct assimilation of dew, fog, mists and low clouds, and another third from near-surface aquifers that continually wet soils. In any particular location, the actual proportions may vary considerably.

Highly heterogeneous rangelands, with variable slope and aspect conditions, experience equally variable solar energy inputs and wind exposure rankings for each and every habitat. When combined with dynamic atmospheric heat/water processes, it quickly becomes apparent that mountain rangelands and their intermontane basins have high levels of meteorological heterogeneity and uncertainty (Zou et al. 2014). This condition effectively diminishes the usefulness and reliability of normal climate indicators such as average rainfall and median temperatures.

Similar difficulties are faced in classifying soil conditions or assessing vegetation communities. As a result of variable meteorological and topographic conditions, habitats and their microclimate conditions may change within metres. In detailed studies of watershed ecosystems, statistical quadrant or transect sampling can miss critical riparian soil ecosystems completely (Tane and Williams 1999). In the headwaters region, geographic heterogeneity is so diverse and the meteorological energetics so complex that grouping large areas into a single climate, soil or vegetation category is very misleading. Terrain types, meteorological processes and climatic conditions in high country rangelands are so spatially variable that it is necessary to investigate microclimate ecotypes at the habitat scale to achieve acceptable levels of accuracy and reliability. Comprehensive mapping and modelling of habitats and ecosystems are required to gain a reliable assessment of microclimate conditions.

Generally speaking, several interacting terrain influences affect meteorological processes in mountain rangelands:

(a) *Altitude and exposure* at higher elevations found in the Huang He headwaters (>4000 m asl) have incoming levels of solar radiation that are more than twice that of lowland terrains at the same latitude (Ruijun 2006). This has serious consequences where vegetation cover is short or absent. Sunburnt soils become a serious problem as soil organic matter is oxidised and volatilised, leaving desiccated and mineralised skeletal soils. At the same time, readings are lower for atmospheric pressure, air density, oxygen content and atmospheric moisture (Ruijun 2006).
(b) *Solar aspect and slope* affect local climates by increasing/decreasing solar energy m^{-2} $year^{-1}$. In the valley bottoms above 3500 m and on exposed ridges and meadows above 4500 m subalpine, severe cold air exposure and frost hollows are typical conditions. On mountain mid-slopes with sunny aspects, more temperate conditions are found in well-sheltered sites creating solar belts and thermal basins. This produces a vertical mosaic of highly diverse habitats with widely varying microclimates.
(c) *Water stored in aquifers/biomass and atmospheric humidity* is intricately linked to microclimate conditions in dynamic ways that vary daily. Water stored in biomass and atmospheric humidity are important regulators of heat/water cycle dynamics underpinning local and regional climates (Kravcik et al. 2007). Wetlands, forests and woodlands can absorb large amounts of solar heat energy without heating the ground surface, by converting the incoming solar energy to latent heat of evapotranspiration. This process moderates temperature extremes in habitats with substantial water storage and taller vegetation biomass. By comparison, shorter terrestrial grassland communities do not perform well in this respect. Lacking the buffering effects of large amounts of water stored in their biomass, the ground heats and cools more rapidly. Unable to maintain sufficient moisture to assimilate incoming solar energy, grassland habitats heat up quickly during sunny days and lose their warmth more rapidly during the night, resulting in higher frequencies of radiant frosts, temperature extremes and soil permafrost conditions. Significant spatial and temporal differences in microclimate, vegetation and ecosystem attributes are typical of habitats in the Huang He headwaters.

13.4.3 Microclimate Ecotypes

Microclimate ecotypes commonly occurring in the headwaters region trend from temperate forests, woodlands and shrublands (up to and over 4000 m asl) through subalpine frost hollow and exposed ridge ecotones, to alpine and nival zones of permanent rock and ice. In the upper reaches, forest and woodland ecotypes are restricted to habitats and hillslopes with good solar access, moderate shelter and good cold air drainage. Frost hollows with subsoil ice are common in valley floors above 3500 m where they are (a) constrained climatically by severe cold air drainage, (b) greatly diminished biomass and (c) depleted water storage in near-surface aquifers. These factors result in more frequent and widespread freezing soil conditions.

Extensive tracts of temperate zones in the Huang He headwaters are ecologically capable of sustaining self-regenerating shrublands, woodlands and forests. Above the cold valley floors, on hills and mountain slopes with sunny aspects, thermal belts and solar basins receive enhanced levels of solar energy which moderate temperatures. Solar energy is stored in the terrain during warm, sunny periods and released during colder periods, greatly reducing the constraints and impacts of colder weather on soil and vegetation communities. Field surveys revealed the tree line extends up to 4400 m asl on sunny hillslopes at 35° N. On colder southern hillslopes, the tree line may be as low as 4000 m asl. Forest, woodland and shrubland ecotypes are still partially visible in many headwaters districts; from remnant trees and forests, as well as ecological indicators, including pioneering shrubs, fungal soils and wood charcoal in buried soils (Miehe et al. 2007; Opgenoorth et al. 2010).

13.4.4 Vegetation Communities and Tree Zones

In the Huang He headwaters, true alpine zones are restricted to the high mountain rangelands above 4500 m, giving way to subalpine meadows and rocky talus and screes with shrub communities. The only nival zones in the headwaters region are restricted to the mountaintops of Maqen Kandri and other peaks over 5500 m. As very few glaciers feed into the Huang He, glacier discharges are rather insignificant (refer Huang et al. 2016, Chap. 4).

Below the alpine zones, the ecological "tree line" forms an ecotone that is more than 100 m wide in most places. Subalpine ecotones separating forest and woodland communities from alpine areas were found between the upper woodland belt (4400 and 5000 m asl) with the elevation for the highest shrubland sites, depending on slope and aspect, solar access and wind exposure. Sheltered hillslopes with sunny aspect supported subalpine ecotone communities up to 5500 m asl.

From field evidence, a general model of climatic climax vegetation communities for the Huang He headwaters was developed. It is consistent with the generalised model of rangeland tree belts published by Miehe et al. (2007). Field surveys revealed an intricate tapestry of microclimate ecotypes generated by highly variable rangeland terrain types each with different altitude, slope, aspect and exposure conditions. A generalised model of the microclimate ecotypes and their ecological vegetation communities for the headwaters regions is shown in Fig. 13.4.

The geographic distribution of “climatic climax” or “potential ecosystem” grassland communities are now difficult to demark on the Qinghai–Tibet rangelands, as a result of widespread habitat degradation and transformation of vegetation communities resulting from many millennia of pastoral grazing (Miehe et al. 2014). Once again it is necessary to turn to ecological indicators.

Natural grassland communities co-evolve with soils containing nitrogen fixing rhizobial bacteria on which they rely for the uptake of nutrients. Communities dominated by rhizobial bacteria are most common in terraqueous habitats: the scientific ecological description for “wetlands”. In terraqueous habitats, the decomposition of accumulating organic matter is primarily a bacterial process. Bacterial soil types typically develop in wetlands, such as bog-flush meadows and seepage swales, where terraqueous conditions inhibit fungal communities.

Wetland terrains were once much more widespread on the Qinghai–Tibet rangelands (Gao et al. 2013). Before succumbing to the cumulative impacts of hard-hoofed grazing animals, which destroy critical cryptogam bioseals regulating the release of aquifer springs and groundwater mounds, most grassland meadows were terraqueous not terrestrial habitats. The widespread occurrence of relict black soils rich in organic materials, so commonplace on terraqueous footslopes and river floodplains is an ecological indicator of prior terraqueous habitats in which bacteria dominated plant-soil nutrient cycles.

By comparison, the nutrient cycles of woody plant communities such as shrubs, trees and forests depend on soils dominated by fungal mycorrhiza. The widespread occurrence of fungal soils occupying terrestrial habitats in the Huang He headwaters region points to an ecological heritage of woody plant communities. Because the prevalence of fungal habitats is usually considered detrimental to the health of grazing livestock, in the Qinghai–Tibet rangelands woody weeds and fungal soils are ranked among the main “pastoral problems”. From an ecological perspective, fungi and their mycorrhizal communities are ecological indicators of prior shrublands, woodlands and forests.

In valley depressions kept free of grazing livestock, terrains are more inclined to be dominated by terraqueous habitats that generate organic soils and wetland meadows. Trees and forests do not regenerate readily in these depressions because wetland habitats tend to favour bacterial rather than fungal soils required by woody communities. The exception to this is the elevated river formed floodplain levees, which are able to support hardy willow communities in areas such as the Zoige Basin (Brierley et al. 2016b, Chap. 3; Yu et al. 2014). Wherever wetlands are grazed, slowly but surely they are drained, degraded and dehydrated into terrestrial habitats, increasing the likelihood of “permafrost” conditions. This aggravated permafrost predicament is now characteristic of many low-lying valley and intermontane basin terrains.

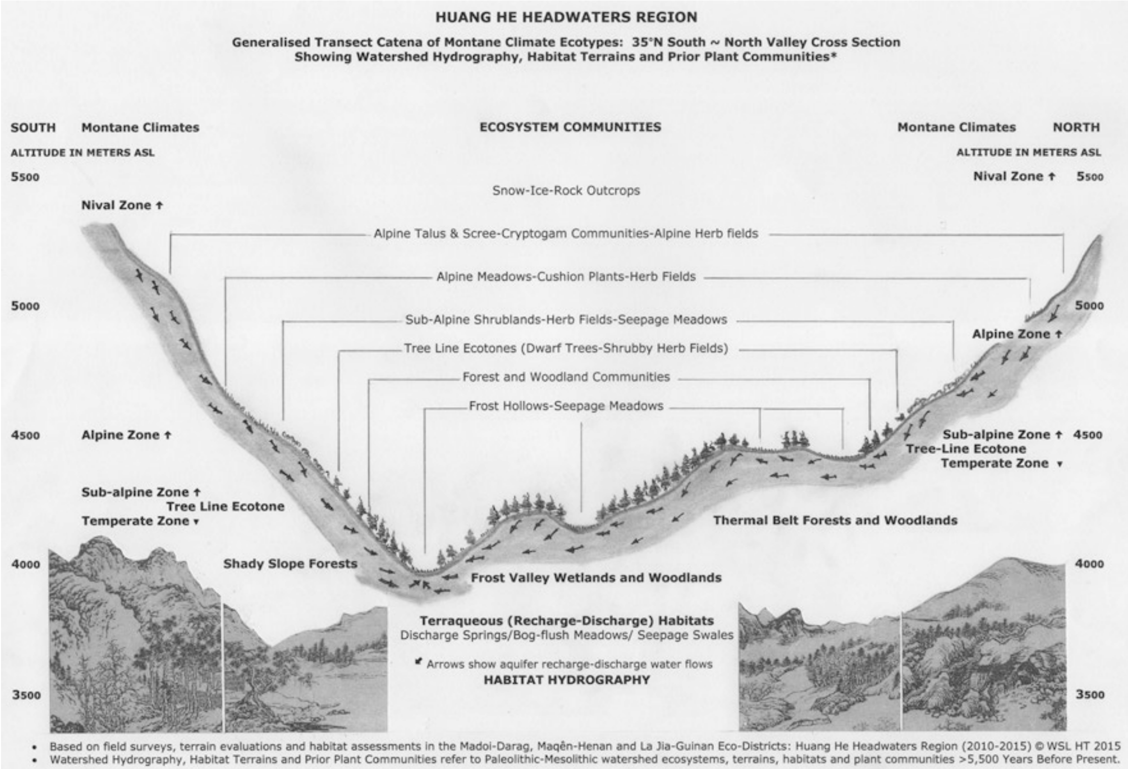


Fig. 13.4 Catena transect of microclimate ecotypes and their vegetation communities in the Huang He headwaters. Elevations above 5500 ± 250 m asl are characterised by nival zones of rock, ice and snow with some hardy lichens. Between 4500 and 5500 ± 250 m asl, the alpine zone is made up primarily of lichens and mossy mounds, with rocky screes and some wetland meadows. The subalpine ecotone at elevations from 4250 to 4500 ± 250 m asl is made up primarily of dwarf shrubs, herbs, grasses, cushion plants and cryptogams. Below this, from 3000 to 4250 ± 250 m asl, the cool temperate zone made up of forest/woodland/shrubland zones extends up to 4400 m asl. Below 3000 m asl, the mild temperate zone has a wide range of tree crops and woodland communities

Wherever soil and vegetation biomass are reduced and degraded, and aquifers and wetlands are dehydrated, the normal heat/water energy cycles that moderate microclimatic conditions are severely disrupted and rendered dysfunctional. Consequently, the ground heats up excessively during the day and cools down excessively at night, leading to human-induced permafrost conditions. The prevalence of permafrost conditions in lower lying terrains (below 4000 m asl) is more likely than not an ecological indicator of severely degraded valley floodplains and intermontane basins.

As a result of freezing cold air drainage, radiant frosts and frost hollow effects, riverine habitats in higher-altitude floodplains of the Qinghai–Tibet rangelands (above 4000 m asl) are commonly subjected to subalpine microclimate conditions that support wetland communities such as bog-flush meadows, chains-of-ponds, distributary channels and floodplain swales with herbs and grasses. Dwarfed shrubs and willow trees are only likely on more elevated sites.

Below 4000 m, the floodplain basins and river valleys contain a tattered tapestry of remnant wetlands among severely degraded pastures with planted trees showing browse and graze damage. These relationships occur even where attempts have been made to fence out grazing animals.

13.4.5 Animal Resource Ecography of Grazing Flocks and Herds

Pastoral communities in the Huang He headwaters graze herds and flocks of yak, sheep, goats, horses and cows. These hard-hoofed animals have been bred and grazed in flocks and herds for so long and so extensively that they have induced short, tough "golf course" grasslands throughout the headwaters region (Miehe et al. 2009, 2014). Shown in Fig. 13.5, there are also many areas where selective browsing and grazing habits have induced a wide range of unpalatable poisonous and thorny plant communities.

The biology, ecology, habitat and husbandry of yak, as well as its place in Tibetan culture, are well reported by Weiner et al. (2003/06). Arguably the yak is the hardiest, toughest, very agile and most versatile of all hard-hoofed, browsing and grazing animals. It is unsurpassed for its ability to access and browse, graze, track, trample, muck and pug, climb and swim to access all sorts of edible vegetation. Only the most poisonous of plants repel the yak. They can access virtually all areas. They plough up terrace edges with their horns, wallow in wetlands and congregate in herds at critical aquifer discharge zones. They are truly remarkable rangeland engineers, albeit lacking ecological foresight of the damage they generate.

By comparison, Mongolian communities in the Huang He headwaters are readily identified by prominent statues of their distinctive, dramatic "fire" horses ~ super horses able to traverse hundreds of kilometres in a day carrying a heavy load ~ notably a mounted warrior with armour and sword. Shown with sun symbols displayed prominently, these "fire horses" were the horses ridden by their

Fig. 13.5 Golf course pastures in the headwaters region are being gradually invaded in many places by poisonous plants and thorny shrubs

greatest warrior kings. Horse and pony pastures were once connected by an intricate network of hoof-hardened trails and roads.

As the totemic icons of Tibetan and Mongolian cultures, the hardy yak and fire horse are revered in ways that can only be fully appreciated by traditional

Shamanist cultures (Fig. 13.6). On the other hand, minority Islamic communities in the headwaters region follow the Old Testament edict that only those who sacrifice sheep or goat to God are welcome in Heaven. Islamic communities graze flocks of sheep and goats wherever they can, including in their towns and villages. The landscapes of Islamic communities are readily recognised by the intricate criss-cross patterned tapestry of sheep and goat trails carved into the soils.

13.4.6 Habitat Indicators: Water Birds, Amphibian Reptiles and Raptors

Remnant and relic aquatic and amphibian fauna in the headwaters indicate that wetlands and water bodies were once more plentiful. In remoter areas of the headwaters, in terraqueous discharge seeps in thermal zone footslopes, amphibians such as frogs and geckos are still common.

Water birds were observed in relatively lower numbers than expected for healthy high country watersheds with arrays of aquatic and terraqueous habitats. Geese, herons and crested grebes are locally common, though not numerous in summer. Water fowl relying on riparian ecotones and other wetlands have been seriously impacted by hard-hoofed livestock pugging, tracking and trampling their nesting and feeding habitats. The grebe's floating nest has helped it survive better than most (Fig. 13.7). Water birds and pasture birds are predators of insect pests. Their droppings provide biologically active fertiliser. Birds and insects play crucial roles in nutrient transfer processes particularly between high-nutrient riparian zones and low-nutrient slopes, spurs and ridges. Healthy populations of birds and insects redistribute significant loads of nutrient on lands they occupy and range over.

Raptors such as eagles and falcons are sacred birds in Shamanist cultures. Falcons were once used for hunting game birds, hares and rabbits, though this is now rare. Eagles are top predators. They perform multiple ecological functions from predating small mammals such as pika, vole and rabbit, scavenging livestock carcases, to devouring human bodies dissected on hilltops near Tibetan towns. Given their role, eagles have unique spiritual status.

There are still abundant eagle populations present in the upper headwaters region near Maduo. Old telegraph poles retaining their crossbars have been adapted by eagles to make their nests and roosts. In recent years, government authorities have re-erected old telegraph poles in deforested districts to increase nesting habitats for eagles. This action reflects as much as anything the loss of trees and forests for eagle nesting habitats. Before the trees and forests were consumed, the bodies of deceased Tibetans were burnt on funeral pyres of stacked logs in much the same way as their Nepali neighbours further south. Today their cairn-like pyres have much smaller fires intended for other social and spiritual purposes.

Fig. 13.6 Yak and fire horse statues at historic sites and headwaters towns: Latticed landscapes from sheep/goat grazing present a stark contrast to nescient romantic notions of pristine natural landscapes in the Qinghai–Tibet region cared for and tended by a spiritual people living in harmony with Nature. The animal resource ecology of grazing flocks and herds over millennia has transformed the watershed ecosystems of the Huang He headwaters into anthropocentric landscapes bearing little resemblance to original ecosystems

Lead author at the Yak Monument at Zhaling Lake

Fire horse in Henan

Fire horse at Maqen

Fig. 13.7 Grebe nests at Shining Star Lake Maduo. Gazelles browse the shoreline edges. Browsing and tugging at roots of plants erodes the riparian edge habitat, simultaneously piercing the algae/cryptogam seals that cover the silty mud which controls the release rates of ground water from nearby soils and aquifers. Piercing of ecohydraulic bioseals controls the release of water supplies stored in aquifers and soils. It results in the demise of aquifers, springs and streams. The riparian ecotone ends up desiccated, degraded and derelict

Geese grazing

Gazelle grazed lake edges

Grebe nest at Shining Star lake, near Maduo

13.4.7 Predatory Bears, Wolves, Foxes, Weasels and Snow Leopards

Tibetan and Mongolian pastoralists are keen hunters of livestock predators and edible game, often carrying guns and ammunition with them on their daily rounds. Tibetan stores in headwaters towns sometimes display guns and ammunition for sale. Wolves and foxes are prime targets for pastoral people because they predate their grazing livestock. To protect grazing livestock from predatory animals, they are guarded by aggressive, large wolf-like dogs. At night, Tibetan graziers often corral their flocks and herds in secure barns and yards for safety.

Greatly reduced numbers of predators such as bears, wolves, foxes and snow leopards means livestock can be grazed most everywhere without too much worry. And they do, from the very mountaintops, to the islands in the middle of lakes, as yak are all terrain ungulates. While this may be a fortunate situation for pastoralists, the consequences for the health of riverine ecosystems are not good, as healthy populations of predatory animals are usually necessary to maintain the health of rangeland and riparian ecosystems.

Predator–prey relationships are important for maintaining resilience and stability in rangeland ecosystems. Whether it is bears, wolves, foxes or snow leopards, flocks and herds of grazing animals are kept on the move by the presence of predators. Sick animals, careless offspring wandering away from the herd, or those lagging behind the rest are prime targets for predators. Grasslands evolving under grazing regimes where predators have been eliminated or their numbers greatly reduced should be considered as human-induced ecosystems.

13.4.8 Animals of Ecosystem Disturbances—Animals of Ecosystem Restoration

Domestic herds of hard-hoofed grazing yaks, sheep and goats are agents of radical geomorphological and ecological change, degrading and transforming ecosystems (Tane 2009; Trimble and Mendel 1995). They can be major drivers of pastoral desertification (FAO 2006; UNESCO 2009; UNEP 2010). Contrary to some people's beliefs, the social and ecological behaviour of feral ungulates, contrasts starkly with the behaviour of wild populations (Muir 1977).

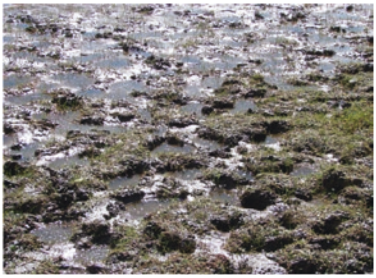
Antelope, ass, deer, donkeys, gazelle, goats, sheep, yak and their close companions pika, vole, marmot, hares and rabbits are the dominant animal communities in the Huang He headwaters. While domesticated communities of hard and soft footed animals are ubiquitous, wild free-ranging populations of these companion communities are not uncommon.

Feral and domesticated animals usually keep clear of each other. The much smaller feral flocks tend to move through the terrain quickly in pulses, grazing along the way in areas free of faeces. By comparison, their domesticated counterparts slowly graze the meadow to the ground while eating through their own faeces, before moving on to repeat the ecological offence time and time again (Fig. 13.8).

Grazing deforestation erosion

Accelerated drainage from grazing

Pugging from tracking and treading



Close up of pugging from treading

Pugging riparian ecotones

Pastoral land degradation

Pastoral desertification

Pastoral desertification

Fig. 13.8 Hard hoof flocks, herds, horses and ponies are classic examples of animal-induced ecosystem disturbances. Tracks and yards become compressed hard from years of traffic. Riparian habitats and terrace edges are exposed by horns and hooves to make soil baths, as they roll around in the soil and mud. Tibetan ponies ridden by locals compress the ground along ancient mountain trails to such a degree that the trails resemble "hard surface" roads. Tracking and treading compress some soils so hard they can serve as a road without any further materials

Hard-hoofed animals are renowned road makers. A characteristic feature of Roman road construction in ancient times involved flocks of sheep compressing the road foundations. Today they have been replaced by large sheep-foot rollers towed by tractors. Softer, finer wet silty soils tend to go muddy from continuous hard hoof traffic. However, below the surface muck, hard hoofs compact *B* and *C* horizons, inhibiting aquifer recharge. Hard surfaces also accelerate rainfall runoff eroding soils and generating flash flooding (Tane 2009).

13.5 Part 2: Cultural Ecology of Pastoral Rangelands

Chinese culture evolved from animist views of the world, which hold that everything is an integral part of open living systems sustained by living water. In China, this is expressed by the term "Dao". The fundamental nature of Chinese culture enshrining its character and disposition is expressed in the Dao de Jing, the leading text of Chinese "Dao" culture. Dao culture is the traditional animist culture of the first Chinese farmers from the time of Huang Di to modern times. Dao culture survives and thrives in Chinese communities honouring the water dragon above the hard-hoofed animals, and practicing traditional terrace farming and paddy pond terraquacultures.

Since the Legendary Kings Period around 5000 years ago, Chinese Dao cultures have recognised that pastoral grazing diminishes and destroys the watershed ecosystems on which their water-based farming system depends. From this perspective, when "*pastoral barbarians in the western regions*" destroyed the forests and woodlands of their rivers' headwaters, watershed ecosystems were so extensively and seriously damaged, they inadvertently created a legacy of flash floods and prolonged droughts (Tane 2012). Since the times of the Legendary Kings, China has opted for the cooperative watershed farming approach of village farmers operating zero-grazing systems. No fences, gates or similar structures were needed to protect crops in gardens and farms because livestock were barn raised, and there were no grazing animals to threaten them.

The cultural intelligence of Neolithic watershed communities forged in China's cultural heartlands produced archetypes for some of the most productive farming systems in the world (Bellwood 2005; Ruddle and Zong 1988; Tane 2009). While these systems were copied by farming communities throughout Asia and transported to the Americas and Oceania over 4000 years ago (Carter 1961), they were most unwelcome in regions where pastoral religions such as Shamanism and Lamaism prevailed, such as in the heartlands of Mongolia-Tibet. After nearly 10,000 years of open-range pastoral grazing, the resistance to Asia's zero-grazing farming systems remains as strong as ever among pastoral cultures who revere the yak (Tibetans), horse (Mongolians), or sheep and goats (Muslim).

Tibetan, Mongolian and Muslim herders have rarely adopted barn farming with zero-grazing practices developed in the Middle Kingdom realm of China (Chang et al. 2012). Perhaps for religious reasons and preferred lifestyles, traditional pastoral communities failed to learn (or refused to adopt) the crucial lessons of rangeland ecosystems and their resource economies ~ that the productivity of pastures and the health of livestock are superior when they are confined to enclosed barns and sheltered yards, and their fodder harvested and fed to them, well clear of their faeces and urine.

The high country of central Asia is often referred to as an alpine zone climatically unsuited to arable farming with pastoralism the only realistic option (Harris 2010; Weiner et al. 2003/06). Yet Tibetans farm barley, their staple cereal, and harvest a range of feral foods and medicines which could be cultivated in their wetlands, shrublands and remnant forests. In recent years, Tibetans and other pastoral communities have turned to cultivating extensive areas for hay production. Perhaps the reasons for preferring pastoralism are more cultural than climatic.

In the collective cultural heritage and memory of grazing communities in the headwaters region, there still can be found numerous artefacts, ceremonies, rituals and recollections from early times when there were extensive habitats and terrains of terraqueous habitats, tall grasslands, shrublands, woodlands and forests. Many are carefully recorded and displayed in the Qinghai Museum, and other museums located in and around Xining. For example, the Mongolian Cultural History Museum in Henan County has a particularly valuable resource of artefacts and displays revealing how extensively rangeland habitats and ecosystems in the Huang He headwaters districts have been transformed since the Yuan Dynasty, less than 1000 years ago. A growing body of palaeo-ecological research corroborates the dramatic transformation of ecosystems on the Qinghai–Tibet rangelands by these pastoral cultures (Miehe et al. 2007, 2008, 2009, 2014; Opgenoorth et al. 2010). Older Lamaseries and sacred sites retain further evidence of the close connections between Tibetan culture and wooded ecosystems (as noted by Miehe et al. (2003) in their paper entitled "*Sacred Forests of Tibet*").

13.5.1 Cultural Ecology of Pastoral Peoples

The cultural heritage and spiritual practices of human communities are often key factors in the ecogenesis of cultural habitats and ecosystems (Proshansky et al. 1970; Tane 2009). Cultural ecology is the study of human cultures and their communities. It entails the following: (a) mapping and describing human interactions with their home habitats (Bardon 1991; Sveiby and Skuthorpe 2006), (b) modelling ecological processes creating and evolving cultural ecosystems (Tane and Wang 2007) and (c) explaining impacts and adaptations to their watersheds and broader territories (Tane 2010; Tane et al. 2014).

The evolution of Tibetan and Mongolian pastoral cultures occupying high country rangelands in central Asia covers more than 10,000 years (Aldenderfer et al 2011;

Chang et al. 2012; Miehe et al. 2009, 2014; Opengoorth et al. 2010). From cultural iconography and symbolism displayed on their temple architecture, sacred sites and pastoral accessories, Tibetans and Mongolians have adapted and practised a special blend of traditional Palaeolithic Shamanism characteristic of central and northern Asia. As a result of their contacts with Han Chinese, during Neolithic times they incorporated an unusual blend of Dao Animist symbology, including the *tai'ji dao* symbol seen at Kumbum Lamasery and elsewhere. Subsequently, in more recent times, Tibetans incorporated their version of Buddhist liturgies and rituals delivered locally in special blends, depending on historic community and regional affinities.

As warriors with highly developed hunting and fighting skills, Tibetans and Mongolians have a reputation for disputes with their neighbours, particularly over grazing lands. As hunter/pastoralists with limited options for fresh vegetable foods, they are confirmed eaters of animal meat. From these perspectives, it is clear Tibetans are not Buddhists. They refer to themselves as Lamas and their religion as Lamaism. Until recent times, Lamaseries such as Kumbum Lamasery near Xining were educational academies and professional institutes, as well as spiritual temples. Among pastoral religions such as Lamaism and Islam, religiously proscribed pastoralism is not a farming system based on scientific knowledge. Like Mongolian Shamanism, Tibetan Lamaism and Islamic Monotheism, pastoral religions require a high degree of conformity and compliance with traditional beliefs, religious rituals and cultural values among their communities.

13.5.2 Palaeolithic Cultural Impacts—Qinghai Tibet Rangelands

The earliest recorded human occupation on the Qinghai–Tibet rangelands occurred during the last glacial maximum when cool-temperature forests and woodlands of juniper (*Juniperus genus*), fir (*Picea genus*), willow (*Salix genus*) and birch (*Betula genus*) were common on sunny hillslopes up to 3500 m asl (Han et al. 2016, Chap. 12; Miehe et al. 2003, 2007; Opgenoorth et al. 2010). Post-Ice Age warming has pushed the forest tree line more than 1000 m higher, with remnants of juniper forests evident at 4900 m asl (Meihe et al. 2007). Disappearance of these woodlands and forests most likely reflects the impacts of human occupations, including the clearing of trees and forests to increase grazing areas (Aldenerfer 2011; Miehe et al. 2009; Opgenoorth et al. 2010).

Archaeology of the Qinghai–Tibet rangelands places the earliest occupations in the northern extents at the Lesser Qaidam (33,000 years ago), though recent reassessments of the site suggest it may be more recent (see Han et al. 2016, Chap. 12). In the south of the Qinghai–Tibet rangelands at Chusang, the earliest occupations are dated between 28 and 32,000 years ago; a date confirmed by recent cross-checks (Aldenerfer 2011). In the north-east sector of the Qinghai–Tibet rangelands, which includes the headwaters of the Huang He, the dates are more recent. The Qinghai Lake district records human impacts from around 15,000 years ago.

La Jia Forest *Remnant juniper trees*

Fig. 13.9 Photographs of La Jia Forest and woodland. Fire is still being used as a tool for clearing trees and scrub and any other unwanted vegetation, particularly from dry warm sites, such as sunny hillslopes, thermal belts, solar basins and sheltered gorges where fire flourishes and spreads readily in dry weather

While cultural, ecological and museum evidence points to early Palaeolithic settlements on the Qinghai–Tibet rangelands, scientific archaeology, genetics and palaeo-geography only recently confirmed from field evidence that the Plateau was occupied in the Late Pleistocene perhaps as early as 25–33,000 years ago (Aldenerfer 2011; Miehe et al. 2009, 2014; Opgenoorth et al. 2010).

While anthropocentric fire may have played a lesser role in deforestation of the Qinghai–Tibet rangelands than in other rangelands globally, considerable evidence found in buried subsoil strata reveals burnt tree stumps and woody debris (Miehe et al. 2009). Evidence for fire includes fire cairns found near villages and at sacred sites and pastoral camps, the widespread occurrence of burnt tree trunks in places where trees and forests survive, and the sight of Tibetan yak herders gathering around their bonfires in the evening. These all attest to a pastoral culture that embraced fires for many social, cultural and economic purposes, not just fuel and warmth (Fig. 13.9).

13.5.3 Mesolithic and Neolithic Cultures

The evolutionary pathways of ecosystems in mountain rangelands occupied by pastoral peoples are not only remarkable case studies in cultural ecology, they reveal the ecological dynamics of converting small populations of wild ungulates migrating over extensive territories to much larger flocks and herds of domesticated ungulates constrained by grazing boundaries. As the numbers of grazing livestock increase and competition for grazing land grows, watershed habitats, underlying ecostructures and rangeland ecosystems are slowly but surely modified and transformed into terrestrial biomes that are no longer able to serve essential functions of watershed ecosystems (Tane 2009).

Recent reviews of palaeo-ecological evidence suggest the onset of pastoralism on the Qinghai–Tibet rangelands began by the onset of Mesolithic times 10,000 years ago (Miehe et al. 2009, 2014). Evidence of Palaeolithic occupations has been largely obliterated over extensive areas by storm and tempest, episodic floods and cycles of erosion. As a result of widespread erosion, there are few sites where the aggradational history of soil terrains remains sufficiently intact to provide a chronological story. As a result, archaeological evidence cannot be relied upon for a complete picture of pastoral impacts, as the evidence has been compromised, disturbed and dispersed by episodic events and widespread erosion. The alternative is to compile the presence of human communities from surrogate sources such as ecologic and geomorphic indicators, palaeo-ecology and Quaternary research and ecographic mapping and modelling. Taken together they reveal consistent evidence of human activities and their impacts (Kaiser et al. 2007; Aldenerfer 2011; Miehe et al. 2009, 2014). By the onset of the Neolithic Age 5000 years ago, pastoralists had already induced profound ecological changes to Huang He watersheds, their habitats, regoliths, vegetation and wildlife communities.

More consistent, reliable and widespread evidence has been found of Mesolithic and Neolithic people's impacts on the headwaters region from 10,000 to 3000 years BP (Miehe et al. 2014). Mesolithic communities began clearing forests and woodlands, to expand grazing areas to accommodate their growing numbers of livestock, ponies and horses. Neolithic people's impacts included clearing woodlands and forests; burning trees, scrublands and grasslands; draining wetlands; grazing domesticated herds in critical watershed habitats; hunting wildlife; and eliminating predators. Together, these activities amounted to a major assault on the watershed ecosystems of the headwaters region.

As the Mesolithic peoples cleared and expanded their grazing lands, they came into conflict with other pastoral tribes doing the same. By the time Neolithic peoples were adapting and evolving their communities more than 5000 years ago, they were forging closer settlements in the Huang He headwaters. Competition for grazing lands in rangelands commonly grows into territorial conflicts, forging the arts and technologies of warfare between neighbouring tribes. By Neolithic times, intertribal warfare was commonplace, revealing a level of competition for grazing territory that resulted in a wave of extensive environmental impacts that transformed watershed ecosystems over large areas. Weaponry artefacts in the Qinghai Museum reveal intertribal wars were common at this time. Fatal conflicts between neighbouring communities likely reflected territorial conflicts for grazing lands. By the Tang Dynasty (618–906), the King of Tibet had amassed a large, well-equipped horseback fighting force that defeated the Tang Emperors Armies in 763 AD, taking control of the Huang He headwaters as far east as Chang'an in Shaanxi. A similar pattern of fighting activity and weapons manufacturing is presented in the Mongolian Cultural Heritage Museum at Henan County as recently as 1000 years ago, when the Yuan Dynasty was flourishing. These conflicts are reflected by increases in erosion rates from relatively low rates in the early Holocene to relatively high rates of erosion during Neolithic times through to the present (Miehe et al. 2014).

Territorial conflicts between pastoral communities indicate increasing pressure on essential resources for sustaining livelihoods: woodlands for fuel and timber, and grasslands for grazing lands. Across the world, pastoralists have displaced hunter-gatherers, followed by pastoralists fighting pastoralists and pastoralists fighting farmers over the use of key resources (Bellwood 2005). In this respect, the history of traditional watershed farming in China is a salutary lesson in human survival, for Chinese sedentary watershed farming communities were continually faced with hostile invasion by pastoral people including the Jin, Tibetans, Mongolians and Manchurians (Tane 2009; Tane et al. 2014).

In the heartland of China, a long, lamentable legacy of devastating wars between farmers and herders attests to the fact that Asia is home to both farming and pastoral cultures. Since the beginning of Neolithic China, represented by the first three "Legendary Kings" (Fu Xi, Shen Nong and Huang Di) around 5000 years ago, conflicts between pastoral and farming cultures in China have been resolved by the simple expedient of separating them by enforcing natural boundaries and building high earthen walls. Wherever possible, pastoral tribes were relocated to the western mountain regions outside the walls. This made fenced fields and gates unnecessary for Chinese farmlands.

In China's traditional watershed farming cultures, livestock are barn raised. Zero-grazing systems were adopted and enforced. The outcomes were mutually beneficial for both cropping farmers and livestock farmers remaining within China, with both groups achieving higher production and more profit for their efforts. When Huang Di and his contemporaries came to this realisation around 5000 years ago, they undertook the pre-emptive step of separating the two conflicting cultures by expelling the pastoral communities to the far western regions and building huge walls to keep them there. It took another 3000 years of repeated conflicts between farmers and herders before the walls were expanded and linked into a series of Great Walls protecting China from invasion by pastoral grazing cultures.

From the perspectives of pastoral cultures, the ecological impacts of grazing animals are the natural and necessary consequences of land use systems proscribed by their pastoral religions. Vedic and Shamanist religions worship cows and other "power animals", at the same time persecuting and vilifying those who cherish non-pastoral farming pathways. Ever since Biblical and Vedic times (post-4000 years BP), pastoral religious myths and dogmas have distracted from closer, objective observations of the ecological consequences of pastoral grazing in rangeland watersheds (Tane 2009; UNESCO 2009).

13.5.4 Prevailing Grazing Cultures

While Tibetans, Mongolians and Muslim minorities practise a range of spiritual and religious beliefs, they are all God fearing, meat eating pastoral farming communities. Tibetans and Mongolians practise a unique type of Shaman–Lamaism that is intricately tied to their hunting and grazing activities. Islamic communities follow the Abrahamic religious edict, grazing sheep and goats everywhere they can.

When Tibetans and Mongolians were nomads, they followed the migratory patterns of feral ungulates and moved on with their flocks and herds before too much damage was inflicted on critical watershed ecosystems. The ecological impacts of domestic herds of grazing animals became more serious when they settled down and simply rotated their herds on the same land year after year (Weiner et al. 2003/06). This revelation is confirmed by Li et al. (2010) who commented that: "*Since the 1950's the human population of the region has trebled, and livestock numbers have doubled. Grassland overgrazing is most pronounced in spring. It results in sparse, low and degraded cover and enhanced growth of plants toxic to livestock*".

13.5.5 Tree and Timber Dependency of Tibetan Culture

As nomadic pastoral people with seasonal patterns of rangeland grazing, yak herders used a traditional round felt covered structure called a yurt. The traditional home of Tibetans, the yurt is a remarkable example of design and construction requiring specialty timbers. The roof cover is supported by a radial array of light and springy timber beams held in place by a circular wooden frame into which the beams are slotted. The walls are a lattice structure of crosslaced timber slats and supports. A wooden frame and door complete the yurt. To warm the yurt, an iron stove takes central place, with the chimney poking through the roof cover. Once the stove burnt fragrant juniper boughs, the knotty birch and clean burning willow wands. Now these trees are gone, the Tibetan pastoralist are forced to burn yak dung, collected, dried and stacked by Tibetan women wearing face masks to safeguard themselves from cold air and respiratory infections. Their colourful clothing embellished with amber and turquoise necklaces is strikingly beautiful. Amber is particularly cherished by Tibetans ~ derived from tree resin, amber is a cultural treasure.

Tibetan culture is reliant on trees and timber for a wide range of everyday items, from their yurt timber slat structures to spiritual flag poles which they raise annually on outstanding peaks, mountain passes and river gorges (Fig. 13.10). Wooden pegs are essential tools used for securing dogs, tethering yaks and dogs and pegging down yurts. Tibetan Lamaseries are traditionally built of timber with internal fittings and furniture made of wood. Traditional Tibetan prayer wheels are made of wood. Their spiritual altars, cairns and campsite fire pits are constructed to burn wood. In the markets and shops of Tibetan towns, there are still many traditional farming implements made of wood. At local markets, bunches of juniper boughs are sold as incense. These are not items produced by treeless grasslands. While modern truck transport now provides ready access to imported wood and timber supplies in the past Tibetans relied on local woodlands and forests for their needs.

Tent poles, wood stove, amber beads

Wooden structure (frame) of a yurt

Ceremonial flag poles

Ceremonial spears

Fig. 13.10 Photographs of Tibetan women wearing amber beads, preparing food in their wooden frame yurt. Spiritual poles, wooden implements and cairns for burning juniper are Tibetan cultural icons

13.5.6 Rangeland Deforestation

From the perspective of the cultural ecology of pastoral peoples in the Qinghai–Tibet rangelands, clearing and felling of trees and forests were traditional activities for Tibetan and Mongolian herders engaged in forging pastoral grasslands since the earliest days. This entailed using wood for fires, wooden slats for their yurts and huge timbers for their bridges and temples. Expanding their home grazing areas to their present territories was a major accomplishment. It took at least 8000 years.

The destruction of woodlands and forest ecosystems was paralleled by draining and grazing of wetland meadows and other terraqueous habitats to expand terrestrial habitats more suited as grazing areas. Incessant grazing prevented regrowth of woody communities, with the exception of unpalatable poisonous and thorny species. Today, remnants of the once widespread montane forests of fir and juniper, and woodland communities of birch, willow and buckthorn (*Sarchi*) are only found in the most remote steep hill slope and inaccessible gorges (Miehe et al.

2009, 2012). Exploitation of vegetation since ancient times has not only generated severe erosion processes, it removed forests, woodlands and shrublands from extensive areas suited to tree growth (Aldenderfer 2011; Miehe et al. 2007, 2008, 2009, 2014; Opengoorth et al. 2010).

13.5.7 Transforming Vegetation Communities

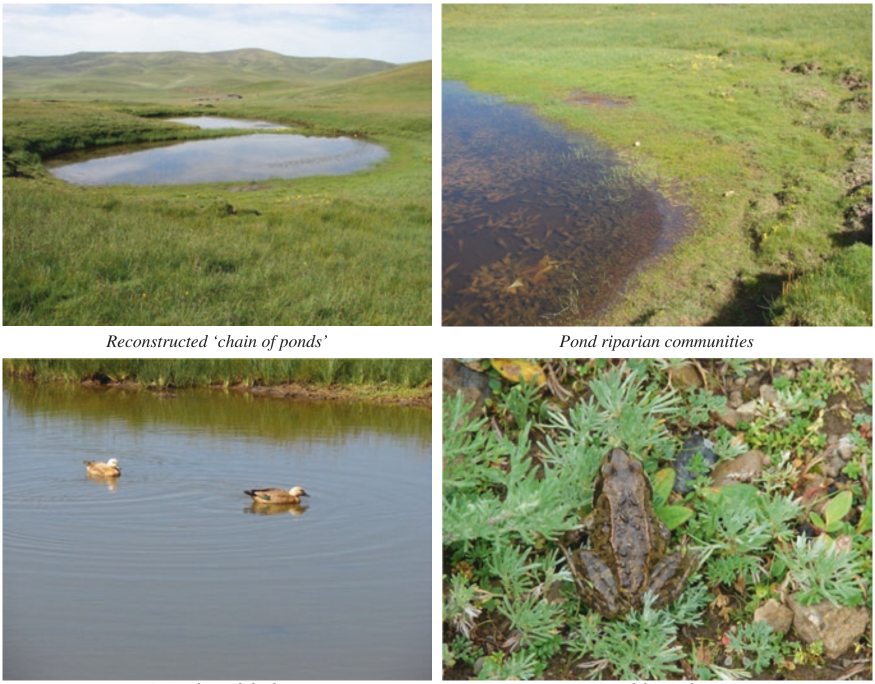
Watershed habitats suiting trees, woodlands and forests have been transformed into grassland disclimax communities by combinations of dynamic activities. This includes clearing trees and forests, burning regrowth, draining wetlands and regular grazing by hard-hoofed livestock. When combined strategically, burning, grazing, taking timber and collecting woody fuel offer very effective activities for hindering woody regeneration, drying out wetlands and dehydrating watersheds (Muir 1977; Tane 2009; Tane et al. 2014).

The dehydration of terraqueous habitats and destruction of their wetland communities is particularly damaging to watershed ecosystems for they are critical surficial reservoirs for aquifers and ecostructures (Tane 2009). Once very common, intact suites of chain-of-ponds typical of healthy rangeland ecosystems are now very rare (Fig. 13.11).

Burning of rangelands is largely restricted to habitats where following a dry period, the vegetation dries out sufficiently to carry fire. This can be any time of the year in some localities, like the La Jia Gorge. Some vegetation communities maintain high moisture levels in all seasons, limiting their susceptibility to wildfire hazards and “burning off”. Open intermontane basins with extensive floodplain wetlands and water bodies may have resisted fires for long periods, until soil moisture was depleted. It is likely that habitats carrying fire most readily were the well-drained sunny hillslopes, terrestrial woodlands and temperate zone thermal belts and solar basins that once supported woodlands and forests. These were favoured camp sites for livestock, particularly in cold weather.

Selective browsing and grazing, coupled with regular tracking, trampling and treading are ecological impacts with serious long-term consequences. Typically, watershed ecosystems respond in three ways when the ecological impacts of pastoral grazing accumulate. Over time, the most palatable floras are eliminated, leaving the thorniest and most unpalatable plants. As vegetation cover is depleted and the ground compressed, Nature sends in small mammals such as pika or rabbit to remedy the ecological and hydrological damage. If grazing is allowed to continue, communities of these soft footed mammals continue to grow, eventually reaching pest proportions. Allowing grazing to continue, stimulates invasions of poisonous plants and thorny scrubland and before long, degraded and eroding soils become commonplace (Li et al. 2010, 2016, Chap. 7).

Pastoral agricultures are recognised by UN agencies such as UNESCO and FAO for their radical ecological impacts on rangeland watersheds. Pastoral grazing systems have converted whole biomes from wetlands and woody vegetation to



Reconstructed 'chain of ponds' *Pond riparian communities*

Pair of wood ducks *Pond fringe frog*

Fig. 13.11 Intact floodplain ponds are now very rare along the Upper Yellow River; they are effectively restricted to spring–pond–stream sequences in mountain rangelands. The remote rangeland saddle site east of Maduo (one of the few remaining examples) sustains a pair of resident wood ducks and relict amphibian communities. This site was partially reconstructed by a Tibetan yak farmer to help ensure winter fodder and water supplies for his livestock

dry lands with grassy vegetation, as a prelude to more serious ecological problems (FAO 2006; UNESCO 2009). From ecological perspectives, pastoral agricultures generate profound impacts with long lasting consequences for watershed habitats and rangeland ecosystems. Arguably, the most serious consequences are soil sunburn, eroded and gullied terrains, dryland salinity and pastoral desertification.

13.5.8 Aggravating Atmospheric Aridity and Climate Extremes

Clearing trees and forests usually means habitats and their vegetation communities are transformed to much lower levels of total biomass. This in turn corresponds with greater temperature extremes above and below ground level (Geiger 1950), decreased atmospheric humidity and declining aquifer water storage (Tane 2009). In pastoral rangelands dominated by grasslands, devoid of woodlands and forests, typically the average humidity is reduced over summer months from 50–60 % in forest and woodland habitats, to around 20–30 % for grasslands and bare ground (Geiger 1950; Tane 2009). The consequences of radical biomass reduction are severe disruptions to the heat/water balance with an increase in climatic extremes such as atmospheric aridity and climate chaos (Geiger 1950; Kravcik et al. 2007; Tane 2009). There are also serious impacts upon soil and water ecosystems.

13.5.9 Soil Indicators of Pastoral Desertification

Soils are complex living organisms that import, export and transform matter and energy. They are dynamic open ecosystems with spatial discontinuities, time lags and feedback mechanisms that generate ecological potential. Most soils are polygenetic, meaning they adapted and evolved over time under changing circumstances. In this respect, soil systems can contain various sources of information about historic conditions including changing climatic and ecological conditions, prior communities and how they were transformed.

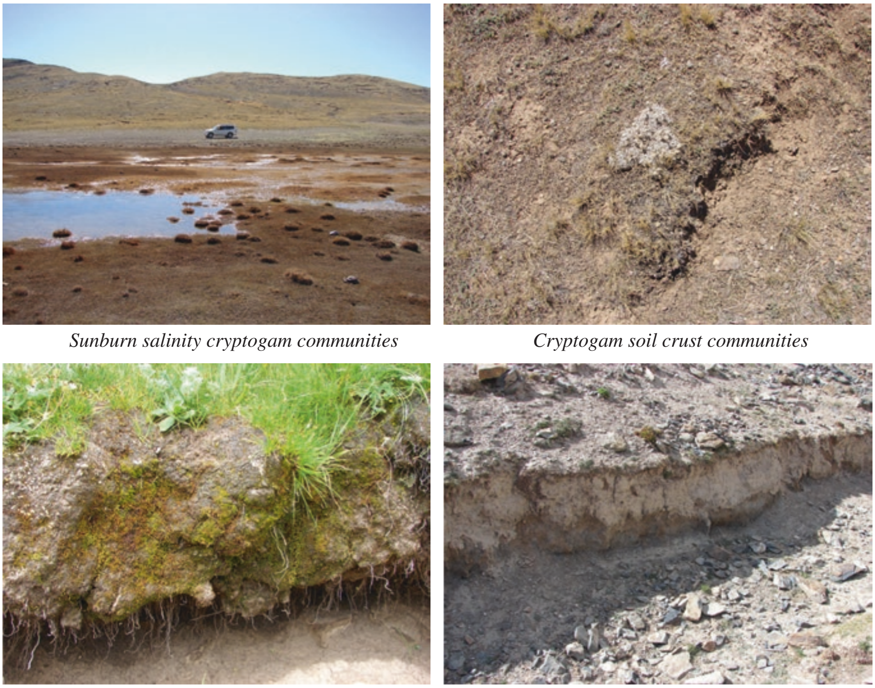
Atop the Qinghai–Tibet Plateau, many areas are characterised by prior terraqueous habitats and relic wetland soil ecosystems. Indicators include black humic soils rich in organic materials with gley substrate commonly associated with wetland meadows. Gley subsoils are indicators of anaerobic processes occurring during subsoil formation. They are typical in wetlands with impeded drainage.

In glaciated mountains, montane basins, river valleys and rangeland regions with deserts, transported materials, atmospheric dust and soil nutrient cycles are closely related. Alluvial, colluvial and aeolian deposits contribute to aggradational soils, building and creating new terrain layers, sometimes burying old ones completely. In eroding rangelands such as the Huang He headwaters, the Quaternary history of soil ecosystems is continually being lost to the forces of land degradation. As few areas retain near-complete soil sequences, evidence for palaeoenvironmental conditions must be gleamed from other indicators of ecosystem potential.

13.5.9.1 Soil Sunburn

Soil sunburn is a serious hazard in rangeland ecosystems, as reduced vegetation biomass allows solar radiation to burn organic matter and oxidise the topsoil. The gradual reduction in the height and density of pastoral grasslands in the Qinghai–Tibet region has elevated sunburn risks and hazards to serious levels.

When organic soils are exposed to direct sunlight, their fragile organic compounds oxidise and volatilise leaving a residual mineral dust that is prone to wind and water erosion. Sunburnt, mineralised soils are a conspicuous feature of the headwaters region (Fig. 13.12). This feature of rangeland soils is sometimes wrongly blamed on climate change, when in fact it is more often a coincident



Sunburn salinity cryptogam communities *Cryptogam soil crust communities*

Cryptogam soil crust communities *Soil sunburn and cryptogam crust*

Fig. 13.12 Indicators of soil sunburn: cryptogam communities on mineralised soils near Maduo

symptom of human-induced land degradation and pastoral desertification (Tane 2009). High-altitude rangelands are exposed to some of the highest levels of solar radiation on the planet. Sunburn times for exposed human skin are measured in minutes; and so it is for exposed habitats grazed down to short swards and bare ground. Ecological indicators of severe sunburn in the Huang He headwaters region include plants with growing leaves and stems turning red and purple as a safeguard against excess solar radiation, scabby burnt bark on the sunny side of Rosacae, scalded soils with cushion plants, very low levels of soil organic matter, mineralised topsoils and bare ground held together by cryptogam communities (Eldridge and Tozer 1997).

13.5.9.2 Soil Erosion

When intense rainfall events rake sunburnt soils with flash floods, they induce widespread soil erosion, often in association with slips, slumps and stream gullying (refer Hu et al. 2016, Chap. 5). Topsoils are stripped away, leaving skeletal subsoils with low nutrient levels. These destructive events inhibit the functionality of watershed aquifers by removing their eco-hydraulic bioseals that regulate water flows through ecostructures and soils. As a result, aquifers drain dry instead of storing water for drier times (Tane 2009).

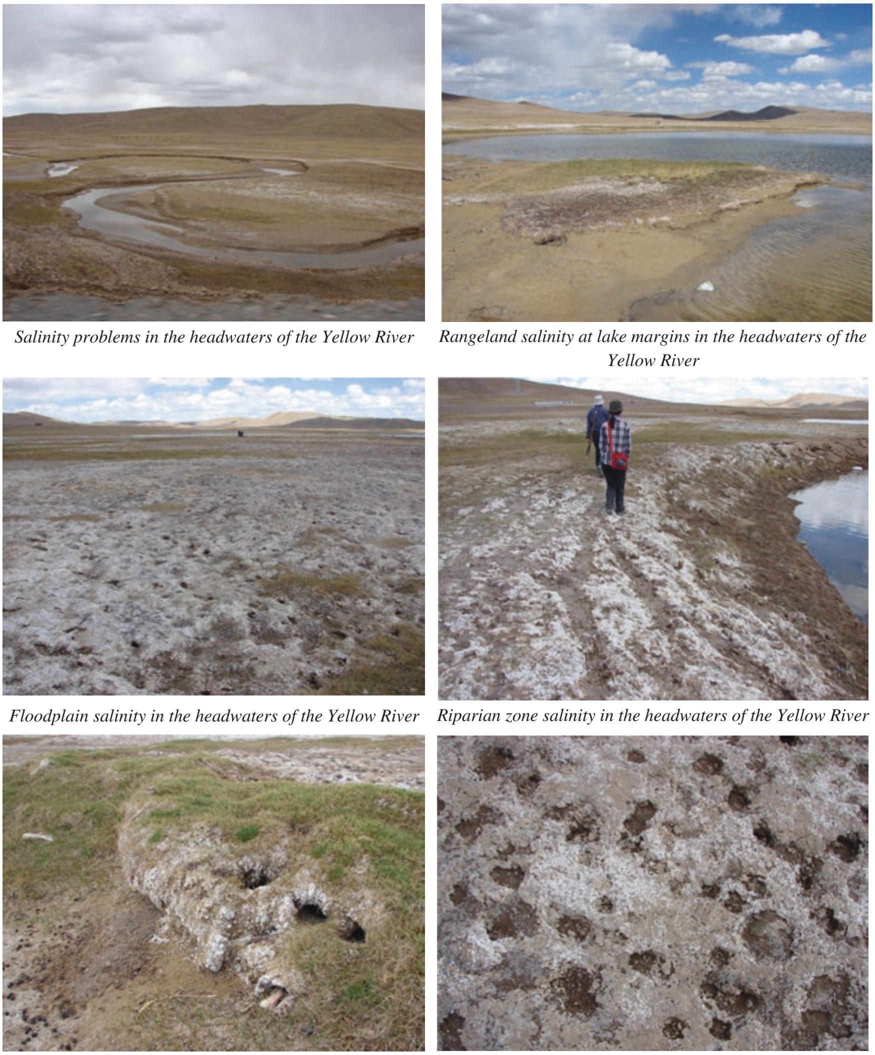
The incremental impacts of continuous hard hoof tracking, treading and pugging, combined with pathogenic pollution from incessant excrement, go largely unnoticed by local pastoral communities until the situation becomes perilous and soil erosion is widespread. By this time, however, greatly enlarged populations of soft footed mammals are helping to restore critical aquifer recharge/discharge dysfunctions by digging holes through the compacted ground and loading the entrance with their nutrient loaded pellets (Tane 2012). Rainwater washes the pellets into the warrens to recharge soil water and aquifers; instead of running off overland to generate flash floods loaded with nutrients. In seeping and filtering through regolith strata, recharge water is cleansed of nutrients, pathogens, salts and sediments by (a) deep rooting plants (b) ecological communities of microbiota and (c) integration into senescent clay layers (Hancock et al. 2005; Goonan et al. 2015; Tane and Williams 1999). When aquifers are recharged, they overflow, pushing fresh clean water continuously through seeps and soils, springs and streams. These elements and interactions are linked together by riparian ecostructures, thereby providing perennial water supplies to soil and plant ecosystems (Tane 1996, 2009; Tane et al. 2014).

13.5.9.3 Soil Salinity

With soil erosion and severe gullying, subsoil clays are quickly desiccated. Prone to shrinking and cracking as they progressively dry out, this predicament enables water to flow through their substrata, flushing and leaching out salty wastes stored in senescent clay layers over millennia. In drier seasons, the saline solutions rise through capilliaries spreading across the surface where they quickly evaporate, leaving behind white crusts of salt. These salt crusts dissolve in the next significant rainfall event to be conveyed into streams, rivers and lakes, where they accumulate to create saline water bodies. These soil salinity processes begin within a few decades of pastoral degradation and are exacerbated as grazing continues. Salinity has already reached calamitous levels in the Huang He headwaters near Maduo and elsewhere (Fig. 13.13).

Soil salinity is like cancer. It spreads unseen within the terrain until it reaches serious levels when it breaks out and spreads across the surface, leaving a trail of dysfunctional habitats and dying communities in its wake. When it reaches elevated levels, salinity kills soil and vegetation communities and pollutes waterways making them unfit for essential fresh water purposes.

Rehydrating the terrain is the traditional proven solution to salinity management, because intact saturated clay layers effectively lock up excess salts (Tane 1996). Removing grazing animals and rehydrating the floodplain greatly reduces salinity as floodplain aquifers are recharged, soil moisture levels are enhanced, and springs and streams start running again (Tane 1996; Tane and Andrews 1998; Tane and Williams 1999; Andrews 2006).



Salinity problems in the headwaters of the Yellow River

Rangeland salinity at lake margins in the headwaters of the Yellow River

Floodplain salinity in the headwaters of the Yellow River

Riparian zone salinity in the headwaters of the Yellow River

Saline soil discharge

Salty soil crusts

Fig. 13.13 Soil salinity in the Maduo district

The Maduo district, including Zhaling and Eling lakes and the Huang He downstream, is affected by serious salinity levels. Viewed from prominent hills overlooking the lakes, historic evidence of old salt harvesting structures are evident in shallow bays. Is it possible both Zhaling and Eling were fresh water lakes in Palaeolithic times, before gradually becoming saltier and saltier as their watershed systems were desiccated and degraded by pastoral desertification?

Sunburn, soil erosion and salinity are key ecological indicators of watersheds suffering from severe pastoral desertification in degraded rangeland watersheds with a history of pastoral grazing (Tane 2009; Tane et al. 2014). Impacts of grazing, sunburn, soil erosion and salinity over hundreds of years inevitably result in extreme pastoral desertification. The consequences for aquifer recharge, storage capacity and discharge volumes are severe to fatal.

13.5.10 Disrupting Aquifer Recharge—Accelerating Overland Run-off

Rates of rainfall run-off vary considerably, depending on the nature of land use and vegetation cover. Typically, habitats in healthy functioning floodplains achieve relatively high levels of rainfall recharge to surficial aquifers. Indeed, more than two-thirds of significant rainfall events are taken directly into aquifer storage in ecologically functional rangeland watersheds (Tane 2009). As a result of slow water transmission rates through riparian ecostructures and near-surface aquifers in healthy watersheds (transmission rates measured at <1 m day^{-1}), time lags and net water flux over time eliminate the deleterious effects of seasonal droughts through spring discharges, increasing subsoil moisture and stream flows (Tane 1996; Tane and Andrews 1998).

Pastoral grazing of rangeland watersheds impacts aquifer recharge/discharge processes in several ways. Tracking and treading compacts the soil surface and subsurface layers inhibiting aquifer recharge and increasing overland run-off. Pastoral grazing gradually reverses the rainfall run-off ratio with more than two-thirds of significant rainfall events flowing overland in swales and runnels, streams and rivers. The consequence of accelerated rates of rainfall run-off is a substantial decline in the recharge rate of aquifers and increased surface erosion. With aquifers starved of their recharge waters, their storage gradually declines and over time such that they can fail completely (Tane et al. 2014).

The hard hooves of grazing livestock pierce the bioseals of aquifers and ecostructures. As a result, discharge rates of aquifers are accelerated, draining aquifers dry much more quickly (Tane 2004, 2009; Tane et al. 2014). The combined outcomes of impeded aquifer recharge and accelerated aquifer discharge bring about substantial declines in aquifer recharge, storage and discharge for rangeland ecosystems. This results in perennial streams from living watersheds becoming ephemeral storm drains for dying catchments (Tane 1996, 2004, 2009). As a result, springs, streams and rivers fail. Droughts alternate with flash floods to become serious hazards, limiting prospects for sustainable human communities, as farmland degradation is followed by food and water insecurity and entrenched poverty.

Pastoral desertification typically induces a ten-fold decline in the water stored in floodplain aquifers (Tane 1996, 2009; Tane and Andrews 1998). Proven methods for reversing soil salinity and pastoral desertification incorporate zero grazing with barn farming of hard-hoofed livestock (Andrews 2006; Tane and Andrews 1998; Tane and Williams 1999; Tane et al. 2014). As outlined below, barn farming with zero grazing is already being implemented in some districts of the Huang He watershed (eg Ninxia, Shaanxi and Shanxi) with outstanding results.

13.6 Part 3: Adaptive Management of Rangeland Economies

The evolution of habitats and ecosystems are unstoppable, ongoing processes. Consequently, unless human communities adapt and change their resource economies to reflect changing ecological conditions, they will find themselves faced with intractable resource problems. This situation looms large in the headwaters region.

In an age of dynamic uncertainty, with chaotic climates, food and water insecurity, and entrenched rural poverty, adaptive management of watershed ecosystems and their resource economies is essential (Drucker 1959; Fulmer 2000). Proceeding from this perspective, we begin to outline the necessary processes for effective, equitable and efficient governance. This is not a linear process. At each stage, the outcomes must be related back to previous stages, to ensure they were completed correctly and properly aligned to over-arching objectives.

The key steps for good governance of and strategic planning for the Huang He headwaters can be summarised as follows:

- Formulate clear, unequivocal policy priorities and plain language policy guidelines
- Undertake a comprehensive geospatial inventory of watershed habitats, communities and ecosystems
- Complete an environmental health audit of watershed ecosystems and their resources
- Develop community and regional planning strategies for sustainable development through participatory watershed programmes involving all community stakeholders in each watershed
- Initiate practical and applied watershed models with watershed communities and
- Publicise and reward successful ecological restoration through sustainable development by rewarding successful "champion teams and communities".

When these tasks have established the necessary policies, performance parameters and successful models for sustainable development and environmental protection, then it is appropriate to address the need for integrated landuse planning for resource economies, their development and management, with safeguards in place to protect essential life support systems for all watershed communities.

In the Huang He headwaters, pastoral farming communities are facing issues such as farmland degradation and food and water insecurity. Most are a consequence of "human induced" incremental degradation of watershed ecosystems from wide-ranging impacts that can be lumped together under the label "rangeland desertification". This is a worldwide calamity. It arises from deforestation, unsustainable pastoral agriculture activities, destructive mining and engineering works and measures, and indiscriminate use of ecotoxic agrochemicals destroying the self-healing capabilities of communities and ecosystems (Tane 2009, 2010; UNEP 2010).

13.6.1 Reversing or Adapting to Climate Change

From ecological and geological perspectives, climate change is natural, normal and probably necessary to maintain homeostasis of key ecosystems on the planet. Climate change enables co-evolution of living communities within reasonably stable environs. As a complex open system surrounded by a bacterial biosphere, importing thousands of tonnes of cosmic ice laden with galactic dusts and viral materials every day, planet earth is much more than a physical entity (Consigli 2008). Referred to as a sentient living planet by leading astronauts (Kelley 1988), planet Earth is living, dynamic, complex organism capable of significant climatic oscillations in response to major calamities (such as volcanic activity). This situation is rarely fatal because there is inbuilt resilience in healthy watershed ecosystems. The planet's ecocybernetic system can return regional climates to moderate conditions. However, the planet's self organising ecosystems are being massively degraded and disrupted by human-induced desertification. The outcome is chaotic climate change: an avoidable calamity largely induced by human activities disrupting the planet's meteorological systems, notably the heat/water balance of watersheds at local and regional levels (Geiger 1950; Kravcik et al. 2007; Tane 2009). From this perspective, the primary solutions include reforesting steep lands, reviving river floodplains and restoring watershed ecosystems and ecostructures (Tane 2009; Tane and Andrews 1998).

Human-induced desertification and resulting chaotic climate changes are impacting the headwaters region in ways that are already compromising essential life support systems that sustain human ecosystems. The situation is increasingly viewed as perilous by community and spiritual leaders in the headwaters region.

Drivers of grassland degradation atop the Qinghai–Tibet rangelands are highly contested (Harris 2010; Gao et al. 2013; Li et al. 2016, Chap. 7). Qiao and Wang (2010) concluded that while the headwaters region has experienced severe ecosystem deterioration in recent decades "*there are no obvious trends for either precipitation or evaporation over the past 50 years*". Average annual temperatures have risen by only a small fraction of a degree Celsius corresponding perhaps with the slight increase in sunshine hours. The authors concluded with the statement "*Human activities were found to be the leading causes of vegetation degradation in the region*".

Contrary to the position taken by closed system rangeland scientists like Harris (2010), drivers and generators of rangeland degradation cannot be reduced to simple "causes", primarily because watersheds are complex open systems with a multitude of dynamic factors acting in concert. Because these factors are changing daily and seasonally, their dynamic behaviour, time lags and spatial discontinuities prevent cause-and-effect analysis. For these reasons, objective heuristic experiments using complex open system geosciences are required to diagnose ecosystem dysfunctions and ecological strategies for correcting them (Tane 2009; Tane et al. 2014).

13.6.2 Predominant Functions of Rangeland Watersheds

Mountain–river–lake watersheds provide essential life support functions in the Sanjiangyuan region. They are relied on to sustain communities with hundreds of millions of people in the Chinese heartlands and South-east Asia. These headwaters regions are required to provide reliable supplies of fresh living water free of unnecessary risks and hazards. This poses challenges for equitable and efficient governance in the headwaters region (Ci 2004).

From the perspective of pastoral communities inhabiting the upper reaches of the Huang He, the overriding purpose of the watersheds is grazing their domestic herds of ponies, yak, sheep, goats and cattle. To support them in this endeavour, they evoke gods and deities using a formidable blend of religious proscriptions, spiritual practises and cultural forces. It has worked that way for millennia. Reconciling cultural cognitive dissonance without hostile conflicts will be difficult if not intractable, without participatory watershed programmes building cooperative community approaches.

Arguably, long proven cultural strategies empowering traditional cultural intelligence of a united China provides the only safe way forward (Fig. 13.14). History has demonstrated time and again, that reconciling the two cultures is only feasible or possible by following the central theme of Chinese, Mongolian and Tibetan cultures: by *living in harmony with Nature.* Inscribed for posterity by Lao Zi in the Dao de Jing (circa 2500 Years BP), the way of living in harmony with nature is represented by elevating the water dragon representing living water (huo shui) over the hard hoof fire horse (Qilin) representing dead and dying water. The alternative is bleak and depressing; involving endless hostilities over grazing rights and privileges, with dying rivers and dysfunctional watersheds draining catchments of dead water (shi shui) (Tane 2009).

In pursuing sustainable development through adaptive management of resource economies in the headwaters, maintaining and protecting the integrity of watershed systems is fundamental for:

- Amplifying and protecting watershed ecosystems for storing, cleansing and supplying abundant fresh clean water distributed through watershed aquifers and ecostructures operating sustainably for free.

Fig. 13.14 In the seventh century when the King of Tibet's cavalry forces invaded China, soundly defeating the Tang Emperor's armies, he won the Emperor's beautiful princess for his wife. They were married on the shores of Zhaling Lake. At Dari, in the centre of the headwaters region, impressive monuments have been erected showing Tibetans rule the mountains, and Chinese rule the rivers

- Maintaining the integrity of meteorological systems and stability of local and regional heat/water cycles by helping reverse pastoral desertification by preventing sunburn, soil erosion and salinity.
- Developing effective strategies for reducing risks and hazards from floods, droughts, seismic stress, high intensity storms and regional food and water security.

Policies defining constraints and opportunities are needed urgently to provide the guiding framework for planning and development. At present, mainstream research is overly focussed on pastoral grassland problems. This "pastoral problem mindset" is distracting attention from discovering and developing sustainable farming systems, while indirectly perpetuating dysfunctional activities and unsustainable grazing systems in the headwaters region. New programmes are needed to address the collapse of watershed ecosystems threatening the future of water supplies from the Huang He.

Restoring the functionality of watershed ecosystems in the headwaters region requires a range of initiatives and programmes including initiating *Participatory Community and Regional Watershed Programs* for the following:

- Rehydrating degraded floodplains
- Restoring desertified rangelands with strategic reforestation
- Reviving springs, streams, rivers and lakes
- Alleviating soil hazards ~ sunburn, salinity, soil erosion

- Appraising weeds as ecological resurrection floras for restoring degraded habitats
- Researching pests as ecological indicators of dysfunctional/unsustainable land use systems
- Modelling the community ecology of grazing animals/soft footed burrowing mammals
- Developing sustainable pasture systems for zero-grazing watersheds with barn farming
- Engaging local schools in measuring, monitoring and evaluating environmental health and
- Establishing joint venture research in partnership with pastoral communities.

Is there a sustainable farming system, one that can enhance rather than degrade the watershed ecosystems of the Huang He headwaters? Based on successess reviving mountain rangelands in other Chinese Provinces as well as other countries, the answer is an unequivocal “yes”. Before this issue can be addressed successfully in Xinghai-Tibet rangelands however; it is first necessary to resolve dilemmas distracting attention from critical matters.

13.6.3 Overcoming Cultural Cognitive Dissonance

Cultural heritage is central to the principles of sustainable development and environmental protection in UN Agenda 21’s key principles. Following formal adoption as the Rio Accord in 1992, culminating a process began by UNESCO and global science fraternities in 1968, more than two-thirds of countries globally have become cosignatories (UNEP 2010; UNEP and FAO 1997, 1999). As a result, the 27 key principles of UN Agenda 21 have been elevated to de facto international law through their formal adoption in many international treaties and conventions. However, such principles provide little guidance on how to resolve seemingly intractable watershed conflicts exemplified in the headwaters region of the Huang He.

Standoffs between farmers and pastoralists are classic case studies in cultural cognitive dissonance. The dilemma arising out of cultural cognitive dissonance revolves around differing beliefs, antagonistic attitudes and conflicting perceptions. They lead to opposing parties being unable to see things the same way or agree on basic premises. This predicament renders them disagreeable on the most basic aspects of any issue.

Cultural perceptions of mountain rangelands are varied and divergent. With the benefit of historical hindsight recorded over millennia, it is apparent that many pastoral communities continue relentlessly with their destructive deforestation and grazing practices until their rangeland ecosystems are completely derelict (Hillel 1991; Tane 2009). This human predicament is widespread in cultures which view wetlands as water-logged wastelands, unpalatable floras as noxious weeds and normal flooding as “natural hazards”. There are however; several successful

Reforesting rangelands in La Jia

Reforested river valleys

Reforested dune compromised by grazing

Juniper replanting at higher altitudes

Reforested eroding rangelands

Tree planting for fuel and shelter

Fig. 13.15 Examples of reforestation in the headwaters of the Huang He

examples of progressive attitudes to reforestation in the headwaters region that deserve closer attention (Fig. 13.15). These ecological restoration strategies and practices await acceptance by local pastoral communities. In this respect, a broader range of sustainable land use activities need to be identified, proven and promulgated through participatory watershed planning and development programmes (Tane 2009).

13.6.4 Transcending the Natural Versus Cultural Dichotomy

In cultural ecography and watershed ecology, there is no fundamental difference between native and exotic, natural and artificial. These are subjective, anthropocentric concepts reflecting the compartmental mindsets of taxonomists and biologists, not the co-evolutionary processes of symbiotic communities, the ecosynthesis of ecosystems, or the ecogenesis of watershed ecosystems. As noted by UNESCO in their Man and the Biosphere Program (1970):

> To the ecologist, there is no fundamental difference between natural, wild or modified, semi-natural or developed, domesticated or purely artificial vegetations. The laws governing these ecosystems are identical.

Degradation of streams, soils and salinity, vegetation and wildlife communities and watershed ecosystems in the headwaters is a product of dynamic interactions between ecological processes and cultural impacts. The main drivers of degradation, however, are unsustainable human activities undermining the stability and resilience of ecosystems. Understanding how this occurs is hindered, if not prevented, by engaging in natural versus cultural debates. They are integral parts of the same complex open ecosystems which cannot be separated scientifically into biological compartments for closed system analysis (such as the analysis underpinning the yak farming versus pika "pests" debate (Tane 2012; see Li et al. Chap. 7; Fig. 13.16).

Resolving this dilemma is a straightforward matter of inventorying and auditing watersheds objectively, establishing the conditions of habitats and communities and the potential of their ecosystems (Tane and Nanninga 1992; UNESCO 1970, 2009). Without this watershed inventory and performance audit, policies and guidelines are unable to address the situation accurately and reliably. Problem-oriented management approaches cannot be conducted without bias or prejudice

Yak grazing and grooming has a wide range of impacts on landscapes and ecosystems. Physical impacts include destabilisation of edges/banks, compaction of soils, acceleration of runoff, depletion of aquifers and reductions to biomass.

Pika burrows aerate soils and accelerate aquifer recharge. This is especially important in areas where hard hooved animals have compacted soils.

Fig. 13.16 Animals of ecosystem disturbance—animals of ecological restoration until a comprehensive inventory and objective audit of habitats and ecosystems are completed. Overarching policies relating to the whole watershed can be compiled and condensed during the audit. Promulgating watershed policies in plain and simple language with maps and illustrations that are easily understood by all members of the community is fundamental.

13.6.5 Watershed Hazards and Environmental Risk Management

Human activities and land use systems are drivers and generators of environmental risks and hazards, particularly where they are compromising critical functions supporting watershed ecosystems. A typical example from the headwaters is how pastoral desertification generates flash floods and more frequent incidences of severe droughts, while loading waterways with pathogen-laden nutrients, sediments and salts renders the water unfit for human uses (Tane 2009).

There are other human impacts to address as well. Ecotoxic agrochemicals and engineering infrastructure networks like roads, railways, towns and industrial areas have potential to severely disrupt watershed ecosystems. Environmental performance safeguards are required if they are to be used or operate successfully in rangeland ecosystems without exacerbating the destruction of watershed ecosystems, depletion of aquifer systems or generation of new hazards (Tane et al. 2014).

13.6.6 Adapting to the Dynamics of Change and Uncertainty

Pastoral grazing cultures worldwide tend to ignore or overlook the impacts of their grazing activities, blaming the inevitable consequences of grazing herds of hard-hoofed livestock on external "causes" over which they have no control (Hillel 1991). Typically, pastoral cultures blame pests and weeds, climate change or global warming for land degradation, viewing pastoral grazing as inherently natural, normal and necessary. As yet they have not learnt to adapt their farming systems to the sustainable development parameters or requirements of watershed ecosystems (Hillel 1991; Tane 2009).

More than 8000 years of pastoral adaptation in the Huang He headwaters has resulted in the slow but steady degradation of watershed ecosystems, in ways remarkably similar to the pastoral desertification of the Middle East under Abrahamic pastoral cultures; India's rangeland degradation under Hinduism; and the human-induced desertification of Australian and New Zealand rangelands under pastoral Christianity (Fig. 13.17). In these global regions, blame for these calamities is often laid by pastoral leaders on global warming or an unreliable capricious Nature (Andrews 2006; Tane 2009).

Grazing tracks accentuate hillslope erosion, creating terracettes with broken cryptogam bioseals.

Tracks from sheep and goats indicate a nearby Moslem village that supports arable farming and tree cropping in the upper Huang He valley

Terracettes produced by tracks and trails are ecological indicators of severe to extreme pastoral degradation of rangelands

Track and trail terracesttes further drain dry moist soils, providing nesting habitat for burrowing mammals such as plateau pika

Fig. 13.17 Sheep and goat terracettes ~ incremental terrain degradation

As renowned river makers Rajendra Singh and Peter Andrews have demonstrated in Rajasthan and Australia, when provided with the right opportunity, riverine ecosystems can repair themselves through adaptive ecosynthesis (Andrews 2006; Tane1996). Ecosynthesis is the co-evolutionary re-building of new ecosystems through progressive community adaptations integrating habitats and regoliths that forge watershed ecostructures.

As zoologist Monbiot (2013) records in his book *Feral*, some human communities are re-engaging with Nature to re-discover a traditional indigenous way of living sustainably and more productivity. In adopting feral approaches, Nature is allowed freedom to find its own way without human interference, enabling ecological processes to repair essential life support systems. Monbiot describes this way as living in harmony with Nature. Aligning with traditional Dao culture and modern restoration ecologists, Monbiot recommends we restore degraded environs ecologically by allowing feral communities free range instead of grazing domestic ungulates. His advice paraphrases strategies implemented by Andrews (2006) and outlined in Lao Zi's *Dao de Jing*.

It is perhaps remarkable that there is still very little cultural awareness evident in the headwaters region of how free-range grazing of hard-hoofed livestock ~ yak, cows, horses, sheep and goats ~ are radical agents of geomorphic change and champions of ecological degradation. Ecogenesis of the Qinghai–Tibet rangelands indicates that formerly widespread shrublands, woodlands and forest communities have been replaced by habitats with eroding skeletal soils partially covered by tough grass mats, complete with pastoral pests and weeds. Over extensive areas, aquifer springs, discharge seeps, wetland meadows, bogs and flushes have collapsed into corrugated terrains characterised by erosion gullies and moving sands, shining white with salt.

The first step to address these perilous issues entails auditing the ecological status of watershed habitats and their land use communities of soils, vegetation, livestock and wildlife, including springs, streams, rivers and watershed ecosystems.

13.6.7 Auditing Rangeland Watersheds for Ecologically Sustainable Development

Compliance and performance audits of watershed ecosystems are increasingly necessary to diagnose their dysfunctions as a prelude to ecological restoration programmes (Tane and Nanninga 1992, 1995; Tane and Williams 1999). Similar methods were used for validating traditional methods for rehydrating degraded floodplains ecosystems (Tane and Andrews 1998). The methodology is called Eco^3 Sustainability auditing (Tane and Yu 2002; Tane et al. 2014). Eco^3 Sustainability is a function of integrating ecography.ecology.economy using geospatial sciences with image-based geospatial intelligence systems like watershed iGiS (Tane and Nanninga 1992; Tane and Yu 2002; Tane et al. 2014).

Mapping habitats and modelling ecosystems is called ecography: from *ecos* (home habitat) and *graphy* (to map, model or draw). When watershed habitats are accurately and reliably mapped and modelled, it is possible to diagnose their complex ecological relationships and evaluate their economic implications. Ecography is a traditional cultural practice in the Asia-Pacific region. It is commonly used to define a community's home territory, showing the distribution of habitats, resources and their assignment among members of the community (Tane 2009). In Mesolithic and Neolithic times, similar methods were used for recording the assignment of resources in the Qinghai–Tibet rangelands. A traditional Tibetan mandala woven in rugs on display in the Qinghai Museum was described by the Tibetan guide as representing the home territory of a community complete with resource rights of families. Much later, when Buddhists arrived from India, they adapted Tibetan manadas to create spiritual maps of the cosmos.

Eco^3 Sustainability audits of watershed ecosystems have been used in Australia, New Zealand, India and China to diagnose ecological dysfunctions of watersheds. They provide a platform for community and regional participatory watershed programmes (Tane and Yu 2002; Tane 2009; Tane et al. 2014). A similar methodology was used in reconnaissance field surveys for the present study.

13.6.8 Sustainable Watershed Systems

In mountain rangelands with heterogeneous terrains and climates, it is usual to find land use systems based on self-regenerating or planted forests. Self-regenerating forests and woodlands provide diverse habitats for wide-ranging food/fuel forest resources including medicinal herb and fungi, specialty timbers, renewable fuels, wildlife habitat and farming communities. They are also able to be adapted to recreation parks, wildlife conservation reserves and religious tourism resorts. When accompanied by ancillary activities such as goose and duck farming, freshwater aquiculture, and farming activities that enhance the performance of watershed systems (maintaining aquifers, riparian ecotones and their terraqueous ecostructures), they comply with the principles for ecologically sustainable development integrating ecosystem protection (UN Agenda 21).

Environmental health and animal welfare are closely intertwined. The health of animals reflects the quality of the water they drink, the food they consume and the habitats and ecosystems they occupy. Consequently, the health of grazing livestock is jeopardised by (a) water supplies contaminated with animal excrement and human faeces, (b) pastures contaminated with excreta, dangerous pathogens and poisonous plants and (c) habitats polluted with ecotoxic agrochemicals such as herbicides and pesticides. When food and water supplies are polluted with disease-laden pathogens and algae, and pastures are contaminated with faecal matter and ecotoxic agrochemicals, animal health and welfare suffers.

Viewed from the perspective of pastoral cultures, grazing is *believed* to be natural, normal and necessary. Viewed from the perspective of sustainable development of watershed ecosystems, pastoral grazing is a land use activity that is fundamentally incompatible with the primary functions of rangeland watersheds. Participatory watershed programmes are proven ways of providing a mechanism to assess this cultural dissonance and resolve it.

Tibetan and Mongolian farming systems previously involved a complicated resource assignment process involving clans and families, with kings and deities empowering and enabling pastoral grazing on accessible terrains. Under the contemporary household responsibility system, leasehold land tenures were introduced with exclusive family occupation blocks based on sedentary farming systems. Under this approach, open ranges are being fenced and subdivided into exclusive family parcels of private property able to be sold and traded. At the same time, more intensive pastoral grazing practices have emerged, unleashing dire consequences for watershed ecosystems.

Assuming that Tibetan, Mongolian and Moslem communities will persist with livestock farming as a central theme in their rangeland culture, there is an urgent need to find a way to accommodate hard hoofed livestock while protecting watershed ecosystems. A traditional farming system eminently suited to resolving this cultural dilemma is evident in Tibetan, Mongolian and Moslem rangeland land settlement systems. Pastoral farming settlements with high stone-walled yards and enclosed sheds where livestock are kept secure from predators at night provide an

Traditional stock land/farm

New barn livestock management

Zero grazing farmland

Zero grazing trenches as part of water management (irrigation) schemes

Fig. 13.18 Examples of zero-grazing farmlands

excellent start. These hamlets are usually surrounded by grasslands which would flourish and recover if they were unimpeded by trampling herds of hard-hoofed animals.

The solution may be closer than expected. In recent years, an advanced livestock farming method has been introduced to Qinghai, achieving higher levels of production with better stock health. It builds on traditional Tibetan practices of securing livestock in barns and yards overnight. Enclosed yards for securing flocks and herds against predators and thieves provide an important cultural connection leading directly to modern barn farming with zero grazing (Fig. 13.18).

In zero-grazing farming systems, all the food and fodder for livestock are harvested and taken to the animals kept in purpose-built barns complete with exercise yards (Muel et al. 2012). Livestock barns and their exercise yards have specific location and terrain requirements. Ideally, livestock barns and adjacent yards should be constructed in warmer thermal belt zones on hills and mountains, at sites where browsing and grazing animals typically congregate in cold weather. These elevated locations allow nutrient-rich effluents to be injected into mid slope recharge zones, to seep through aquifer networks and ecostructures, enabling effluents to fertilise and nourish the pastures lower down the slopes. With zero grazing and nutrient flows re-established through near-surface aquifers, lowland meadows can recover more quickly, gradually returning to denser, taller grasslands. Sustained by wetter soil conditions, meadows will become more productive, with aquifer flows alleviating summer droughts while sustaining perennial springs and streams.

Barn farming with zero-grazing achieves superior animal health and welfare with higher productivity. Because all the fodder is kept clear of the ground on feeding racks, barn-fed livestock are able to consume their food, free of their faeces which drops into clean straw or wood chips. Straw spoiled with animal wastes is cleaned out regularly and fed to worm farms or applied as mulch to pastures well away from watercourses. By these simple expedient measures, animals no longer need to eat through their faeces, as they do in free-range grazing. As a result, pathogenic pathways in ruminant animals are interrupted and broken, effectively reducing animal infections and diseases. Nor are the livestock infecting water courses with their pathogens, or mucking and pugging riparian habitats. The outcomes are beneficial for water resources springs, streams and rivers.

13.6.9 Sick Rivers Can Be Saved

Eliminating grazing by hard-hoofed animals is a time-proven, commonly used solution to help regenerate sick streams, dying rivers and degraded watersheds. Although China is now a world leader in these methods, very few constraints on grazing are effective in the headwaters region. While domestic grazing impacts have been reduced (in some areas) in the headwaters district around Zhaling and Eling lakes, effective river restoration is still a long way off. The severity of degradation and erosion is so great in the headwaters district that drastic measures are necessary. It will be a challenging task, particularly in a predominantly pastoral district where conventional wisdom holds that everything that can be grazed should be grazed. There is also a need for ensuring continuing pressure from predators to prevent feral grazing animals from occupying critical riparian zones too frequently.

As noted in the recovery plans for the largest freshwater lake in China (Poyang Lake in Jiangxi Province), an integrated watershed strategy is required to alleviate and diminish the calamitous impacts of human activities like grazing and mining. A simple and effective strategy is needed which acknowledges and enhances the ecological and economic connectivity of mountain-river-lake regions:

> To fix the lakes, first fix the rivers
>
> To fix the rivers, reforest their watersheds
>
> To reforest the watersheds, eliminate poverty
>
> (by providing sustainable livelihoods)

Technology changes culture

Horse trails as hard as roads

Reservoir fish farms

Honey production

Forestry and tree crops

Tree farms and barn-raised livestock

Fig. 13.19 Farming futures for the headwaters

Dysfunctional watersheds can be restored and sick rivers can be saved. World-renowned "river makers" Rajendra Singh (Rajasthan) and Peter Andrews (Australia) have shown how the cultural intelligence of indigenous peoples can be adapted to revive dead streams and dying rivers (Tane 2003). By taking the pre-emptive step of removing all hard-hoof livestock, allowing pastoral weeds to flourish, and planting willows to repair floodplain headlands, re-establish aquifers, and restore ecostructures, these river makers liberated ecological processes to revive streams and rivers, and recover perennial stream flows and environmental health (Tane 2009). In the absence of grazing animals, ecogenesis leads to ecosynthesis and the restoration of ecostructures. Ecostructures are fundamental to the health of watershed ecosystems for these ecologically linked suites of habitats and regoliths, function as self-regulating systems for harvesting, storing, cleansing, diffusing and releasing fresh clean water throughout floodplains and watersheds (Tane 2004, 2009).

The success of the twin policies (zero-grazing and rangeland reforestation) in restoring watersheds and rebuilding functional ecosystems provides a cost-effective pathway for reviving streams and rivers while reducing climate chaos. Destocking and reforestation allow the revival of terraqueous habitats and recovery of the heat/water balance. These actions remain the most effective strategies for reversing pastoral desertification (Tane et al. 2014) while providing opportunities for sustainable development of farming in the headwaters (Fig. 13.19).

In order to maintain the integrity of living watershed systems of the Huang He headwaters, hard-hoofed livestock should be secured in barns and yards and their feed taken to them. By this approach, practical farming of mountain rangelands may enhance watershed systems in an ecologically sustainable manner (Tane et al. 2014).

13.7 Conclusions

In this chapter, a transdisciplinary approach has been used to examine ecological relationships among habitats, regoliths and meteorological processes in the Huang He headwaters to reveal ecogenesis of watershed ecosystems their habitats and ecostructures. From information gathered over five years of fieldwork, ecological performance and dysfunctions were assessed. The assumptions and procedures are those of complex open system sciences: eclectic, integrative, and geospatial.

A strategic combination of reconnaissance surveys, site visits and literature reviews reveals how human-induced desertification was generated in repeated cycles over millennia by pastoral communities grazing flocks and herds of hard-hoofed animals everywhere possible. Urgent action is needed to halt and reverse human-induced desertification before salinity compromises the complete river system.

The Qinghai–Tibet rangelands are consistently ranked by UN agencies among the most severely degraded regions on the planet. How this occurred and what can be done about it requires engaging pastoral communities in the new sciences of cultural ecography, watershed ecology and resource economy. These geosciences do not rely on traditional alpha-numeric closed system analytical methods; nor do they focus on pastoral problems. They employ geospatial intelligence developed using complex open system ecosciences in efforts to revive ecological functions and restore resource prospects. They also build on the traditional cultural intelligence of indigenous cultures in ways that are more easily understood by local farming communities, using ecographic models and pictorial representations, rather than esoteric alpha-numeric research in languages foreign to local communities.

Summarising, the transdisciplinary geospatial approach applied in this chapter helped to:

- Assess hydrographical and meteorological processes connecting habitats and regoliths with their land use and vegetation communities
- Integrate disparate findings of separate disciplines and subjects using transdisciplinary research and development methods to provide a consistent evaluation of land degradation and desertification processes and
- Distinguish the cultural beliefs of different ethnicities and the subjective perceptions of specialist scientists from the objective ecological conditions prevailing in watersheds.

Our evaluation of watershed ecogenesis has confirmed how during Mesolithic and Neolithic times through to the heydays of the Tibetan Empire in the seventh century, and modern times, incremental deforestation combined with transformation of terraqueous wetlands to much drier terrestrial grassland pastures, amplified human impacts, until critical watershed systems in the headwaters region succumbed and failed. This calamitous predicament is known globally as pastoral desertification of rangeland watersheds.

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References

Aldenderfer, M. (2011). Peopling the Tibet Plateau: Insights from archaeology. *High Altitude Medicine and Biology, 12*, 141–147.

Andrews, P. (2006). *Back from the brink*. Sydney: ABC Books.

Bardon, G. (1991). *Papunya Tula: Art of the western desert*. Marleston, South Australia: Gecko Books.

Bellwood, P. (2005). *First farmers: The origins of agricultural societies*. New York: Blackwell.

Ban-ki Moon. (2011–2014.) UN Secretary-General on climate change, dryland degradation and rural poverty. UN News Centre UNCCD online

Brierley, G. J., Li, X., Cullum, C. et al. (2016a). Introduction: Landscape and ecosystem diversity in the Yellow River Source Zone. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 1–34). Berlin: Springer.

Brierley, G. J., Li, X., Cullum, C. et al. (2016b). Geomorphic diversity of rivers in the upper Yellow River basin. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 59–78). Berlin: Springer.

Carter, G. F. (1961). Movement of people and ideas across the Pacific. In J. Barrau (Ed.), *Plants and the migrations of pacific peoples, tenth pacific science congress, Honolulu Hawaii 1961* (pp. 7–22). Hawaii: Bishop Museum Press.

Chang, K. C., Xu, P. F., Lu, L. C., et al. (2012). *The formation of Chinese civilization: An archaeological perspective*. US: Yale University, New World Press.

Ci, L. J. (2004). *Combating desertification, in regional sustainable development review China, UNESCO encyclopaedia of life support systems*. Oxford: EOLSS publishers. http://www.eolss.net. Retrieved 14 June 2011

Consigli, P. (2008). *Water, pure and simple. The infinite wisdom of an extraordinary molecule*. London: Watkins Publishing.

Curry, R. R. (1976). Watershed form and process: The elegant balance. *Geology, 400*, 1–27.

Drucker, P. (1959). Long range planning means risk taking. In D. W. Ewing (Ed.), *Long range planning for management* (pp. 7–20). New York: Harper and Row.

Eldridge, D., & Tozer, M. E. (1997). *Soil lichens and bryophytes of Australia's dry country*. Sydney: Land and Water Conservation.

FAO. (2006). *Livestock's long shadow: Environmental issues and options*. Rome, Italy: UN Food and Agriculture Organisation.

Fulmer, W. E. (2000). *Shaping the adaptive organisation*. New York: Amazon.

Gao, J., Brierley, G., Cheung, A., et al. (2013). Geomorphic-centered classification of wetlands on the Qinghai-Tibet Plateau, Western China. *Journal of Mountain Science, 10*, 632–642.

Geiger, R. (1950). *The climate near the ground*. (German by M. Stewart et al., Trans.) for Blue Hill Meteorological Observatory, Harvard University, Harvard University Press.

Goonan, P., Jenkins, C., Hill, R., et al (2015). *Subsurface groundwater ecosystems—A briefing report on the current knowledge, monitoring considerations and future plans for South Australia*. Environmental Protection Authority, Adelaide

Han, M. Q., Brierley, G. J., Cullum, C., et al. (2016). Climate, vegetation and human land use interactions on the Qinghai-Tibet Plateau through the Holocene. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 253–274). Berlin: Springer.

Hancock, P. J., Boulton, A. J., & Humphreys, W. F. (2005). Aquifers and hyporheic zones: Towards an ecological understanding of groundwater. *Hydrogeology Journal, 13*, 98–111.

Harris, R. B. (2010). Rangeland degradation on the Qinghai-Tibet plateau: A review of the evidence of its magnitude and causes. *Journal of Arid Environments, 74*, 1–12.

Hillel, D. J. (1991). *Out of the earth: Civilization and life of the soil*. New York: The Free Press Macmillan Inc.

Holling, C. S. (1978). *Adaptive environmental assessment and management*. London: Wiley.

Hu, X. S., Brierley, G. J., Cullum, C., et al. (2016). Hillslope stability in the Yellow River source region. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 101–116). Berlin: Springer.

Huang, H. Q., Liu, X. F., Brierley, G. J., et al. (2016). Hydrology of the Yellow River Source Zone. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 79–100). Berlin: Springer.

Kaiser, K., Schoch, W. H., & Miehe, G. (2007). Holocene paleosols and colluvial sediments in Northeast Tibet (Qinghai Province, China): Properties, dating and paleoenvironmental implications. *Catena, 69*, 91–102.

Kelly, K. W. (1988). *The home planet: Images, and reflections of earth from space explorers*. Moscow: Mir Publishers.

Kravcik, M., Pokorny, J., Kohutiar, J., et al. (2007). *Water for the recovery of climate—A new water paradigm*. Slovakia: People and Water NGO and Associations of Towns and Municipalities.

Li, X., Perry, G., Brierley, G., et al. (2010). Grassland degradation of Alpine Meadow in the Sanjiangyuan region. In G. J. Brierley, X. Li & G. Chen (Eds.), *Landscape and environment*

science and management in the Sanjiangyuan region (pp 138–147). Qinghai: Qinghai People's Publishing House.
Li, X., Perry, G., & Brierley, G. (2016). Grassland ecosystems of the Yellow River Source Zone: Degradation and restoration. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 137–166). Berlin: Springer.
McGregor, G. R. (2016). Climate variability and change in the Sanjiangyuan region. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 35–58). Berlin: Springer.
Miehe, G., Kaiser, K., Co, S., et al. (2008). Geo-ecological transect studies in northeast Tibet (Qinghai, China) reveal human-made mid-Holocene environmental changes in the upper Yellow River catchment changing forest to grassland. *Erdkunde*, 187–199.
Miehe, G., Miehe, S., Bohner, J., et al. (2014). How old is the footprint in the World's largest alpine ecosystem: A review of multiproxy records from the Tibetan Plateau from the ecologists' viewpoint. *Quaternary Science Reviews, 86*, 190–209.
Miehe, G., Miehe, S., Kaiser, K., et al. (2009). How old is pastoralism in Tibet? An ecological approach to the making of a Tibetan landscape. *Palaeogeography, Palaeoclimatology, Palaeoecology, 276*, 130–147.
Miehe, G., Miehe, S., Koch, K., et al. (2003). Sacred forests in Tibet: Using geographic information systems for forest rehabilitation. *Mountain Research and Development, 23*, 324–328.
Miehe, G., Miehe, S., Vogel, J., et al. (2007). Highest treeline in the Northern Hemisphere found in Southern Tibet. *Mountain Research and Development, 22*, 169–173.
Monbiot, G. (2013). Feral: Searching for enchantment on the frontiers of rewilding. UK: Allen Lane.
Muel, M., van Passel, M. S., & Fremaut, D. (2012). Higher sustainability performance of intensive grazing versus zero grazing systems. *Agronomy for Sustainable Development (German), 32*, 629–638.
Muir, J. (1977). *The mountains of California*. Berkeley, California: 10 Speed Press.
Naiman, J. N., & Decamps, H. (1990). *The Ecology and Management of Aquatic-Terrestrial Ecotones* (Vol. 4, Man and the Biosphere Series UNESCO). Paris: The Parthenon Publishing Group.
Opgenoorth, L., Vendramin, G. G., Mao, K. S., et al. (2010). Tree endurance on the Tibetan Plateau marks the world's highest known tree line of the last glacial maximum. *New Phytologist, 185*, 332–342.
Proshansky, H. M., Ittelson, W. H., & Rivlin, L. G. (1970). *Environmental Psychology: Man and his Physical Setting*. New York: Holt, Rinehart and Winston Inc.
Qiao, Y., & Wang, Q. (2010). Driving forces of alpine meadow degradation in the Yellow River Headwaters. In G. J. Brierley, X. Li & G. Chen (Eds.), *Landscape and environment science and management in the Sanjiangyuan region* (pp. 149–165). Xining: Qinghai People's Publishing House.
Ruddle, K., & Zong, G. F. (1988). *Integrated agriculture-aquaculture in South China*. Cambridge: Cambridge University Press.
Ruijun, L. (2006). Alpine rangeland ecosystems and their management in the Qinghai-Tibet Plateau. In G. Weiner et al. (Ed.), *The Yak* (2nd Ed.). Bangkok: UN FAO (Chapter 13).
Sveiby, K.-E., & Skuthorpe, T. (2006). *Treading lightly: The hidden wisdom of the worlds oldest people*. Crows Nest, NSW, Australia: Allen and Unwin.
Tane, H. (1996). The case for integrated river catchment management, keynote address international conference on river catchments, Scotland, 11–13 Sept 1996. In *Multiple land use and catchment management* (pp. 5–9). Aberdeen, Scotland: Macauley Land Use Research Institute
Tane, H. (2003). Water first project: Gujarat India. Project reports for the National Organisation for Sustainable Development, Anan Gujarat, by the Watershed Systems Foundation, Oceania
Tane, H. (2004). Infrastructures and ecostructures: Environmental planning for sustainable settlement. *NZ Plan Q*, 54

Tane, H. (2009). Habitat and riparian management in rangeland ecosystems. In UNESCO's digital Encyclopaedia of Life Support Systems (Ed.), *Rangeland and animal sciences, food and agriculture* (52 p). Oxford: EOLSS publishers. http://www.eolss.net. Retrieved 18 May 2011.

Tane, H. (2010). *The crucial roles of willows in sustainable river management*. Twizel Aotearoa: The Watershed Foundation.

Tane, H. (2012). The Yellow River watershed in Qinghai's Sanjiangyuan region. In G. Chen, X. L. Li, J. Gao, et al. (Eds.), *Wetland types and evolution and rehabilitation in the Sanjiangyuan Region* (pp. X92–109). Xining: Qinghai People's Publishing House.

Tane, H., & Andrews, P. (1998). *Natural farming sequences*, Tarwyn Park. Woodward-Clyde, Canberra Scientific audits and validation of natural farming sequences restoring land and water systems on degraded floodplain in rangelands, Australia

Tane, H., & Dai, X. D. (1993). Catchment planning and conservation strategies in the Murray Darling Basin. *Australian Journal of Soil and Water Conservation, 6*, 35–39.

Tane, H., & Nanninga, P. (1992). Mapping and modelling the River Murray for ecologically sustainable development. In *Mapping for a green future. Proceedings of the 1st Australian conference on mapping and charting* (pp. 44–54). South Australia: Australian Institute of Cartographers, State Print

Tane, H., & Nanninga, P. (1995). *River Murray mapping—Technical manual and conference papers*. Canberra, Australia: Murray Darling Basin Commission.

Tane, H., Sun, T. H., Zheng, Z. L., et al. (2014). Auditing reforested watersheds on the Loess Plateau, Fangshan, Shanxi. *Ecological Indicators, 41*, 96–108.

Tane, H., & Wang, X. J. (2007). Participatory GIS for sustainable development projects. In P. Whigham (Ed.), *Proceedings of the 19th spatial information research consortium conference*. Dunedin: University of Otago.

Tane, H., & Williams, B. (1999). Upper Billabong Creek catchment: reports for Holbrook Landcare Group. A8601608 HXT/BW Woodward Clyde Canberra

Tane, H., & Yu, X. B. (2002). *Lake Poyang watershed: An integrated framework for sustainable development*. Resource Management and Environment Protection of the Mountain-River-Lake Region Jiangxi Province, China. MRL DO China, Watershed Systems NZ, GFA Terra Systems Germany, Nanchang, China

Trimble, W. T., & Mendel, A. C. (1995). The cow as a geomorphic agent: A critical review. *Geomorphology, 13*, 233–253.

UNEP. (2010). *Assessing the international impacts of consumption and production*. Report of the International Panel for Sustainable Resource Management

UNEP and FAO. (1997). *Negotiating a sustainable future.* Rome: UNEP/FAO.

UNEP and FAO. (1999). *The future of our land—facing the future*. Rome: UNEP, FAO.

UNESCO. (1970). Use and conservation of the biosphere. In *Proceedings of the intergovernmental conference of experts on the scientific basis for rational use and conservation of the resources of the biosphere*, Paris, Sept 1968

UNESCO. (2009). *Ecological sciences for sustainable development: Drylands and desertification*. Paris: Educational Materials for Schools. http://unesco.org

Walters, C. J., & Holling, C. S. (1990). Large scale experiments and learning by doing. *Ecology, 71*, 2060–2068.

Watts, A. (1972). The art of contemplation. Reprinted in cloud hidden whereabouts unknown. Mt J, Jonathon Cape London 1974

Weiner, G., et al. (2003/06). *The Yak* (2nd ed.). Bangkok: FAO (1st ed. by Li C, Weiner G).

Wilhelm, R. (1962). *The secret of the golden flower (Translation of the T'ai Chin Huan Tsung Chi)*. London: Routledge and Kegan.

Yu, G., Brierley, G. J., Huang, H. Q., et al. (2014). An environmental gradient of vegetative controls upon channel planform in the source region of the Yangtze and Yellow Rivers. *Catena, 119*, 143–153.

Zou, H., Zhu, J., Zhou, L., et al. (2014). Validation and application of reanalysis temperature data over the Tibetan Plateau. *Journal of Meteorology, 28*, 139–149.

Chapter 14
Socio-economic Development and Its Effects on the Ecological Environment of the Yellow River Source Zone

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Abstract Socio-economic development and protection of ecological environments are critical mutual challenges to human growth. This chapter provides an initial overview of the relationships between economic activity and the eco-environment in the Yellow River Source Zone on the Qinghai–Tibet Plateau. The broad geography, regional context and economic situation in the Yellow River Source Zone are first outlined. The catchment area and administrative districts of the Yellow River Source Zone are summarized, and the population history is overviewed. Key elements of the regional economy, animal husbandry and agricultural prospects are appraised. Landscape changes, grassland degradation and the causes of ecological degradation are related to the impacts of economic activities and legal considerations, showing how policy framings and management practices have affected the health of rangelands in the Yellow River Source Zone. These factors underpinned to the establishment of the Sanjiangyuan National Nature Reserve for ecological protection.

Keywords Alpine grasslands · Grazing · Animal husbandry · Ecological degradation · Economic activity · Eco-environment protection · Tibetan areas · Qinghai–Tibet Plateau · Sanjiangyuan National Nature Reserve

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14.1 Introduction

The Yellow River Source Zone is an important part of the Sanjiangyuan region. It has a similar geographical position, soil conditions and climatic conditions to those experienced in the source regions of the Yangtze River and the Lancang (Mekong) River. However, different trajectories of change are evident for these three rivers. In recent years, the annual run-off of the Yellow River Source Zone has significantly reduced, while flow of the Yangtze River and the Lancang River has remained stable or even risen (Yellow River Source Zone research group of Qinghai Province, 2005). Since 2005, the Yellow River has dried up several times. Problems of ecological degradation in the Upper Yellow River Basin are much more severe than those in the adjacent Upper Yangtze River Basin. For these reasons, the Yellow River Source Zone has attracted much attention from "natural" scientists, but to date research on the relationship between social sciences and environmental impacts has received very limited attention. This chapter seeks to address this limitation, providing an initial overview of the relationships between economic activity and the eco-environment in the Yellow River Source Zone.

Given its clear boundary and ease of access to historical records of population and economy, the Yellow River Source Zone is described in this chapter solely in relation to administrative districts within Qinghai Province. In this definition, the Yellow River Source Zone refers to 15 counties, which includes six counties in Golou, four counties in Huangnan and five counties in Hainan prefectures. This covers a total area of 137,700 km^2 (see NDRC 2014). Importantly, this definition is consistent with that used in the Qinghai Ecological Protection and Construction in the Sanjiangyuan—Phase II, which has been implemented in the Yellow River Source Zone since 2013 and for which most of the environmental data are available (NDRC 2014) (Fig. 14.1).

Given its special geographical location and natural resources, the Sanjiangyuan region has distinctive circumstance in relation to its social and economic development. The natural resources in the region are very abundant, but their development and utilization are constrained by many factors, including the physical environment, accessibility and logistical considerations, available funding and investment and access to recent technology. Like other places in the region, the economy of the Yellow River Source Zone relies heavily on animal husbandry, with a limited area of farmland in the east and south-east of this region, and a very small industrial area in an early stage of development. Despite pockets of development, the region as a whole remains underdeveloped.

In this chapter, we use historical records from the late Qing Dynasty until the present to assess stages of economic development and their relationships to the environment. We identify two turning points in development trends: (a) the foundation of the People's Republic of China in 1949 and (b) the establishment of the Sanjiangyuan Provincial Reserve in 2000.

Historically, the region between the Yellow River and the Yangtze River was referred to as Amdo. This was one of the three traditional regions of Tibet, the

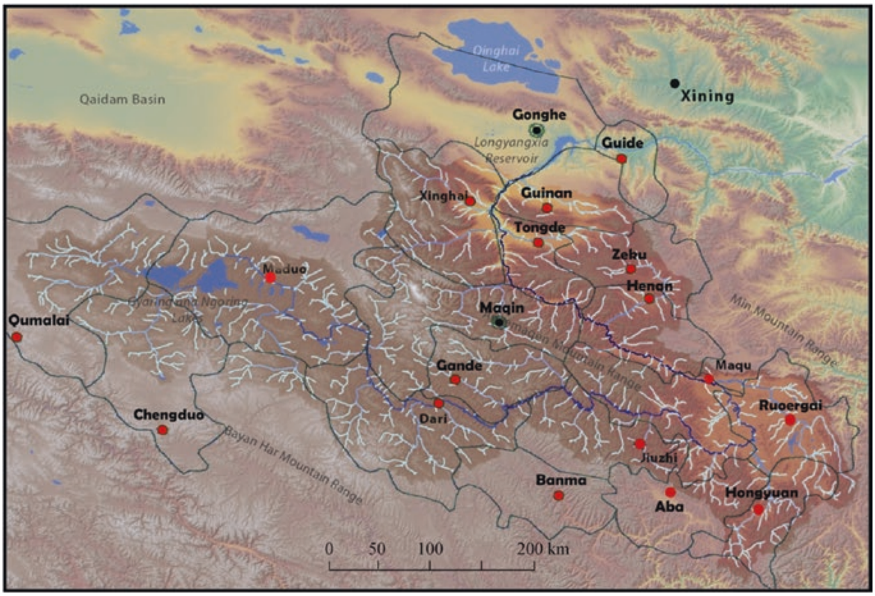

Fig. 14.1 The catchment area and administrative districts of the Yellow River Source Zone. The catchment area is from Blue et al. (2013), and the administrative districts with 19 counties are from the administrative maps of Qinghai, Sichuan and Gansu provinces. In this chapter, the Yellow River Source Zone refers solely to the 15 counties in Qinghai Province (i.e. Aba, Hongyuan and Ruoergai counties in Sichuan and Maqu County in Gansu are excluded)

other two being Ü-Tsang and Kham. While historically, culturally and ethnically a Tibetan area, Amdo has been administered by a series of local rulers since the mid-eighteenth century and the Dalai Lamas have not governed the area directly since that time (although the 14th Dalai Lama was born in this area in 1935). From 1917 to 1928, much of Amdo was intermittently occupied by the Hui Muslim warlords of the Ma Clique. In 1928, the Ma Clique joined the Kuomintang, and during the period from 1928 to 1949, much of Amdo was gradually incorporated into Qinghai Province (and part of Gansu Province) of the Nationalist Republic of China. By 1952, Chinese Communist forces had defeated both the Nationalist Army and the local Tibetans and had assumed control of the region, solidifying their hold on the area by 1958 and formally ending the political existence of Amdo as a distinct Tibetan province.

A harmonious relationship between economic development and the ecologic environment was evident in the late Qing Dynasty. The foundation of the People's Republic of China initiated economic development, increases in population and an increase in livestock numbers. In combination with declining rainfall, these changes triggered an ecological crisis in the Yellow River Source Zone, characterized by the emergence of "*Heitutan*" (degraded alpine meadows, see Li et al. 2016a, Chap. 7). The foundation of the Sanjiangyuan Provincial Reserve in 2000 (upgraded to a national reserve in 2003) has brought about moves towards restoration and protection of the ecological environment. Approaches to ecological restoration and protection remain a contentious issue, competing against pressures for economic development in this region. This presents significant concerns for researchers and for the national and provincial governments.

This chapter is structured as follows. First, the broad geography, regional context and economic situation in the Yellow River Source Zone are outlined. Second, the population history is overviewed. This is followed by an appraisal of key elements of the regional economy, focusing on animal husbandry, agricultural prospects more broadly and the limited industrial development of the region. Fourth, a summary of ecological degradation is presented, focusing primarily upon grassland degradation and the emergence of *Heitutan*. Section 14.5 relates ecological degradation to the economic situation. The next section describes the establishment of the Sanjiangyuan Reserve and efforts to protect and restore ecosystem services in the region. The chapter closes with a comment on future prospects, highlighting how future environmental conditions are intimately linked to socio-economic circumstances.

14.2 Economic Status of the Yellow River Source Zone

By the end of 2013, the population of the Yellow River Source Zone was 0.92 million. Tibetans comprise 77.6 % of this population. 75.5 % of the population was made up of herdsmen or farmers.

The gross domestic product of Yellow River Source Zone was 21.57 billion RMB (Chinese yuan). Of this, 25.1 % was contributed by the primary production (animal husbandry, agriculture and forestry), 45.1 % from the secondary sector (manufacturing, mining and construction) and 29.6 % from the tertiary service sector (which includes commerce, transport and tourism). The disposable income of urban residents was 19,657 RMB per capita per year, while that of farmers and herdsmen was 5458 RMB per capita per year.

14.3 Historical Population Changes in the Yellow River Source Zone

Because of the geography, climate, environment and economy, the population density in this region is, and always has been, very low. Based on existing historical materials, the earliest record of population in the region dates from the Daye period in the Sui Dynasty (607–615), which refers to Guide County in Hainan Prefecture (Cui et al. 1999). There were 2240 households in this prefecture in the Daye period of the Sui Dynasty (607–615). Later, in the 6th year of the Yonghui period of the Tang Dynasty (655 AD), there were 4261 households with a population of 24,400 people. At the time of the Zhiyuan period of the Yuan Dynasty

(1264–1294), there were about 6000 households, while in the 11th year of the Qianlong period of the Qing Dynasty, in 1746, the population was over 115,601. By 1853, the population of Guide County had exceeded 198,050 people (GSHTAP 2009).

According to the “Local Records of Toshi, Annals of Sichuan” (1814), there were 350 households in Golou, with a population of 1510. In 1941, there were 51 tribes in Golou, with 13,300 households (GSGTAP 2009). In the late Qing Dynasty in 1914, the population was about 70,000 (map annals of Ganzi County, 1961; Zhou 1968). In 1949, the census reported the population of Golou Prefecture as 53,652 (Committee of Qinghai Provincial Conditions, 1986).

Jing and Xu (2005) estimate that the total population of the Sanjiangyuan region in 1814 was about 40,000, growing to 150,000 by 1949. These figures suggest that a population increase of 75 % (about 5.61 % per year) occurred in the Sanjiangyuan region from the mid-Qing Dynasty to the Min period (1814–1914). The rate of increase was notably faster in the Min period (1914–1949), with a 90 % increase at an average rate of 18.62 % per year.

After the foundation of the People’s Republic of China, the four prefectures of Sanjiangyuan region (Yushu, Golou, Huangnan and Hainan) were founded, and the population grew dramatically. In 1953, the population in the Yellow River Source Zone was 249,841, but had almost quadrupled by 2013 (Table 14.1).

In terms of population density across the Yellow River Source Zone, numbers increased from 1.12 people km^{-2} in 1964 to 1.45 in 1970, 2.2 in 1982, 2.31 in 1985, 2.74 in 1995, 3.28 in 2005 and 4.16 in 2013. The impact of human activities upon the environment is likely to be closely related to population density. However, it should be remembered that the overall population density in this area is very low, with some places largely uninhabited.

Table 14.1 Population changes in the Yellow River Source Zone 1953–2013, based on census data

Prefectures	1953	1964	1982	1990	2000	2010	2013
Hainan	115,721	166,699	324,995	361,355	401,743	441,689	463,440
Huangnan	79,800	85,463	147,364	181,995	225,462	256,716	268,061
Golou	54,320	56,067	103,708	119,973	140,397	181,682	192,926
Total	249,841	308,229	576,067	663,323	767,602	880,087	924,427

Notes The data were collected from the Qinghai statistical yearbooks published in 1954, 1965, 1983, 1990, 2001, 2011 and 2014 (QBS 1952, 1954, 1965, 1983, 1990, 2001, 2011, 2014). In Golou, there were no data published for 1953, so the data from 1952 are substituted. Note that Yushu Prefecture is part of the Upper Yangtze River Basin and is not included here

14.4 Economic Activity in the Yellow River Source Zone

Animal husbandry, agriculture, forestry, mining, industry, commerce, transportation industry, tourism, engineering construction and service provision are the primary economic activities in the region. The influence of human activities depends not only on population size, but also on the industrial structure. For instance, vegetation destruction and soil erosion in the Yellow River Source Zone are mainly associated with animal husbandry, while localized water and air pollution mainly result from mining and industry.

14.4.1 Animal Husbandry

Since ancient times, animal husbandry has been the key primary industry of the Yellow River Source Zone. Western Qiang people were the first tribe to develop animal husbandry in the Yellow River Source Zone, followed by nomadic peoples of Xianbei, Tuyuhun, Tibet and Mongolia (Zhai and Cui 2004). Unfortunately, historical records retain little information on the livestock population. The first record referred to as "notes of Qinghai" stated that in the late Qing Dynasty (around 1910), the livestock belonging to Mongolians in Qinghai and Tibetan people around Qinghai Lake totalled about 2.52 million (Kang 1968). Based on these numbers, the total livestock in Qinghai Province would have been more than 4 million. This estimate contrasts with the estimate of the total livestock in Qinghai Province in the early Min period (around 1915) provided by Zhai and Cui (2004) of 7.53 million, rising to 12.28 million in 1937 and 7.49 million in 1949. In 2013, the total livestock in the Sanjiangyuan region took up 53.3 % of the total livestock in Qinghai Province. Based on this ratio, estimates of the livestock population in the Yellow River Source Zone from 1814 to 2013 are summarized in Fig. 14.2.

After the foundation of the People's Republic of China, animal husbandry developed rapidly, especially in the 1970s and the 1980s. Data trends in recent years can be derived from the analysis of the Qinghai statistical yearbooks (QBS 1996, 2006, 2011, 2014). In 1995, the gross productivity in the Yellow River Source Zone was 2 billion RMB, and the productivity of animal husbandry was 1.02 billion (i.e. 51 % of gross productivity). However, by 2005, the gross productivity was 5.97 billion RMB, only 1.79 billion of which came from animal husbandry (a reduction in contribution rate to 29.9 %). By 2009, the gross productivity was 10.84 billion RMB, of which animal husbandry provided 3.07 billion (a further decrease to 28.3 %). Finally, by 2013, the gross productivity was 21.57 billion RMB, of which animal husbandry provided 5.42 billion (25.1 %). These data indicate that industrial structures in the region changed significantly over this period (see also Li 2007a).

Three key traits can be discerned in the recent history of economic performance of the Yellow River Source Zone. First, while productivity increased sharply, the

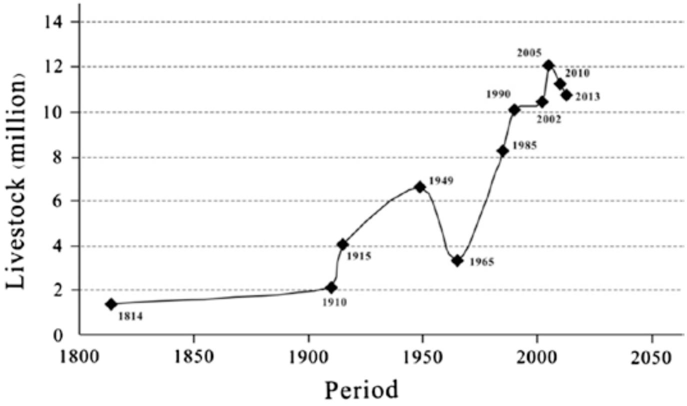

Fig. 14.2 Estimated livestock population (yak and sheep) in the Yellow River Source Zone from 1814 to 2013 (see text for details). (Nb. The units are individual animals, not "sheep unit")

Table 14.2 The composition of livestock in Golou Prefecture of the Yellow River Source Zone (*Source* QBS 1996, 2014)

Year	Yak number (×10,000)	Sheep number (×10,000)	Yak proportion (%)	Sheep proportion (%)
1995	103.15	136.21	43	57
2013	61.52	55.16	53	47

contribution rate from animal husbandry declined significantly. Second, although livestock numbers initially increased, since around 2003 they have decreased. Third, the composition of livestock has changed significantly, with the number of yak increasing while the number of sheep has decreased. This latter trend is evidenced from Golou Prefecture from 1995 to 2013, where the proportion of yak increased by 10 %, while the proportion of sheep decreased by 10 % (Table 14.2).

14.4.2 Agriculture/Crop Planting

Crop planting in Qinghai Province is located primarily in the Hehuang Valley, making up only a very small area in the Yellow River Source Zone. Minor areas are located along the main valley floors in Tongde, Xinghai, Zeku and Maqin counties. The cropped area in the Yellow River Source Zone has remained relatively stable in the last 30 years (2.66×10^4 hm^2 in 1985; 2.41×10^4 hm^2 in 1995; 2.66×10^4 hm^2 in 2013; QBS 1986, 1996, 2014).

14.4.3 Industry

Since ancient times, industrial development in the Yellow River Source Zone was largely restricted to a little traditional handicraft. As more and more machinery and equipment came into the area since the 1960s, various small enterprises such as factories and mines started to develop, marking the initial phases of emergence of an industrial system. Industry expanded to include processing of animal products, coal, power, gold mining, construction and wood processing. Industrial growth and economic development has been especially pronounced since the 1990s. The gross value of industrial output in the Yellow River Source Zone was 0.43 billion RMB in 1995, rising to 1.37 billion RMB in 2000, 2.40 billion RMB in 2005 and 9.72 billion RMB in 2013 (data from the Qinghai statistical yearbooks published in 1996, 2001, 2006 and 2014, adjusted for inflation). In 2013, there were 28 industrial enterprises, with 5 in Huangnan, 22 in Hainan and one in Golou prefectures.

14.4.4 Mining

The Yellow River Source Zone is relatively rich in mineral resources. Golou is mainly rich in coal, alluvial gold, lake salt, limestone and stibnite. Hainan is mainly rich in copper and ferroalloy. Existing records provide little indication for extraction of these resources prior to the foundation of the People's Republic of China. Mining commenced after 1958, with the rapid development in the 1980s and 1990s associated with the rapid growth of population, the formation of towns and the establishment and development of local industry. For example, the output of raw coal in 1958 (2.16×10^4 t) rose to 6.49×10^5 t in 1995. Since 2005, government policies for environment protection have brought about gradual decreases in the output of raw coal (QBS 1959, 1996, 2006).

Golou is rich in alluvial gold. Initial mining endeavours began in the 1920s and 1930s. By 1985, the population of gold miners was 12,000, and two years later, the discovery of some major deposits brought about a significant increase in the number of gold miners and the amount of gold production. From 1996 to 1999, the cumulative production of gold in Golou was 419.38 kg and then fell to 94.84 kg in 2000 and 96.77 kg in 2001. A big copper mine in Maqin County has an annual production of around 110,000 tons. The mining industry in Huangnan was relatively small prior to 1992 but has experienced significant and rapid development since then with the development of many silicon carbide and ferrosilicon factories. In 2000, a big aluminium profile factory was set up here, generating 1157 t of aluminium ingots in 2005.

Summary of mining production statistics for the Yellow River Source Zone in 2013 is as follows: copper = 2.988×10^4 t, cement = 63.3×10^4 t, ferroalloy = 3.5×10^4 t, non-ferrous metal = 3.2×10^4 t and electrolytic aluminium = 3.2×10^4 t (data from the 2014 Qinghai statistical yearbook). The rapid development of the mining industry brought about a major boost to the local economy, but at the same time, it also impacted upon grassland vegetation cover and the local ecological environment.

14.5 Landscape Change and Grassland Degradation

14.5.1 Change in Land Use and Land Cover

Pan and Liu (2005) and Huang (2012) note significant changes in land use and land cover in the Yellow Region Source Zone between 1986 and 2005. Construction land, unused land and cultivated land area increased rapidly, while the area of grassland was reduced, changing mostly into unused land. Wetland and the forest land decreased markedly. The degree of landscape fragmentation and the diversity index increased, as the land cover became more heterogeneous. The eco-environment was very vulnerable and sensitive to land use change, resulting in land desertification (Li and Wang, Chap. 8), soil and water loss (Tane et al. 2016, Chap. 13) and degradation of high-cold meadow vegetation (Li et al. 2016a, Chap. 7) and wetlands (Li et al. 2016b, Chap. 9; Gao 2016, Chap. 10).

14.5.2 Grassland Degradation

Based on the interpretation of 10.44×10^4 km^2 of satellite remote sensing images, Wang et al. (2004) noted that the rate of grassland degradation in the 1980s–1990s was twice the rate of degradation experienced in the 1970s–1980s. Dai et al. (2006) stated that the grassland area changed greatly in the period of 1992–2000, decreasing at a rate of 1151.5 km^2 year^{-1}. Decreases in the average coverage of vegetation have been accompanied by an expansion in the area of land desertification. According to Jing et al. (2005), the grassland degradation in the Yellow River Source Zone is much more severe than that in the source region of the Yangtze River and the Lancang River (Table 14.3).

Table 14.3 Comparison of grassland degradation in three areas of Sanjiangyuan region (*Source* Jing et al. 2005)

Land kind	Yellow River Source Zone (%)	Source regions of the Yangtze River and the Lancang River (%)
Desertified	17.84	12.37
Pest infested	33.15	13.30
Heitutan	7.34	3.36
Secondary bare land	16.87	5.48

14.6 The Cause of Ecological Degradation

Controversy abounds in determining underlying causes of grassland degradation in the Yellow River Source Zone (e.g. Harris 2010; see Li et al. 2016a, Chap. 7). In broad terms, researchers can be divided into two groups, those who favour a "natural" cause and those who favour an "anthropogenic" cause. The "natural" cause group believes that environmental changes in the Yellow River Source Zone are the result of global climate change, manifest as elevated temperatures, reduced precipitation and increased evaporation. Taken together, these factors have induced a drought trend that is considered to be the main cause of environment degradation in the region (Tang and Wu 1996; Wu and Li 2004). The "anthropogenic" cause group suggests that climate change is ultimately a relatively slow process and that overgrazing has been the main reason for degradation of grassland ecosystems in recent decades. Overgrazing is considered to have reduced grass biomass, changed the species composition, changed the compaction of grassland and promoted rodent outbreaks, such that all of these factors collectively have broken the balance and stability of the eco-system (Li et al. 2013, 2014). Given sustained high grazing pressure, the ecological environment has suffered continuing deterioration (Chen et al. 2014; Cheng and Wu 2007; Fan et al. 2010).

In reality, degradation of ecological environments in the Yellow River Source Zone is likely a response to both natural and anthropogenic causes. Climate changes are undoubtedly vital over long timescales, but over shorter (annual–decadal) timescales, many scientists and the government consider the effects of overgrazing (and associated economic development and resource depletion) to have induced enhanced desertification across much of Northern China, including the Yellow River Source Zone (Chen et al. 2014; Kang et al. 2007; Wang et al. 2007; Xue 1996; Yang et al. 2015).

Here, we review trends of environmental degradation in relation to the main anthropogenic causes, focusing upon the population record and economic data.

14.6.1 Economic Activity

A clear linear relationship is evident between environment deterioration and population, livestock, economic development and industry structure. With the increase of population, the area and scope of human economic activities expanded and extended significantly. In the Yellow River Source Zone, the industry structure is almost entirely dependent upon animal husbandry. As a consequence, overgrazing has become the main cause of ecological degradation since the 1970s and 1980s. This period of rapid population growth across China was coincident with the fastest economic growth period in the Yellow River Source Zone. The population and livestock size in the Yellow River Source Zone in the 1980s were twice those experienced in the 1960s. By 2013, population and livestock size had increased by

Table 14.4 Carrying capacity calculation table of usable grassland in the Yellow River Source Zone (units: 10,000 hm^2, 10,000 sheep unit)

Prefecture	Available grassland after grazing prohibition		Existing artificial grassland		Existing improved grassland		Total theoretical capacity	Actual carrying capacity	Theoretical livestock reduction
	Area	Theoretical capacity	Area	Theoretical capacity	Area	Theoretical capacity			
Golou	223.91	198.08	1.78	13.66	1.38	4.14	215.88	455.48	-261.76
Hainan	245.62	92.48	1.74	15.47	2.68	8.04	115.99	593.04	-477.05
Huangnan	84.2	50.55	1.45	11.44	0.36	1.08	63.07	237.59	-174.52
Total	553.73	341.11	4.97	40.57	4.42	13.26	394.94	1296.11	-913.33

Data in the table were collected from the report of the second phase for the ecological protection and restoration of NRSS (NDRC 2014) and the general situation of Tibetan Autonomous Prefecture of Haungnan (Duojiecairang et al. 2009), Golou (Huagongjie et al. 2009) and Hainan (Doubenjia et al. 2009)

3.7 times. After the Reform and Opening-up of China, and the associated development of secondary and tertiary industries, the relative proportion of primary industries to total economic production continued to decrease. However, the absolute productivity from animal husbandry only decreased by a small proportion at this time, such that overgrazing in the Yellow River Source Zone became severe (Table 14.4).

The cost of economic development, especially consequences for overgrazing and excessive excavation, has accentuated grassland degradation and desertification on the one hand, but on the other hand, it has brought about heightened awareness of environmental sensitivity and impacts of human activities/behaviour. Under the influence of a market economy, modern herdsmen have become "economic practitioners", increasingly maximizing economic benefits by increasing stocking production and changing routines in their daily life. The law of a market economy that seeks to maximize economic benefits for minimum economic costs has indirectly brought about significant damage to the ecological environment of the Yellow River Source Zone.

14.6.2 Regulations, Policy, Legal and Cultural Factors

First, from the regulatory perspective, the household contract responsibility policy did not work very effectively in Qinghai Province, with significant consequences for environmental management in the area. Since 1984, in the early stages of this policy, livestock production was greatly increased in all pastoral areas of the Yellow River Source Zone. Undue emphasis upon "separation" while excluding concerns for "integration", along with the market-based economic philosophy, brought about overgrazing and ecology deterioration in this area and other pastoral areas in China (Li 2007b).

Second, from a legal point of view, the Grassland Law issued in 1985 regulated between state and collective ownership, but the specific provisions for collective ownership were unclear. Furthermore, the separation of ownership of grassland surface resources and underground resources meant that grasslands often lacked an appropriate guardian, presenting an opportunity for their excessive exploitation (Wu 2014).

Third, from a cultural point of view, the traditional way of life, including the use of cattle and sheep manure for heating and cooking, has indirectly aggravated the ecological destruction of grassland (Dong 2009; Luo and Yang 2011). In the daily life of Tibetan herdsmen, 90 % of the total energy consumption is domestic energy, 99 % of which was provided by cattle and sheep manure, along with tree and grass roots. The average consumption of manure ranges from 5000 to 8000 kg for each family (Yu 2010). When manure is burnt, nutrients are not returned to the soil, such that the grasslands are slowly but surely stripped of nutrients (see Tane et al. 2016, Chap. 13).

14.7 Impact of Policy Framings and Management Practices upon the Health of Rangelands in the Yellow River Source Zone

Rangelands in China have been utilized for thousands of years with little trace of degradation. This likely reflects the limited intensity of land use practices. The mere fact that most rangelands of concern are considered to have been in much better condition only a few decades ago indicates that traditional pastoral systems are not inconsistent with long-term sustainability (Harris 2010). As such, these practices, of themselves, are not the underlying cause of grassland degradation. Sustainable production systems require a harmonious relationship between human utilization and natural resources, wherein grazing intensity does not impact negatively upon the health of rangeland ecosystems. Over the last 40 years, however, the rate of degradation has increased dramatically.

Rangeland degradation on the Qinghai–Tibet Plateau has been coincident with the rapid growth of human population, changes to land tenure that contracted rangeland areas to pastoralists (and subsequent increases in livestock numbers that induced overstocking) and subsequent irruptions of small mammals (Li et al. 2013). The population of pastoral areas in Qinghai doubled from 1949 to 2003, and livestock numbers increased 2.96 times during the same period, doubling the intensity of grazing in rangelands (Li et al. 2013). The urge to have large stocks resulted in an inadequate reserve of fodder and forage. Local animal husbandry production cannot escape the cycle of "survival in summer, fattening in autumn, thinning in winter and death in spring". As a result, some pastoralists are forced to graze their livestock at higher elevations, spreading anthropogenic impact and damage to wider areas (Li et al. 2013). These factors, in turn, have accelerated rangeland degradation and contributed to rodent damage in some areas. Unfortunately, it is not possible to increase livestock size through purchasing more fodder as this is beyond the financial means of the pastoralists.

Grazing exerts an important influence upon plant community structure and productivity in natural grasslands (Li et al. 2016a, Chap. 7). In some instances, fencing to exclude grazers is viewed as an important management practice to "protect" grasslands. However, Wu et al. (2009) showed that while fencing significantly improved above-ground vegetation productivity, it reduced plant density and species diversity.

Overgrazing over an extended period gradually lowers the density of vegetation cover, leading to the degradation of alpine meadow. Original species are progressively replaced by unpalatable and even toxic plants, and soil fertility is depleted. Irreversible rangeland degradation and the formation of the "black soil beach" (*Heitutan*) in meadow areas is characterized by coarsening of the surface layers of the soil, increases in bulk density, porosity and saturated hydraulic conductivity, and a decrease in the water-holding capacity of the soil. These changes create favourable conditions for native rodents to thrive, which in turn accentuates the formation of *Heitutan*. The rapid expansion in numbers of native rodents over the past 40 years reflects alterations to the structure of the food chain of the plateau ecosystem. In addition, illegal hunting has restricted the beneficial role of eagles (*Accipiter* spp.), Tibetan fox (*Vulpes ferrilata*) and weasels in limiting the impacts of harmful rodents upon grassland (Li et al. 2013).

Notions of assumed sustainability and resilience of traditional herding systems framed in relation to large-scale movements to mediate short-term livestock–pasture imbalances often naively ignore the desires of some pastoralists for more sedentary lifestyles that include better access to schools or medical care. Inevitably, nomadic pastoralists respond to economic and political incentives, choosing the path that they perceive will bring the most benefit and least pain to themselves and their families (Harris 2010). Prior to imposition of state control, this meant a traditional semi-nomadic pastoral lifestyle, in which herd sizes were limited by a combination of natural factors and the needs of a largely subsistence lifestyle. During the collectivization period, when immediate livestock production requiring large numbers of animals was mandated by policy, herd sizes were increased to levels beyond what could be sustained. This encouraged high livestock densities. With the dissolution of collectives and the rapid transition to a market economy in the 1980s, many pastoralists modulated their herd sizes to those which they perceived would make them the most money (e.g. Cincotta et al. 1992; Zhang et al. 2004). With the increased prices available for sheep and goat products (largely arising from outside the local area) and the increased ease of access to distant markets (largely in the form of mobile livestock purchasers from Xinjiang, Gansu or eastern Qinghai), larger herds meant larger short-term profits (Harris 2010). Lack of power to negotiate higher prices meant that higher profit could only be achieved by increasing herd size.

Ecological modernization narratives take for granted both a crisis of ecological degradation and the premise that the "greening" of the state will improve environmental conditions in Western China (Yeh 2009). However, the contextual underpinnings of these assertions are contested, and significant concerns have been raised for prospective socio-economic and cultural consequences (e.g. Cao et al. 2013; Harris 2010).

Natural grassland has been regionally degrading since the 1980s. This reflects a complex range of factors which vary spatially and temporally across the plateau, including differing combinations of climate warming, increasing population, fast-growing grazing pressure and rodent damage (Chen et al. 2014; Harris 2010; Li et al. 2013). Li et al. (2013) contend that although there is general agreement that the Qinghai–Tibet Plateau is particularly sensitive to global climate change, these considerations have played a secondary role in the degradation of grasslands in this area. The harsh natural environment (e.g. climate and fragile soil) of the area does not cause rangeland degradation in its own right. Rather, the area is inherently vulnerable to degradation due to its fragile eco-environment, such that overgrazing, rodents and exploitative utilization of rangelands do more damage to ecosystems here than in less sensitive environments (e.g. areas with more water resources and more amenable temperatures). Rangeland degradation would not take place in the absence of intensive human disturbances.

Ecologically based technological solutions to reduce overgrazing on the Qinghai–Tibet Plateau include concentrating livestock in places where they can be protected from the elements and provided forage grown off-site, increased fencing to facilitate rotation of pastures, restructuring herds to increase the proportion of reproductive females, and manipulating herd size frequently to reflect seasonal rhythms of vegetation biomass and nutrient levels (Harris 2010). Suggested remedies for rehabilitating degraded rangelands include killing small mammals, temporary or permanent removal of livestock, fertilization and/or reseeding (Harris 2010). Some researchers, such as Wu and Yan (2002), consider the "set of four" programmes including subsidizing construction of permanent winter homes, fences and livestock shelters, providing plots for growing supplemental winter fodder, settling down local people instead of semi-nomadic herding on the plateau and retiring livestock and restore rangeland over the past 40 years, to be a success, whereas others question the effectiveness of these initiatives (cf., Harris 2010; Li et al. 2013). For example, concentrating livestock near settlements and fencing programmes may impact negatively on local vegetation. Use of winter houses for longer periods adversely affects vegetation, increasing the intensity of use and associated impacts of trampling (see Tane et al. 2016, Chap. 13). Liu et al. (2006) found a significant relationship between the severity of degradation with distance from settlements.

Efforts to "retire livestock and restore pastures" also break traditional land use and cultural practices. Even if such initiatives succeed in reducing rangeland degradation (which is questionable, as most rangeland species are adapted to some level of herbivory), it is likely to carry enormous financial burdens and create considerable social and cultural dislocation (Harris 2010). Such endeavours scarcely constitute a sustainable socio-economic, cultural and environmental system.

It seems clear that Chinese policy will not tolerate a return to traditional nomadic pastoralism over large spatial scales, nor does this seem feasible given recent integration of livestock production systems on the plateau with distant markets and with ongoing socio-economic development taking place in pastoral areas (Harris 2010). Some kind of modernized livestock management, even if not what Chinese policy currently promotes, must ultimately be adopted. Ultimately, however, sustainable rangeland management and economic development of the Qinghai–Tibet Plateau is contingent upon local engagement and ownership of actions that fashion appropriate lifestyles and well-being, framing social, cultural and economic measures in an environmental context. Long-term sustainable outcomes will not be achieved unless they incorporate the aspirations of local citizens. Local knowledge and community-based institutions provide greater capacity for adaptation through shaping and mobilizing resource availability to reduce risks (Hu and Xie 2012). Large-scale ecological construction projects fashioned by state institutions provide one mechanism by which this may be achieved, prospectively promoting environmental improvement and economic growth within a virtuous, mutually reinforcing circle (e.g. Yeh 2009).

14.8 Establishment of the Sanjiangyuan National Nature Reserve for Ecological Protection

An initial nature reserve was established in the area in 2000. It was upgraded to a national nature reserve in 2003 (Li et al. 2012). In 2005, the first phase for the ecological protection and restoration of Sanjiangyuan was started, lasting until 2012. Establishment of the Sanjiangyuan National Nature Reserve prospectively provides an important step to address concerns for sustainable water resources management and biodiversity management, especially the protection of endangered flora and fauna (Li et al. 2012). The reserve comprises an area of 152,300 km^2, making up 21 % of the total land area of Qinghai Province (Chen and Zhao 2009; Li et al. 2012). The main protection targets include alpine wetland ecosystems, typical alpine meadow and alpine dry steppe, sparse alpine forest ecosystems and associated targeted wildlife species. The functional area of the Sanjiangyuan National Nature Reserve is divided into core, buffer and experimental areas (Fig. 14.3). *Core areas* are strictly protected areas; buffer areas are important protected areas; and experimental areas are normal protected areas in which consideration is given to both protection and utilization. The 18 core areas take up 31,218 km^2, equivalent to 20.5 % of the total land area of the reserve (Chen and Zhao 2009). Core areas are designated to protect typical natural ecosystems, fostering growth and reproduction of targeted wildlife, plants and organisms and their habitats by separating these areas of environmental protection and restoration from human activities. Zhongtie-Jungong, Douke River, Maixiu and Make River are core areas within the Upper Yellow River Basin that have been designated to protect typical forest and shrubbery, while Animaqin, Xingxingha, Nianbaoyuze, Yueguzonglie and Erlin-Zalin Lake protect wetland ecosystems (Chen and Zhao 2009).

Buffer areas surround core areas, or they connect core areas to assist in protecting targets (i.e. they address concerns for fragmentation), thereby controlling the impact of threatening factors/processes while restoring slightly degraded ecosystems. These areas buffer main protection targets from influences outside the

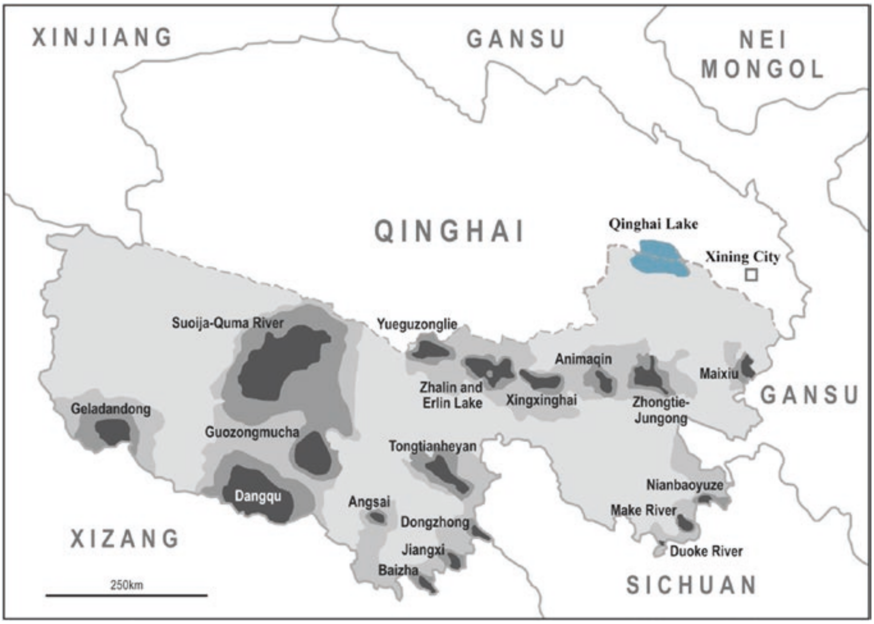

Fig. 14.3 Distribution of core (*dark* tone), buffer (*middle* tone) and experimental (*light* tone) areas in the Sanjiangyuan National Nature Reserve

natural reserve, linking core areas to assist in the protection of wildlife and creating separation from towns, factories and mining sites. Measures taken in the buffer areas include reducing grazing livestock numbers to sustainable forage, controlling grazing intensity through rotational grazing and closing some areas for restoration of forest and grassland vegetation.

Experimental areas outside core and buffer areas take up 81,882 km^2 (53.7 % of the total land area of the reserve). Efforts to assist the restoration and rebuilding of degraded ecosystems in these areas enhance the management of fragmented protection targets by providing a natural defence for core and buffer areas. Projects in experimental areas aim to aid the development and improvement of socio-economic conditions and living standards of herders through measures such as:

- Resettlement away from areas where the carrying capacity is exceeded (i.e. ecological migrants).
- Suspending grazing in some areas based on the assessments of sustainable grazing livestock numbers relative to the quantity of available forage in the area. However, significant controversy and concern have been triggered by the fencing dilemma, as efforts to protect and manage small grassland areas from overgrazing on the one hand may impact negatively upon ecosystem functionality, especially for migratory animals on the other.
- Protect and rehabilitate forest and grassland vegetation, wetlands and wildlife.

- Develop wildlife management programmes, including the banning of fishing.
- Promote water conservancy and improve wetland conditions by enclosing wetland areas to promote self-regeneration of natural vegetation, resowing wetlands that have been subjected to severe degradation and reducing livestock numbers or stopping grazing adjacent to wetlands. Rodent disaster programmes target the management of pica and marmot.
- Undertake small-scale water and soil erosion measures to enhance livestock production and control the spread of desert and areas of degraded grassland.
- Construct water supply facilities and develop new energy for household needs, alongside improvements to local energy sources, enhance herders' income and reduce dependencies upon remaining areas of forest and natural grassland.
- Set up research and monitoring bases.

Over the eight-year period from 2005 to 2012, the Sanjiangyuan National Nature Reserve achieved its planning target for construction and protection and met the objectives and requirements of the State Council "*to realize the protection and restoration of the ecological function, to promote the harmony between man and nature and sustainable development, and to help the farmers and herdsmen to reach a well-off standard of living*".

From 2005 to 2012, the average amount of surface water resources increased by 8.49 billion m^3 with the area of lakes increasing by 760 km^2 relative to the average level from 1988 to 2004. This instigated the recovery of the 'wetland of a thousand lakes' in the Yellow River Source Zone. Over the same period, vegetation coverage in areas of *Heitutan* (degraded alpine meadow) increased from 20 to 80 %, while the average yield of grass increased from 35.5 kg mu^{-1} (1 mu = 0.0667 ha) (2.37×10^4 kg hm^{-2}, average data of 1988–2004) to 45 kg mu^{-1} (3.00×10^4 kg hm^{-2}) in 2012. Also, the area of forestry increased 150 km^2 compared to 2005. In 2012, the annual average sediment concentration from river monitoring stations ranged from 0.046 kg m^{-3} to 4.3 kg m^{-3}, much lower than previous levels (from 1988 to 2004). For example, compared with the records from 2004, the annual average sediment concentration at Zhimenda, Xinzhai and Tongren stations decreased by 11.4, 60.3 and 16.3 %, respectively. The area of desert grassland shrunk by 95 km^2, and the vegetation cover in desertification control areas increased from 15 % in 2004 to 38.2 % in 2012. Water quality improved, enhancing the ecological environment of freshwater areas such that their overall condition was good, and aquatic biological resources were relatively intact.

These improvements in ecological restoration and construction were accompanied by improvements in the lifestyle and productivity of local residents. Between 2004 and 2012, 5×10^4 mu of irrigable forage base, 3.04×10^4 barns and 86 ecological migration communities were constructed. Furthermore, the Provincial Finance spent 0.6 billion RMB to improve the infrastructure of 23 small cities and towns, 30 million to set up a business support fund for ecological migration and 40 million every year (since 2009) as a maintenance allowance for ecological migrants. With this help, the farmers and herdsman in the Sanjiangyuan National Nature Reserve experienced an annual net income increase of 10 % from 2004 to 2012 (see http://cpc.people.com.cn/n/2014/0822/c83083-25519100.html). It should be noted that the investment in the Sanjiangyuan National Nature Reserve to date has been primarily in restoration and construction projects (Ma 2006; Zhou et al. 2010). The improvement in environmental conditions has therefore been mainly as an indirect result of this investment, aided by sustained increases in precipitation from 2004 to present (Qin 2014).

14.9 Summary and Concluding Comment

Although natural and anthropogenic causes have led to ecological deterioration in the source zone of the Yellow River, recent management investment and activities in the Sanjiangyuan National Nature Reserve have started to remedy some of these concerns. Ultimately, this relates to management of problems associated with population density, associated livestock stocking rates and lifestyle practices. These problems became pronounced after the foundation of the People's Republic of China, especially following the rapid growth of population and gross production in the 1970s and 1980s. Accentuated disturbance by human activity had a negative impact on the ecological environment. The incompatibility between ecological health and human economic activities was exaggerated by the relatively unsophisticated forms of animal husbandry production and excessive exploitation of land and water resources, such that the environment in the Sanjiangyuan area was unable to support the population in the region. In response to this concern, ecological protection and construction initiatives in the Sanjiangyuan National Nature Reserve have brought about environmental improvements and the possibility for ecological systems and human beings to coexist in a sustainable fashion. Through policy, institutional and legal systems, humans now have improved prospects. It remains to be seen how progress will be maintained in the second phase for the ecological protection and restoration of the Sanjiangyuan.

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References

Blue, B., Brierley, G., & Yu, G. A. (2013). Geodiversity in the Yellow River source zone. *Journal of Geographical Sciences, 23*, 775–792.

Cao, L., Zhang, K., Dai, H., et al. (2013). Modeling interrill erosion on unpaved roads in the loess plateau of China. *Land Degradation & Development*. In press.

Chen, H., & Zhao, Z.P. (2009). Analysis on the characteristics of land lover change in nature reserves in the Three River Source Region during recent 30 years. *Journal of Geo-Information Science, 11*(3): 390–399. (In Chinese with English Abstract).

Chen, B., Zhang, X., Tao, J., et al. (2014). The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agricultural and Forest Meteorology, 189*, 11–18. (In Chinese with English Abstract).

Cheng, G., & Wu, T. (2007). Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. *Journal of Geophysical Research: Earth Surface (2003–2012*), *112*(F2).

Cincotta, R., Zhang, Y., & Zhou, X. (1992). Transhuman alpine pastoralism in northeastern Qinghai province: An evaluation of livestock population response during China's agrarian economic reform. *Nomadic Peoples, 30*, 3–25.

Cui, Y., Zhang, D., & Du, C. (1999). *The general history of Qinghai*. Xining: Qinghai People's Publishing House (In Chinese).

Dai, J., Guo, W., & Yang, T. (2006). An analysis of grassland change and human factor function in headwater region of Yellow River based on NOAA-AVHRR data. *Technological Management of Land and Resources, 23*, 109–112.

Dong, J. (2009). *Culture introduction of Sanjiang source*. Xining: Qinghai People's Publishing House (In Chinese).

Doubenjia, Suonanjia, Huaqingjia, et al. (2009). *The general situation of Tibetan autonomous prefecture of Hainan, Qinghai province*. Beijing: Nationality Press (In Chinese).

Fan, J. W., Shao, Q. Q., Liu, J. Y., et al. (2010). Assessment of effects of climate change and grazing activity on grassland yield in the three rivers headwaters region of Qinghai-Tibet Plateau, China. *Environmental Monitoring and Assessment, 170*, 571–584. (in Chinese with English Abstract).

Gao, J. G. (2016). Wetland and its degradation in the Yellow River source zone. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and Ecosystem Diversity, Dynamics and Management in the Yellow River Source Zone*. (pp. 209–232). Berlin: Springer.

GSGTAP (General situation on Golou Tibetan autonomous prefecture in Qinghai). (2009). *General situation on Golou Tibetan autonomous prefecture in Qinghai*. Nationalities Publishing House. Xining, Qinghai, 6, the first version (In Chinese).

GSHTAP (General situation on Hainan Tibetan autonomous prefecture in Qinghai). (2009). *General situation on Hainan Tibetan autonomous prefecture in Qinghai*. Nationalities Publishing House. Xining, Qinghai, 7, the first version (In Chinese).

Harris, R. B. (2010). Rangeland degradation on the Qinghai-Tibetan plateau: A review of the evidence of its magnitude and causes. *Journal of Arid Environments*, *74*, 1–12. http://cpc.people.com.cn/n/2014/0822/c83083-25519100.html. Fruitful results were gained from the first phase of the project for ecological protection and construction of Nature Reserve of Sanjiang Source. 25 Aug 2014.

Huagongjie et al. (2009). *The general situation of Tibetan autonomous prefecture of Golou, Qinghai province*. Beijing: Nationality Press (In Chinese).

Huang, Q. (2012). *GIS based research on the changes of ecological environment and the influence of human activities in Sanjiang source region*. Master's thesis, Minzu University of China, Beijing (In Chinese).

Hu, L. and Xie, A. (2012). Supervision Mechanism of the Basic Social Security Benefits of the Ecological Migrants in the Origin of Three Rivers. *Journal of Anhui Agricultural Sciences, 40*(12): 7494–7496.

Jing, H., & Xu, J. (2005). Impacts of human activities on the ecological environment in the source area of Sanjiang source region since middle Qing Dynasty. *New Heights, 24*, 87–92. (In Chinese with English Abstract).

Jing, H., Xu, J., & Liu, A. (2005). The production capacity of land resources and population carrying capacity of the Sanjiang source region. *Qinghai Social Sciences, 26*, 46–49. (In Chinese with English Abstract).

Kang, F. (1968). *Notes of Qinghai*. Taibei: Chengwen Press (In Chinese).

Kang, L., Han, X., Zhang, Z., et al. (2007). Grassland ecosystems in China: Review of current knowledge and research advancement. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 362*, 997–1008.

Li, S. (2007a). *Study on adjustment of industrial structure in the 3 river sources*. Master's degree thesis, Northwestern University, Xian (In Chinese with English Abstract).

Li, T. (2007b). On grassland ecological culture. *Proceedings of the Fourth Symposium on grassland culture in Inner Mongolia*, China. (In Chinese).

Li, X., Brierley, G. J., Shi, D., et al. (2012). Ecological protection and restoration in Sanjiangyuan Natural Reserve, Qinghai Province, China. In D. Higgitt (Ed.), *Perspectives on environmental management and technology in Asian river basins* (pp. 93–120). Netherlands: SpringerBriefs in Geography.

Li, X., Gao, J., Brierley, G., et al. (2013). Rangeland degradation on the Qinghai-Tibet Plateau: Implications for rehabilitation. *Land Degradation & Development, 24*, 72–80.

Li, D., Lijiacairang, Q., et al. (2009). *The general situation of Tibetan autonomous prefecture of Huangnan, Qinghai province*. Beijing: Nationality Press (In Chinese).

Li, X. L., Perry, G., & Brierley, G. J. (2016a). Grassland ecosystems of the Yellow River source zone: Degradation and restoration. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River source zone*. (pp. 137–166). Berlin: Springer.

Li, X., Perry, G., Brierley, G., et al. (2014). Quantitative assessment of degradation classifications for degraded alpine meadows (Heitutan), Sanjiangyuan, western China. *Land Degradation & Development, 25*, 417–427.

Li, Z. W., Wang, Z. Y., & Pan, B. Z. (2016b). Wetland ecosystems of the Yellow River source zone. In G. J. Brierley, X. Li & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River source zone*. (pp. 183–208). Berlin: Springer.

Luo, K. L., & Yang, Z. H. (2011). On the relationship between traditional Tibetan nomadic way and the safety of the sources or three great rivers in China. *Journal of Jishou University (Social Sciences Edition), 32*, 37–42. (In Chinese with English Abstract).

Liu, L., Zhang, Y., Bai, W., Yan, J., Ding, M., Shen, Z., et al. (2006). Characteristics of grassland degradation and driving forces in the source region of the Yellow River from 1985 to 2000. *Journal of Geographical Sciences, 16*(2), 131–142.

Ma, H. (2006). A review of the research on the sustainable development of the Sanjiang source region. *Qinghai Social Sciences, 27*, 49–54. (In Chinese with English Abstract).

Mei, H. X., Zhang, Y., et al. (2009). *The general situation of Tibetan autonomous prefecture of Golou, Qinghai Province*. Beijing: Nationality Press (In Chinese).

NDRC (National Development and Reform Commission, China). (2014). *The second phase for the ecological protection and restoration of Sanjiangyuan*. http://www.sdpc.gov.cn/zcfb/zcfbghwb/201404/W020150203319341893483.pdf. (In Chinese).

Pan, J. H., & Liu, J. L. (2005). Land use and landscape pattern change in source region of the Yellow River. *Bulletin of Soil and Water Conservation, 1*, 29–32. (In Chinese).

QBS (Qinghai Bureau of Statistics). (1952, 1954, 1959, 1965, 1983, 1986, 1991, 1996, 2001, 2006, 2011, 2014). *Qinghai statistical yearbook* (pp 1952–2014). Beijing: China Statistics Press 08 (In Chinese).

Qin, D. (2014). *Ecological protection and sustainable development in Sanjiang source region*. Beijing: Science Press (In Chinese).

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) headwaters. In G. J. Brierley, X. Li, & C. Cullum et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River source zone*. (pp. 275–330). Berlin: Springer.

Tang, C., & Wu, Q. (1996). The effect of climate warming on the Qinghai-Tibet highway, China. *Cold Regions Science and Technology, 24*, 101–106. (In Chinese with English Abstract).

Wang, G., Ding, Y., Wang, J., et al. (2004). Land ecological changes and evolutional patterns in the source regions of the Yangtze and Yellow Rivers in recent 15 years. *Acta Geographica Sinica, 59*, 163–173. (In Chinese with English Abstract).

Wang, X., Lu, C., Fang, J., et al. (2007). Implications for development of grain-for-green policy based on cropland suitability evaluation in desertification-affected North China. *Land Use Policy, 24*, 417–424. (In Chinese with English Abstract).

Wu, X. (2014). On the legalization of ecological environmental protection in the Sanjiangyuan. *Journal of Qinghai Normal University (Philosophy and Social Sciences), 36*, 60–63. (In Chinese with English Abstract).

Wu, G. L., Du, G. Z., Liu, Z. H., et al. (2009). Effect of fencing and grazing on a Kobresia-dominated meadow in the Qinghai-Tibetan plateau. *Plant and Soil, 319*, 115–126.

Wu, Q., & Li, Y. (2004). Ground temperature monitoring and its recent change in Qinghai-Tibet Plateau. *Cold Regions Science and Technology, 38*, 85–92. (In Chinese with English Abstract).

Wu, N., & Yan, Z. L. (2002). Climate variability and social vulnerability on the Tibetan plateau: Dilemmas on the road to pastoral reform. *Erdkunde, 56*, 2–14.

Xue, Y. (1996). The impact of desertification in the Mongolian and the inner Mongolian grassland on the regional climate. *Journal of Climate, 9*, 2173–2189. (In Chinese with English Abstract).

Yang, X., Scuderi, L. A., Wang, X., et al. (2015). Groundwater sapping as the cause of irreversible desertification of Hunshandake sandy lands, inner Mongolia, northern China. *Proceedings of the National Academy of Sciences, 112*, 702–706. (In Chinese with English Abstract).

Yeh, E. T. (2009). Greening western China: A critical view. *Geoforum., 40*, 884–894.

Yu, X. (2010). *The role and mechanism of yak dung on maintenance for Qinghai- Tibetan plateau alpine grassland health*. PhD thesis. Gansu Agricultural University, Lanzhou (In Chinese with English Abstract).

Zhai, S., & Cui, Y. (2004). *Economic history of Qinghai*. Xining: Qinghai People's Publishing House (In Chinese).

Zhang, J., Liu, S., Li. H., & He, X. (2004). Analysis on the retrogression of the pasture in Naqu prefecture, Tibetan Autonomous Region. *Resources Survey & Environment, 25*(2): 116–122. (In Chinese with English Abstract).

Zhou, X. (1968). *Investigation report of Yushu*. Taibei: Chengwen Press (In Chinese).

Zhou, H., Zhao, X., Zhang, C., et al. (2010). The predicament of ecological migrants and sustainable development strategy in the source area of Three Rivers. *China population resources and environment, SS1*, 185–188 (in Chinese with English Abstract).

Chapter 15
Conclusion: Environmental Futures of the Upper Yellow River Basin

Gary John Brierley, Carola Cullum, Xilai Li and Jay Gao

We won't have a society if we destroy the environment.
Margaret Mead

Abstract The distinctive geography, ecology and history of the Upper Yellow River Basin have created a suite of unique, irreplaceable environmental and cultural values. However, significant development pressures present an all-too-familiar example of the challenges faced in achieving sustainability goals. This chapter pulls together various threads of enquiry explored in this book to scope prospective environmental futures of the Upper Yellow River. A socio-ecological systems approach to environmental management demonstrates how landscape approaches can provide a useful tool to negotiate trade-offs between competing social, economic and environmental objectives. Research needs and prospective management approaches to address threats to environmental and societal well-being are outlined. The chapter challenges the proposition that effective environmental protection and conservation can be achieved through a 'reserve' mentality applied independently from lifestyle values of people who live in the area. Participatory practices that frame human activities as part of nature, not separate from it, are required to support 'whole of landscape' approaches to ecosystem

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management that give due regard to social, economic, cultural and environmental considerations. Future prospects for the Upper Yellow River basin are shown to be far from a 'doom and gloom' situation.

Keywords Socio-ecological systems · Environmental management · Environmental protection · Biodiversity management · Ecosystem management · Regional development · Sustainability · Ecosystem services · Environmental history · Environmental futures · Conservation · Restoration/rehabilitation · Resilience · Sanjiangyuan National Nature Reserve

15.1 Introduction

The distinctive geography, ecology and history of the Upper Yellow River Basin have created a suite of unique, irreplaceable environmental and cultural values (see Brierley et al. 2016, Chap. 1). The global significance of the region is a product of its geologic and climatic setting, its ecosystems and resource base, and its cultural associations. However, significant development pressures present an all-too-common example of the difficulties faced in achieving sustainability goals and conservation planning (see Economy 2004; Goodman 2004; Liu et al. 2012; Shapiro 2012). We have a collective responsibility to look after the source zone—for local people, for China and for the world. What is the legacy we leave behind for those that follow?

Because of their history, isolation and variability of habitat, mountain regions are treasure chests of biodiversity and are rich in endemic species and genotypes (Hamilton and Macmillan 2004). Distinctive ecosystems have developed in response to the pronounced altitudinal belts in these areas. However, high-altitude terrains are especially susceptible to human-induced damage, and many elements of these fragile environments are vulnerable to accelerated rates of climate change. Habitat fragmentation and isolation have led to biodiversity losses. Around 18 % of the total number of species in the Sanjiangyuan is threatened (Chen et al. 2007). This is much higher than the world average of 13 %. Numbers of Tibetan antelope, white-lipped deer, red deer and snow leopard have decreased significantly, while alpine musk deer are almost extinct (see Brierley et al. 2016, Chap. 1).

In this chapter, we argue that while environmental protection is a vital consideration in the source zone of the Yellow River, effective conservation cannot be achieved through a 'reserve' mentality that views landscapes and ecosystems as 'museums' that are 'locked in time and space' (cf., Chan et al. 2007; McShane et al. 2011; Ran et al. 2016, Chap. 14). Rather, due regard must be given to the priorities of people who live, work within and shape these living socio-ecological systems, recognizing that these landscapes provide multiple values and services to diverse interest groups (e.g. Lawrence 2010; Sayer et al. 2013). Spatial segregation of protection and production functions of land does not provide a sustainable basis for environmental management. Many local environmental and sociocultural values are vulnerable to development pressures and associated government policies (see Ran et al. 2016, Chap. 14). We contend that visions for an ecologically sustainable future should seek to integrate proactive biodiversity management programmes with coherent strategies that promote regional development and natural resource management.

We feel that future prospects for the Upper Yellow River Basin are far from a 'doom and gloom' situation. Regional water resources remain plentiful and are an exceptionally valuable asset (Huang et al. 2016, Chap. 4). Tourism numbers are booming as infrastructure developments create increasing opportunities for visitors to experience the stunning landscapes and ecosystems of this region. Climate change presents new opportunities for agricultural and land use developments. In an age of increasing concern for food security, there are significant prospects to expand organic farming techniques that build upon traditional lifestyles.

This chapter pulls together various threads of enquiry explored in this book to scope prospective environmental futures of the Upper Yellow River. The chapter is structured as follows. First, a socio-ecological systems approach to environmental management is outlined, viewing human endeavours as part of natural systems. A landscape frame offers an integrating basis to assess prospective social and environmental futures. The second section of this chapter considers steps to support ecosystem management in the region. The third section provides a summary of threats to environmental and societal well-being in the Upper Yellow River Basin. The chapter concludes by identifying steps that can be taken to address these concerns.

15.2 Landscapes and Ecosystems as Socio-Ecological Systems

The mindset with which we see the world fashions our actions. Approaches to environmental management, and the priorities that we place on these measures, reflect societal choice and opportunity. The choices we make reflect our needs, values and perceptions, as we frame recreational, aesthetic and cultural connections in relation to consumptive needs. Choices reflect the values we think matter—what we seek to achieve in our relationship to the natural world and to each other. Opportunity refers to what it is possible to achieve through management efforts and lifestyle choices. Unfortunately, confronting images of degraded ecosystems across much of the planet remind us of the choices we have made to date. In a sense, environmental health can be viewed as a measure of the health of our society.

15.2.1 Humans and Nature: How are we Living with this Planet?

With each passing day, the human imprint upon Planet Earth increases. Humanity is quickly encroaching upon the finite limits of the biosphere. As the global population continues to increase and our technological capacity becomes forever greater, we exert an increasingly profound influence upon the world around us. The Anthropocene is already a living reality. Humankind has become a dominant force of nature, exerting unprecedented pressures on the planet's resources and pushing the Earth's biophysical system far outside of its historic operational range (Steffen et al. 2015). Human impacts upon Earth's life support systems have become so profound that they threaten many of the ecological services that are essential to society (Chapin III et al. 2011). The exponential growth of human activities is raising concern that further pressure on the Earth System could destabilize critical biophysical systems and trigger abrupt or irreversible environmental changes that would be deleterious or even catastrophic for human well-being.

Nature supports our lives. Healthy socio-ecological systems are self-sustaining and resilient. However, unsustainable lifestyles and levels of consumption threaten the viability of these systems, and hence our own well-being. A sustainable world is one in which concerns for socio-economic development and environmental protection are balanced in an equitable manner, such that people live in harmony with ecosystems. At present, this is not the case. Pervasive degradation of environmental systems is testimony to the non-sustainable lifestyles that we live—the choices made by society to date. Recognition of this situation is a critical first step in efforts to reform societal outlook and practice. The goal of Earth Stewardship is not to protect nature from people; rather, it is to protect nature for human welfare (Chapin III et al. 2011).

Sustainability should not be viewed simplistically as a negotiated trade-off. Half a habitat is not a viable option. Ecosystems are either sustained and are sustainable, or they are not. 'Business as usual' will not work. In many instances, societal choice reflects economic circumstance: what is affordable? As noted by Mahatma Gandhi, '*Poverty is the greatest polluter*'. Sustainability questions will always play a secondary role in the immediate quest for survival. Ultimately, however, environmental security is also a prerequisite for human survival. Moves towards sustainability require that we recognize immediately what we cannot afford NOT to do. The cost of environmental protection is cheaper, and more effective, than notional cures.

Proactive approaches to the sustainable management of environmental futures build upon rational plans that assess what to protect where, how to target rehabilitation initiatives and how to engage society in meeting these aims. These are social, economic, cultural, spiritual and attitudinal issues as much, if not more, than they are technical, scientific or technological issues. As yet, there are few indications that these threads are being meaningfully appraised in a coherent (collective) sense in the Yellow River Source Zone.

Efforts to protect and enhance biodiversity and support the intrinsic value of nature are required to ensure ongoing provision of ecosystem services (e.g. improved water quality, fertile and stable soils, drought and flood buffering, genetic diversity and carbon sequestration) that enhance human quality of life (e.g. clean water, food security, enhanced health and effective governance; de Groot et al. 2013; Suding et al. 2015). 'Thinking like an ecosystem' promotes a perspective in which the environment is not 'out-there'—rather, it recognizes explicitly that we live 'within-it'. Both technically feasible goals and scientifically valid goals require social acceptance. Major conservation and rehabilitation efforts will not be successful unless society approves the goals and objectives. Ultimately, environmental protection and repair are collective responsibilities that require appropriate visions, effective implementation and societal 'will' to improve environmental health and societal well-being. Unless applications are 'owned' by the communities involved, prospects for long-term, sustainable environmental health are likely to be compromised. Involving people through multiple avenues—from participation to consumption of ecosystem services to cultural renewal—can promote public engagement and stewardship of local ecosystems.

Environmental degradation and loss of biodiversity affect all of us, though some are affected more than others. Healthy and sustainable environmental systems will not be achieved by passively waiting for someone else to 'fix' the problems. How will we know, before it is too late, that we are approaching the limits to ecosystem viability? Coherent approaches to environmental management are conceptualized and operationalized at the landscape scale.

15.2.2 A Landscape Approach to Environmental Management

Landscape approaches help to negotiate trade-offs between developmental and environmental concerns, providing tools and concepts for allocating and managing land to integrate competing social, economic and environmental objectives. Sayer et al. (2013) define a landscape as an area delineated by an actor for a specific set of objectives. This definition extends beyond notions of landscapes as merely physical spaces. Rather, they are arenas in which physical, biological and social entities interact and change over time. Desirable changes in one component of the landscape may have unintended and undesirable repercussions. Landscape approaches therefore demand an open-minded view of outcomes and acknowledgment of the trade-offs likely to be involved in any system change. As land use and resource policies shape both social and environmental outcomes, clarifying and negotiating competing land use rights and responsibilities has now become a core role of resource management agencies across much of the world. Increasingly, engineering-style command-and-control approaches to resource use and environmental management are being replaced by community facilitation and negotiation between stakeholders (Sayer et al. 2013).

Landscape approaches to environmental management recognize that biological diversity is inextricably linked to the variety of landscapes and land-forming processes in any ecoregion (Wiens 2002; Wohl et al. 2005). The term 'geodiversity' can be considered to represent the diversity within components of the non-living world (i.e. diversity within the geosphere, as opposed to the biosphere; Parks and Mulligan 2010). The evolutionary processes that generate and maintain biological diversity are constrained by environmental processes that reflect landscape patterns and connectivity within a particular area. Patterns of resource availability are structured in space and time by these patterns of geodiversity (Parks and Mulligan 2010). A more varied landscape consisting of diverse habitats offers broader and more varied niche space available for species to fill (Dufour et al. 2006). Associations and habitat uptake vary over time, whether as a consequence of short term (e.g. diurnal or seasonal) variation, or longer term variation through climatic cycles and stochastic events. Thus, conserving geodiversity also conserves the biological processes that generate and maintain biodiversity, ensuring that the foundations for functioning ecosystems will still exist even if the current occupants (species) do not. Inevitably, prospects for recovery are inhibited if source populations are missing, regardless of the management actions we take.

Effective management practices aim to establish systems that are self-sustaining and resilient in a manner that is appropriate for the environmental context and landscape setting (Higgs 2003; Hobbs et al. 2011; Suding 2011). Recognizing explicitly that there are too many species to save them one at a time, extensive landscape-scale endeavours are required to maintain and/or enhance the resilience of ecosystems, supporting capacity for species to disperse, migrate, forage and reproduce. Ecosystems that are structurally and functionally diverse are more likely to be durable and capable of adapting to future challenges of climate change, introduced species and land use change (Suding et al. 2015).

In spatial terms, measures of geodiversity are typically framed in relation to landscape heterogeneity, considering types of entities and assessing how they are interlinked (i.e. their juxtaposition, pattern and connectivity). Not all landscapes and ecosystems are complex—some may be remarkably simple (Fryirs and Brierley 2009). Some boundaries are inherently impermeable; others induce significant constraints upon the operation of particular processes and the range of species (i.e. many landscapes are naturally disconnected; Fryirs and Brierley 2009). If a landscape is naturally disconnected, efforts to increase connectivity 'work against' nature. Conversely, management actions such as fencing programmes and dam construction artificially disconnect (fragment) landscapes and river systems. This impacts upon faunal migration pathways and inhibits prospects that species can reach their dispersal destinations, such that they are forced to live in habitats that are not large enough for their survival as they are unable to achieve genetic exchange. In general terms, decreased variability in habitat availability induces biodiversity loss.

In temporal terms, appraisals of landscapes as dynamic templates emphasize concerns for the range of variability of any given system, recognizing that responses to disturbance are the 'norm'. Hence, adjustments around an equilibrium condition are not always expected (Brierley and Cullum 2012). In this light, assessments of system sensitivity and resilience must be framed in relation to the expected 'range of behaviour', recognizing that surprises are inevitable, and particular combinations of circumstances may trigger unique (not previously experienced) outcomes. Such framings must consider the emergent and uncertain nature of prospective future adjustments, considering risks and threats to public health and safety in an open-ended, non-prescriptive manner.

Ultimately, the use of a landscape template emphasizes the primacy of place as a critical component of environmental management. How readily can lessons learnt at one locality be transferred elsewhere (Brierley et al. 2013)? Given the steep environmental gradients and proximity of different altitudinal zones in mountainous regions, with significant opportunities for biotic adaptation to environmental changes, large areas must be protected to support the adaptive capacity of these systems, giving species the opportunity to migrate to new habitats. Such considerations are particularly important given the large environmental changes that will accompany global climate change in coming decades.

15.2.3 History Provides Clues to the Future: The Importance of Evolutionary Trajectory

Environmental histories provide important guidance with which to inform environmental management. Much can be learned by looking to the past to inform the future, as evolutionary analyses provide fundamental understandings of causes and triggers of change, tipping points and bifurcations in evolutionary adjustment, and contingencies that fashion future adjustments. This helps to guide analyses of the range of potential future states and associated behavioural regimes (Fryirs et al. 2009; Surian et al. 2009). Inevitably, these situations are entirely contextual—they reflect local circumstances alongside broader-scale drivers and pressures for change, and limiting factors which may constrain the future range of variability. Modelling applications can be used to generate insights into the likelihood that a given state will be attained over a given time frame, taking into account prospects for lagged and off-site responses. Assessment of the likelihood of prospective future states/trajectories, alongside appraisals of their desirability, can define 'what is achievable' in relation to 'what is desirable/acceptable' in the management of environmental futures.

However, historical understandings are just that—interpretations of what landscapes and ecosystems used to be like. Although historical knowledge, in its many forms, provides insight into how ecosystems functioned in the past, the unprecedented pace and spatial extent of anthropogenic changes may create conditions that depart strongly from historical trends (Hobbs et al. 2011). Thus, history often serves less as a template and more as a guide for determining appropriate management goals (Balaguer et al. 2014; Higgs et al. 2014). Analyses of past conditions can only provide partial insights into prospective environmental futures. Socio-ecological systems are complex systems, wherein what has gone before does not necessarily provide a complete and reliable picture of prospective future conditions. In a no-analogue world, the emergence of novel ecosystems is inevitable (Hobbs et al. 2006, 2009, 2013).

Recent transitions in management practice emphasize concerns for process-based analyses of evolutionary trajectories as a basis to assess likely future states, rather than framing activities in relation to specific reference conditions that reflect past states. Associated management efforts incorporate future variability through the use of flexible, open-ended and dynamic goals (e.g. Hiers et al. 2012; Hughes et al. 2012). Target conditions that guide adaptive management practices can be viewed as stepping stones along evolutionary trajectories (Brierley and Fryirs 2015). As surprises are encountered and lessons are learned, both the targets and the management activities that aim to achieve these targets are adapted. Such flexibility flies in the face of command-and-control approaches that are often difficult to unpick and reframe, since built infrastructure and path dependencies impose significant constraints upon future management options. Learning to live with variability and complexity requires that we accept and embrace uncertainty. It is impossible to 'know' what the future will bring.

15.2.4 Growth with Safeguards: Balancing Development and Environmental Protection

Efforts to safeguard the future in West China face great challenges in balancing economic development and societal well-being while promoting environmental protection and restoration in the face of climate and land use change. Preventing future deterioration of environmental assets is a critical first step. Importantly, a wide range of landscapes and ecosystems in the upper basin of the Yellow River remain in good condition and continue to provide a host of environmental services. These values underpin prospects for socio-economic development of the region and therefore warrant effective environmental protection. Hence, it is vital to safeguard land and water resources by promoting sustainable land use.

However, what values are we trying to protect in ongoing management efforts in the Upper Yellow River Basin? How consultative are decision-making processes, especially in relation to those who live on (and off) the land? Is there a genuine commitment to participatory practice, remembering explicitly that conservation cannot be sustained through management of 'reserves' or 'parks' independent from people (see Ran et al. 2016, Chap. 14)? This situation is all the more untenable in the light of the grazing-adapted ecosystems shaped by human endeavours over thousands of years in this region (Li et al. 2016a, Chap. 7; Han et al. 2016, Chap. 8; Tane et al. 2016, Chap. 13). Rangelands continue to provide for the livelihoods of local herders. A viable pastoral society is vital to ensuring the sustainability of the prevailing socio-ecological system.

Having said this, rangelands are being degraded due to overgrazing, policy changes and climate change (Li et al. 2016a, Chap. 7; Tane et al. 2016, Chap. 13; Wu et al. 2015). The development of sustainable land use practices needs to draw upon both indigenous knowledge of grazing and rangeland management, as well as modern, more technical methods. Social transformations and economic changes are required to strengthen public participation and cooperation with all types of institutions to formulate appropriate policies and improve public services (Wu et al. 2015). A deep commitment to social and environmental justice underpins the likely effectiveness of such transformations in practice (Westley et al. 2011).

Managing for resilience requires integrative planning from the outset, not ad hoc strategies and actions. Iterative, flexible and ongoing processes of negotiation, decision-making and re-evaluation, informed by science but shaped by human values and aspirations are required (Sayer et al. 2013). We need a clear and shared statement of what we are trying to achieve (vision and goals), what we need to do to get there (strategies to achieve them), prioritization of actions to achieve goals and monitoring programmes to assess the effectiveness of these practices (and implement appropriate responses to lessons learnt). Given inherent complexities and uncertainties, management processes cannot be unduly prescriptive—they must be flexible and adaptive. A clear evidence base is required to support decision-making, identify assets and threats, and establish clear and measurable objectives for desired future states. Support tools are required to:

- Generate a clear understanding of what a sustainable world may look like
- Use foresighting exercises to prepare ourselves for likely futures, identifying circumstances under which changes in system state may occur
- Provide guidance on the steps that must be taken in working towards a sustainable world.

A landscape approach provides a framework to support consideration of choices in the setting, discussion and negotiation among options for environmental futures. In framing these deliberations, differing scenarios can be tested in terms of development, population pressure, climate change, land use, soil and water resources, environmental limits (boundaries), evolutionary traits, thresholds, etc. Environmental modelling applications can support analyses of eco-environmental dynamics, appraising pressures and threats in relation to cumulative impacts, thereby enabling foresighting and scenario-setting exercises to appraise prospective responses to management applications. Environmental Impact Assessments are required to facilitate proactive, precautionary management, using efficient and effective monitoring programmes to measure progress and develop responsive management strategies that learn from experience.

Throughout such endeavours, it must be remembered that the weakest link in any system (whether scientific/technical understanding, socio-economic and/or cultural associations, or managerial/governance issues) limits the performance of the system as a whole.

15.3 Management Responses to Pressures and Threats upon Environmental Values and Societal Wellbeing in the Upper Yellow River Basin

> The dependency of local livelihoods on the services provided by ecosystems is greater in drylands than in any other ecosystems, rendering their inhabitants exceptionally vulnerable to land degradation. Current approaches to managing drylands to mitigate land degradation often fail to produce significant improvements because local knowledge is often undervalued and the complexity of underlying processes leading to land degradation is still not well understood.
>
> Mueller et al. 2014, p. 1.

In some ways, biophysical constraints place significant limits upon development prospects in the Upper Yellow River Basin. For example, although various dam projects will be developed to exploit hydropower resources, there is limited agricultural potential to be gained through irrigation schemes because of altitudinal and climatic constraints upon the short growing season and the limited (often depleted) soil resources with low inherent fertility.

Global climate change is the fundamental natural cause of ecological deterioration in the region. Glacier retreat, ascending snow lines, drying up of wetlands and degradation of alpine permafrost have impacted upon hydrological resources, groundwater reserves, run-off relationships and vegetation patterns. Concerns for water security are also directly tied to land use practices. Reduced run-off has forced herders into other areas, increasing grazing pressure and further degrading grassland areas (Chen et al. 2007). The warming trend has impacted upon agricultural prospects, affecting plant growth, yield and community structure in alpine meadow ecosystems (e.g. Chen et al. 2014; Zhang et al. 2015). Intensified human activities and overgrazing have brought about extensive grassland and wetland degradation in recent decades (see chapters by Qiao and Duan 2016, Chap. 6; Li et al. 2016a, Chap. 7; Li et al. 2016b, Chap. 9; Gao 2016, Chap. 10; Tane et al. 2016, Chap. 13).

Recent changes have markedly decreased primary productivity associated with animal husbandry, threatening people's livelihood. The yield per unit area of grassland, the percentage of elite forage species and vegetation cover have decreased, while the percentage of toxic plants has increased (Fu et al. 2007). Grassland areas are becoming increasingly fragmented, characterized by reverse succession from alpine meadow to degraded alpine meadow to desert in some areas. Biological and ecological changes are increasing susceptibility to invasions by exotic species and rodent irruptions, enhancing soil erosion and salinity problems (Li et al. 2016a, Chap. 7). Forms and rates of degradation vary markedly on differing topographic surfaces, reflecting factors such as sediment thickness, water/nutrient movement, soil fertility/health (e.g. relationships between soil microfauna (bioturbation) and differing hydrological, texture and nutrient properties of soils on differing surfaces), vegetation communities (including weeds) and pica distribution. These relationships, in turn, are influenced by land use practices, especially cultivation and animal management (see Tane et al. 2016, Chap. 13).

Complex ecogeomorphic interactions are clearly exemplified in those areas of the Upper Yellow River that are being subjected to grasslandification, wherein wetlands are drained and modified for use as pasture (Shang et al. 2013). Ultimately, resulting environmental transitions in abiotic and biotic terms are driven by social and economic processes, alongside climate change. Additional research on these relationships is required if concerns for vulnerability, resilience and associated management responses are to be appropriately addressed. Critically, key drivers and underlying processes of degradation must be understood at local/regional scales, building upon situated field-based understandings (see Li et al. 2013). Also, process-based understandings are critical in appraising the likely suitability and effectiveness of rehabilitation initiatives. For example, sustainable stocking rates must be determined for differing types of grassland at differing stages of degradation.

Incorporating local knowledge is fundamental to these endeavours—in environmental, socio-economic and cultural terms. As noted by Mueller et al. (2014, p. 4): '… current approaches to manage drylands to mitigate land degradation often fail to produce significant improvements because local knowledge is often undervalued and not included in land-management approaches, and furthermore, the complexity of underlying processes leading to land degradation is still not well understood'. A landscape approach based on ecogeomorphic principles provides an important basis to address this shortcoming, emphasizing concerns for coupled ecological–geomorphological systems (Mueller et al. 2014). Essentially, local voices must be heard and acted upon, building upon the kind of research outlined in this book and elsewhere (e.g. Shang et al. 2014; Su et al. 2015; Tang et al. 2015; Wang et al. 2015; Zhang et al. 2013, 2015). Ecological degradation and biodiversity losses in the Upper Yellow River region will continue unless human developments are managed appropriately (Foggin et al. 2006).

Environmental protection has emerged as a major issue alongside economic development in China in recent years. The emergence of the Ministry for Environmental Protection marks recognition of the extent of degradation and the priority given to environmental repair. However, ongoing problems such as air and water quality, biodiversity loss, food security and land degradation are indicative of the relative ineffectiveness of measures taken to date.

As economic circumstances improve and aspirations grow, societal expectations for healthy and fulfilling lifestyles and well-being are also likely to increase. Unlike most of the country, and despite some concerns for the degradation of landscapes and ecosystems in the face of climate and land use change (especially in the face of development pressures), environmental conditions remain in a good state in the Yellow River Source Zone. Hence, the primary focus of management efforts in this area is able to emphasize maintenance of environmental health rather than interventions that promote environmental repair. For now, the primary management issue is the protection of key landscapes and ecosystems in the region, such that future generations can enjoy the wonderful values and experiences of this remarkable place (see Brierley et al. 2016, Chap. 1).

Socio-economic programmes are fundamental to future societal and environmental well-being. The remarkable beauty, ecological attributes and sociocultural mix of the region, alongside low levels of industrial and agricultural pollution, present significant opportunities for regional growth, with considerable prospects through ecotourism, organic agriculture and high-value local products (traditional medicines, yak and sheep products, etc.). Working with herders to develop locally owned businesses will enhance retention of resources and profits within the region. Moves towards a win–win 'green economy' aim to protect the environment while improving farmer's income. Recent steps to support such prospects include efforts to develop more intensive industries and training programmes to improve labour skills (Ran et al. 2016, Chap. 14). These include modernization of the animal husbandry industry (including enhanced livestock processing), development of regional grassland industries, production of new Chinese and Tibetan medicines and promotion of ecotourism opportunities.

However, the prevailing Chinese development model seems to adhere to classical modernization theory, embedded in an authoritarian approach. This is similar to the collectivization phases in the Soviet Union and the People's Republic of China, when Stalinist- and Mao Zedong-inspired models were implemented under autonomy and sedentarization regimes (Kreutzmann 2013). Unfortunately, conservation values, policies and practices are not well-integrated in China, with systematic barriers such as weak rule of law, unclear land tenure, top-down government authority and disconnects between scientific research and management implementation (Grumbine and Xu 2011). China's centralized approach to biodiversity conservation, with limited local participation, creates an inflexible and inefficient approach because of conflicts between local communities and national administrators (Zheng and Cao 2015). More effective moves towards an environmentally secure future may ensue if traditional Chinese environmental values are combined with contemporary science and international management practices. Locally based initiatives supported by bridging organizations are required to facilitate community-based approaches to environmental management that incorporate understandings from traditional Tibetan culture using a knowledge co-production approach (Shen and Tan 2012).

Sustainable futures in pastoral regions will not be achieved without adequate participation of stakeholders. Rather than simply legislating for desired behaviours, working towards common goals with local communities as key partners through co-management arrangements is required. Working directly with Tibetan pastoralists offers prospects to enhance societal and economic well-being while protecting cultural values, thereby promoting more sustainable, equitable and economic measures for long-lasting development and environmental conservation in the region, simultaneously meeting local development goals and national conservation goals (Foggin 2011; Foggin and Torrance-Foggin 2011). Conservation-oriented government policies such as ecological migration (*shengtai yimin* in Chinese) threaten not only local pastoralists' livelihood and community structure, but also regional stability, as quota-driven resettlements are married with high levels of unemployment and loss of hope (Du 2012; Foggin 2008, 2011).

15.4 Closing Comments: Managing for the Future

> Harmony with land is like harmony with a friend; you cannot cherish his (her) right hand and chop off his (her) left.
>
> Aldo Leopold

Ultimately, resource and environmental management is not about managing the environment per se, it is about managing people and their relationships to natural resources. People-friendly environmental management practices are required to avoid the tragedy of the commons, where no-one takes responsibility for environmental outcomes. Efforts to think big and long term are most likely to achieve intended and sustainable outcomes when they emphasize concerns for sociocultural connections through inclusive and flexible governance arrangements, moving forward collectively through ongoing commitments to achieve sustained social, economic and environmental improvements into the future.

Working directly with managers within appropriate governance arrangements that support local communities is the key to effective environmental management (Rogers 2006). Fundamental transitions in societal and governance arrangements are required if the quest for sustainable environmental futures is to build appropriately upon the scientific and technical guidance outlined in this book. The quest for sustainability frames environmental condition in relation to socio-economic and cultural considerations—both now and into the future. The only way in which these aspirations and requirements can be met is when the local citizenry, the people who live on (and off) the land are respected as the true custodians of the land. The combination of value to nature and value to community gives rehabilitation activities the capacity to enhance participatory politics and practices. Capacity building at local levels is vital in efforts to support a harmonious society, ensuring that efforts are locally owned and enacted. Effective interventions build upon co-produced knowledge that incorporates local understandings alongside socially situated science and management.

In a similar vein, management initiatives must be sufficiently flexible to enable them to be adapted when the system behaves (or responds) in unexpected ways. An adaptive management approach recognizes explicitly that we do not always know what the consequences of our actions are going to be and we are not always going to get things right. However, if an appropriate commitment to experimentation and documentation is in place, we should learn from experience and respond accordingly in the design and implementation of future measures. In this light, coping with uncertainty becomes a goal of management processes, rather than attempting to remove it or using it as an excuse for inaction (Clark 2002; Hillman and Brierley 2008). In many ways, threats to long-term ecosystem health are most pronounced when management responses seek to protect human values and assets from natural variability. Endeavours not to over-react in times of crisis are critical to the success of such ventures. It is often extremely dangerous to resort to conventional 'controlling' measures that we know are unsustainable in the long term. Ultimately, how we live with risks and hazards reflects the values and importance we give to ecosystem relationships.

In some parts of the world, a 'tide of change' towards restoration and environmental improvement (protection) reflects a new societal accommodation with nature. Widely based societal movements towards environmentally conscious lifestyles reflect increasing recognition of our environmental footprint—the food, energy, water and other resources that we consume. Green economies, green infrastructure, green jobs and green farming are symptomatic of increasing awareness of the consequences of our actions and concerns for future lifestyles and well-being. These movements take different forms in different areas, embracing the diversity and variability of a given place, rather than striving to 'make landscapes or ecosystems the same' (see Tadaki et al. 2014).

Several key principles emerge from this book in efforts to engender sustainable environmental futures in the Yellow River Source Zone. First, we must create a sense of what a sustainable environmental future looks like—one that society desires and owns. Second, strategic plans of action must carefully consider the range of options, at the same time remembering that getting started is more important than waiting for the perfect plan. Defining assets and threats is a key starting point, working out what to protect, and what threatening processes must be addressed in a proactive manner (addressing the causes not the symptoms of change). Hopefully, findings from the book go some way to achieving this. In summary terms, three key principles have emerged:

(a) Frame human relationships as part of nature, not separate from it.
(b) Adopt visionary 'whole of landscape' approaches to ecosystem management, giving due regard for social, economic, cultural and environmental considerations, emphasizing concerns for integrity and resilience over reactive, short-term, issues-based agendas.
(c) Remember that environmental management affects all of us, both now and into the future, such that effective measures and programmes engage effectively with local communities through participatory practices. The adage 'hope inspires, fear paralyses' provides a timely reminder of the fundamental importance of the collective commitment that is required for sustainable practice.

One thing is clear: the pace of change ensures that the Yellow River Source Zone will be a very different place in coming years.

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References

Balaguer, L., Escudero, A., Martín-Duque, J. F., et al. (2014). Historical references in restoration ecology: Redefining a cornerstone concept. *Biological Conservation, 176*, 12–20.

Brierley, G. J., & Cullum, C. (2012). Environmental science and management in a changing world. In: Higgitt, D. (Ed.), *Perspectives on environmental management and technology in asian river basins* (pp. 11–30). Netherlands: Springer Briefs in Geography.

Brierley, G. J., Fryirs, K. A., Cullum, C., et al. (2013). Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. *Progress in Physical Geography, 37*, 601–621.

Brierley, G. J., & Fryirs, K. A. (2015). The use of evolutionary trajectories to guide moving targets in the management of river futures. *River Research and Applications*. DOI: 10.1002/rra.2930.

Brierley, G. J., Li, X., Cullum, C., et al. (2016). Introduction: Landscape and ecosystem diversity in the Yellow River Source Zone. In: Brierley, G. J., Li, X., Cullum, C. et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 1–34). Springer.

Chan, K., Pringle, R. M., Ranganathan, J. A. I., et al. (2007). When agendas collide: Human welfare and biological conservation. *Conservation Biology, 21*, 59–68.

Chapin III, F. S., Power, M. E., Pickett, S. T., et al. (2011). Earth stewardship: Science for action to sustain the human-earth system. *Ecosphere*, *2*(8), art89.

Chen, G. C., Chen, X. Q., & Gou, X. J. (Eds.). (2007). *Ecological environment in Sanjiangyuan natural reserve*. Xining, China: Qinghai People's Press. (in Chinese).

Chen, B., Zhang, X., Tao, J., et al. (2014). The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agricultural and Forest Meteorology, 189*, 11–18.

Clark, M. J. (2002). Dealing with uncertainty: Adaptive approaches to sustainable river management. *Aquatic Conservation: Marine and Freshwater Ecosystems, 12*, 347–363.

de Groot, R. S., Blignaut, J., Van der Ploeg, S., et al. (2013). Benefits of investing in ecosystem restoration. *Conservation Biology, 27*, 1286–1293.

Du, F. (2012). Ecological resettlement of Tibetan herders in the Sanjiangyuan: A case study in Madoi county of Qinghai. *Nomadic Peoples, 16*, 116–133.

Dufour, A., Gadallah, F., Wagner, H. H., et al. (2006). Plant species richness and environmental heterogeneity in a mountain landscape: Effects of variability and spatial configuration. *Ecography*, *29*, 573–584.

Economy, E. C. (2004). *The river runs black: The environmental challenge to China's future*. London: Ithaca.

Foggin, J. M. (2008). Depopulating the Tibetan grasslands: National policies and perspectives for the future of Tibetan herders in Qinghai province China. *Mountain Research and Development, 28*, 26–31.

Foggin, J. M. (2011). Rethinking "Ecological Migration" and the value of cultural continuity: A response to Wang, Song, and Hu. *Ambio, 40*, 100–101.

Foggin, P. M., Torrance, M. E., Dorje, D., et al. (2006). Assessment of the health status and risk factors of kham Tibetan pastoralists in the alpine grasslands of the Tibetan plateau. *Social Science and Medicine, 63*, 2512–2532.

Foggin, J. M., & Torrance-Foggin, M. E. (2011). How can social and environmental services be provided for mobile Tibetan herders? Collaborative examples from Qinghai province. *China Pastoralism, 1*, 1–22.

Fryirs, K. A., & Brierley, G. J. (2009). Naturalness and place in river rehabilitation. *Ecology and Society, 14*, 20.

Fryirs, K., Spink, A., & Brierley, G. J. (2009). Post-European settlement response gradients of river sensitivity and recovery across the upper hunter catchment Australia. *Earth Surface Processes and Landforms, 34*, 897–918.

Fu, Y., Zhang, G. S., & Li, L. (2007). The change features and its tendency of ecological environment on Qinghai-Tibetan plateau. *Journal of Qinghai Meteorology, 2*, 4–10. (in Chinese with English abstract).

Gao, J. G. (2016). Wetland and its degradation in the Yellow River Source Zone. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 209–232). Springer.

Goodman, D. S. (2004). The campaign to "Open up the West": National, provincial-level and local perspectives. *The China Quarterly, 178*, 317–334.

Grumbine, R. E., & Xu, J. (2011). Creating a 'conservation with Chinese characteristics'. *Biological Conservation, 144*, 1347–1355.

Hamilton, L. S., & McMillan, L. (Eds.). (2004). *Guidelines for planning and managing mountain protected areas*. IUCN World Commission on Protected Areas.

Han, M. Q., Brierley, G. J., Cullum, C., et al. (2016). Climate, vegetation and human land use interactions on the Qinghai-Tibet Plateau through the Holocene. In: G. J. Brierley, X. Li, C. Cullum, et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone* (pp. 253–274). Berlin: Springer.

Hiers, J. K., Mitchell, R. J., Barnett, A., et al. (2012). The dynamic reference concept: Measuring restoration success in a rapidly changing no-analogue future. *Ecological Restoration, 30*, 27–36.

Higgs, E. (2003). *Nature by design: People, natural process, and ecological restoration.* MIT Press.

Higgs, E., Falk, D. A., Guerrini, A., et al. (2014). The changing role of history in restoration ecology. *Frontiers in Ecology and the Environment, 12*, 499–506.

Hillman, M., & Brierley, G. (2008). Restoring uncertainty: Translating science into management practice. In G. J. Brierley & K. Fryirs (Eds.), *River futures: An integrative scientific approach to river repair* (pp. 257–272). Washington, United States: Island Press.

Hobbs, R. J., Arico, S., Aronson, J., et al. (2006). Novel ecosystems: Theoretical and management aspects of the new ecological world order. *Global ecology and biogeography, 15*(1), 1–7.

Hobbs, R. J., Hallett, L. M., Ehrlich, P. R., et al. (2011). Intervention ecology: Applying ecological science in the twenty-first century. *Bioscience, 61*, 442–450.

Hobbs, R. J., Higgs, E. S., & Hall, C. (2013). *Novel ecosystems: Intervening in the new ecological world order*. John Wiley & Sons.

Hobbs, R. J., Higgs, E., & Harris, J. A. (2009). Novel ecosystems: Implications for conservation and restoration. *Trends in Ecology and Evolution, 24*, 599–605.

Huang, H. Q., Liu, X. F., Brierley, G. J., et al. (2016). Hydrology of the Yellow River Source Zone. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.) *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 79–100). Springer.

Hughes, F. M., Adams, W. M., & Stroh, P. A. (2012). When is open-endedness desirable in restoration projects? *Restoration Ecology, 20*, 291–295.

Kreutzmann, H. (2013). The tragedy of responsibility in high Asia: Modernizing traditional pastoral practices and preserving modernist worldviews. *Pastoralism, 3*, 1–11.

Lawrence, A. (Ed.). (2010). *Taking stock of nature: Participatory biodiversity assessment for policy, planning and practice.* Cambridge University Press.

Li, X. L., Gao, J., Brierley, G. et al. (2013). Rangeland degradation on the Qinghai-Tibet plateau: Implications for rehabilitation. *Land Degradation & Development*, *24*, 72–80.

Li, X. L., Perry, G., & Brierley, G. J. (2016a). Grassland ecosystems of the Yellow River Source Zone: Degradation and restoration. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 137–166). Springer.

Li, Z. W., Wang, Z. Y., & Pan, B. Z. (2016b). Wetland ecosystems of the Yellow River Source Zone. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 183—208). Springer.

Liu, G., Chen, Y., & He, H. (2012). China's environmental challenges going rural and west. *Environment and Planning, 44*, 1657–1660.

McShane, T. O., Hirsch, P. D., Trung, T. C., et al. (2011). Hard choices: Making trade-offs between biodiversity conservation and human well-being. *Biological Conservation, 144*, 966–972.

Mueller, E. N., Wainright, J., Parsons, A. J., et al. (2014). Land degradation in drylands: An ecogeomorphological approach. In E. N. Mueller, J. Wainright, A. J. Parsons, et al. (Eds.), *Patterns of land degradation in drylands: Understanding self-organised ecogeomorphic systems* (pp. 1–9). Dordrecht: Springer.

Parks, K. E., & Mulligan, M. (2010). On the relationship between a resource based measure of geodiversity and broad scale biodiversity patterns. *Biodiversity Conservation, 19*, 2751–2766.

Qiao, Y. M., & Duan, Z. H. (2016). Understanding alpine meadow ecosystems. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.), *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 117–136). Springer.

Ran, Y. C., Xie, J. X., & Li, X. L. (2016). Socio-economic development and its effects on the ecological environment of the Yellow River Source Zone. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.) *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 331–352). Springer.

Rogers, K. H. (2006). The real river management challenge: integrating scientists, stakeholders and service agencies. *River Research and Applications, 22*, 269–280.

Sayer, J., Sunderland, T., Ghazoul, J., et al. (2013). Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proceedings of the National Academy of Sciences, 110*, 8349–8356.

Shang, Z. H., Feng, Q. S., Wu, G. L., Ren, G. H., & Long, R. J. (2013). Grasslandification has significant impacts on soil carbon, nitrogen and phosphorus of alpine wetlands on the Tibetan plateau. *Ecological Engineering, 58*, 170–179.

Shang, Z. H., Gibb, M. J., Leiber, F., et al. (2014). The sustainable development of grassland-livestock systems on the Tibetan plateau: problems, strategies and prospects. *The Rangeland Journal, 36*, 267–296.

Shapiro, J. (2012). *China's environmental challenges*. Polity.

Shen, X., & Tan, J. (2012). Ecological conservation, cultural preservation, and a bridge between: the journey of Shanshui conservation center in the Sanjiangyuan region, Qinghai-Tibetan plateau China. *Ecology and Society, 17*(4), 38.

Steffen, W., Richardson, K., Rockström, J., et al. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science,* 1259855.

Su, X. K., Wu, Y., Dong, S. K., et al. (2015). Effects of grassland degradation and re-vegetation on carbon and nitrogen storage in the soils of the headwater area nature reserve on the Qinghai-Tibetan plateau China. *Journal of Mountain Science, 12*, 582–591.

Suding, K. N. (2011). Toward an era of restoration in ecology: Successes, failures, and opportunities ahead. *Annual Review of Ecology, Evolution, and Systematics, 42*, 465–487.

Suding, K., Higgs, E., Palmer, M., et al. (2015). Committing to ecological restoration. *Science, 348*(6235), 638–640.

Surian, N., Ziliani, L., Comiti, F., et al. (2009). Channel adjustments and alteration of sediment fluxes in gravel-bed rivers of north-eastern Italy: Potentials and limitations for channel recovery. *River Research and Applications, 25*, 551–567.

Tane, H., Li, X. L., & Chen, G. (2016). Ecogenesis of the Huang He (Yellow River) headwaters. In: Brierley, G. J., Li, X., Cullum, C., et al. (Eds.) *Landscape and ecosystem diversity, dynamics and management in the Yellow River Source Zone*. (pp. 275–330). Springer.

Tadaki, M., Brierley, G., & Cullum, C. (2014). River classification: Theory, practice, politics. *Wiley Interdisciplinary Reviews: Water, 1*, 349–367.

Tang, L., Dong, S., Sherman, R., et al. (2015). Changes in vegetation composition and plant diversity with rangeland degradation in the alpine region of Qinghai-Tibet plateau. *The Rangeland Journal, 37*, 107–115.

Wang, X., Dong, S., Sherman, R., et al. (2015). A comparison of biodiversity–ecosystem function relationships in alpine grasslands across a degradation gradient on the Qinghai-Tibetan plateau. *The Rangeland Journal, 37*, 45–55.

Westley, F., Olsson, P., Folke, C., et al. (2011). Tipping toward sustainability: Emerging pathways of transformation. *Ambio, 40*, 762–780.

Wiens, J. A. (2002). Riverine landscapes: Taking landscape ecology into the water. *Freshwater Biology, 47*, 501–515.

Wohl, E., Angermeier, P. L., Bledsoe, B., et al. (2005). River restoration. *Water Resources Research, 41*, 10.

Wu, X., Zhang, X., Dong, S., et al. (2015). Local perceptions of rangeland degradation and climate change in the pastoral society of Qinghai-Tibetan plateau. *The Rangeland Journal, 37*, 11–19.

Zhang, Y., Gao, Q., Dong, S., et al. (2015). Effects of grazing and climate warming on plant diversity, productivity and living state in the alpine rangelands and cultivated grasslands of the Qinghai-Tibetan plateau. *The Rangeland Journal, 37*, 57–65.

Zhang, H., Gilbert, B., Wang, W., et al. (2013). Grazer exclusion alters plant spatial organization at multiple scales, increasing diversity. *Ecology and Evolution, 3*, 3604–3612.

Zheng, H., & Cao, S. (2015). Threats to China's biodiversity by contradictions policy. *Ambio*, *44*, 23–33.