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Characteristics of water erosion and conservation practice in arid regions of Central Asia: Xinjiang Province, China as an example

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Abstract

Located in the inland arid area of Central Asia and northwest China, Xinjiang has recently received heightened concerns over soil water erosion, which is highly related with the sustainable utilization of barren soil and limited water resources. Data from the national soil erosion survey of China (1985–2011) and Xinjiang statistical yearbook (2000–2010) was used to analyze the trend, intensity, and serious soil water erosion regions. Results showed that the water erosion area in Xinjiang was 87.6×10^3 km^2 in 2011, mainly distributed in the Ili river valley and the northern and southern Tian Mountain. Soil erosion gradient was generally slight and the average erosion modulus was 2184 t/(km^2 a). During the last 26 years, the water erosion area in Xinjiang decreased by 23.2%, whereas the intensity was still increasing. The driving factors from large to small impact included: population boom and human activities > vegetation degradation > rainfall and climate change > topography and soil erodibility > tectonics movement. Soil water erosion resulted in eco-environmental and socioeconomic losses, such as destroying farmland and grassland, triggering floods, sedimentation of reservoirs, damaging transportation and irrigation facilities, and aggravating poverty. A landscape ecological design approach is suggested for integrated control of soil erosion. Currently, an average of 2.07×10^3 km^2 of formerly eroded area is conserved each year. This study highlighted the importance and longevity of soil and water conservation efforts in Xinjiang, and offered some suggestions on ecological restoration and combating desertification in arid regions of Central Asia.

Keywords: Xinjiang; Soil water erosion; Soil and water conservation; Ecological restoration; Arid region

1. Introduction

Arid regions cover ~41% of the Earth's terrestrial area. Land degradation poses a great challenge for sustainable development. In future the rapid population growth to 9 billion by 2050, changing consumption patterns and climate change will add further pressure on land and soil resources. Currently over 2.6 billion peoples are affected by

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desertification globally (Millennium Ecosystem Assessment, 2005; Gabathuler, Liniger, Hauert, & Giger, 2009). Covering Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and Xinjiang Province of China, Central Asia contains 80–90% of the world’s temperate deserts (Li et al., 2015). Hence, Central Asia is a typical arid and ecologically fragile region. Due to climate change, precipitation and shrinkage of glaciers in this region are expected to increase (Hijioka et al., 2014), which would lead to increased surface runoff and even flood. Therefore, soil water erosion in Central Asia should not be overlooked, especially considering the serious desertification, land degradation, and drought problems there. Moreover, soil and water conservation in Central Asia are key scientific issues for sustainable development of the Silk Road Economic Belt (Dong et al., 2015).

Located in the inland area of Central Asia, Xinjiang Province of China contains most of the Tian mountain. The main geomorphologic units in Xinjiang from north to south are the Artai Mountain, the Junggar basin, the Tian Mountain, the Tarim basin, and the Kunlun Mountain. Each mountain–basin system can be further divided into high mountain zone (covered by ice and snow), middle/low mountain and hilly zone, oasis zone, desert–oasis ecotone, and desert zone (He, Li, Hong, Zhao, & Bai, 2013). Since the orography features elevation difference up to 7000 m, strong gradient in mean annual precipitation exists from <50 mm in the deserts to >900 mm in the windward slopes of the Tian Mountain (Böhner, 2006). The most serious water erosion of Xinjiang occurs as flow erosion in the middle/low mountain and hilly zone (i.e., the upper part of river basin), due to snowmelt flooding and heavy rain flooding in spring and summer (Zhang, Qiu, Bai, Chen, & He, 2002; Guo & Li, 2013). The problem of soil and water loss in Xinjiang has lacked sufficient attention for many decades. For example, from 2005 to 2007, a national comprehensive academic investigation on soil water erosion and ecological security was co–organized by the Ministry of Water Resources of China, the Chinese Academy of Sciences, and the Chinese Academy of Engineering, but no eroded area in Xinjiang was investigated. Recently, basic theoretical research on soil and water conservation in Xinjiang is receiving more attention and gained importance. In order to combat desertification induced by water erosion in Xinjiang, a synthesized soil and water conservation model based on erosion characteristics of this region is essential. Such a model might also be useful for protecting similar ecosystems and environments in other countries of Central Asia. Yet, English publications on Xinjiang's soil water erosion issues remain rare.

As such, the purpose of this study was to overview and: (1) explore the trend and intensity of soil water erosion in Xinjiang, (2) understand its driving factors and environmental impacts, and (3) discuss the progress of soil and water conservation measurements in Xinjiang.

2. Materials and methods

2.1. Study area

Located in the northwest of China, Xinjiang has a typically arid and continental climate. The Tian Mountain divides Xinjiang into two parts, north and south Xinjiang. According to Xinjiang statistical yearbooks, the average annual precipitation from 1991 to 2011 was 164.7 mm, while that of north Xinjiang was 239.9 mm, that of south Xinjiang was only 71.0 mm (Zhang et al., 2014). The highest monthly precipitation is in July for both north and south Xinjiang (Fig. 1a). The lowest monthly humidity index of north Xinjiang is in August (Fig. 1b), suggesting relatively high evaporation in this month. The highest monthly temperature of south Xinjiang is in July (Fig. 1c). The newly published soil and water conservation zoning in China (The Ministry of Water Resources of China, 2012) divided soil erosion area in Xinjiang into seven sub-regions (Fig. 2), i.e., (a) north part of Junggar basin, dominated by the north part of Gurbantunggut desert and the Altay Mountain; (b) north part of Tian Mountain, dominated by the north part of Tian Mountain, oases, and the south part of Gurbantunggut desert; (c) Ili river valley, circled by mountains; (d) north part of Tarim basin, dominated by the south part of Tian Mountain, oases, and the north part of Taklimakan desert; (e) Turpan–Hami basin, dominated by desert ecosystems; (f) west part of Tarim basin, dominated by the north part of Kunlun Mountain, oases, and the west part of Taklimakan desert; and (g) south part of Tarim basin, dominated by the north part of Kunlun Mountain and the south part of Taklimakan desert. Most of farmlands in Xinjiang are distributed in oases. The total farmland area is 41.2×10^3 km^2, of which irrigated lands occupy 38.1×10^3 km^2 (Jin, 2012). Major crops grown in this region are cotton, wheat, maize, and sunflower.

2.2. Data source and calculations

The total soil erosion area is the sum of both the wind and water erosion areas. The soil erosion area and the area for each water erosion grade in 1985, 1995, and 2000 of China and Xinjiang were compiled from Li (2010), while data in 2011 was compiled from Guo and Li (2013). These data were obtained by combining field survey and quantitative remote sensing assessment. Remote sensing images used in these four national soil erosion surveys were different, i.e., multispectral scanning system (MSS) image with a spatial resolution of 60 m was used in 1985, thematic mapper (TM) imagery with a spatial resolution of 30 m was used in 1995 and 2000, while satellite for earth observation (SPOT) imagery with a spatial resolution of 2.5 m was used in 2011 (Li, 2010; Li, Liu, Liu, & Gao, 2010). However, the same standard for gradation of soil erosion was used in these four surveys (Li, 2010; The Ministry of Water Resources of China, 2013), making the comparison among the four surveyed results reasonable. In the standards for classification and gradation of soil erosion in China (SL 190–2007), a range of erosion moduli for each soil erosion grade were given. To facilitate calculation of the average erosion modulus for a certain region,

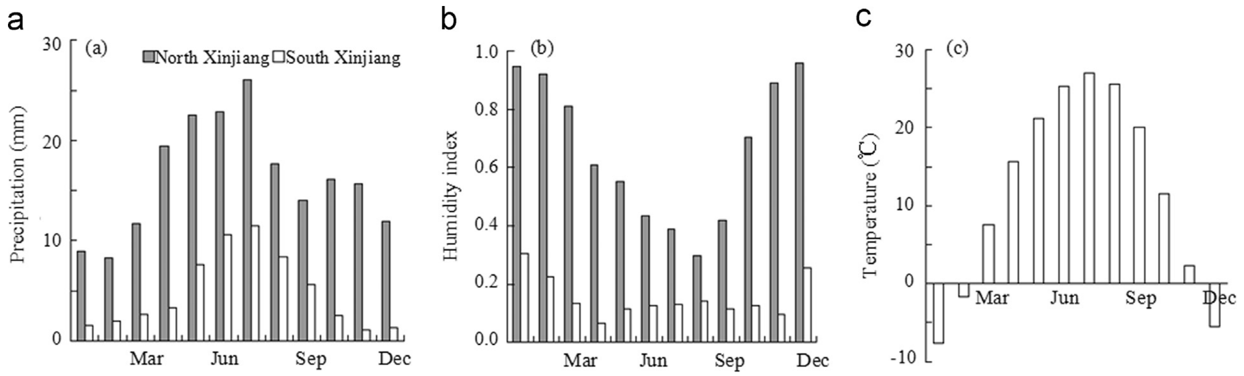

Fig. 1. Monthly precipitation, humidity index, and temperature of Xinjiang. (a) the monthly precipitation of north and south Xinjiang from 1961 to 2013 (Jiang, Liu, Shao, Yu, & Wang, 2014); (b) the monthly humidity index (the ratio of precipitation to potential evapotranspiration) of north and south Xinjiang from 1971 to 2008 (Xing, Ma, Xiao, Yang, & Zhang, 2009a; Xing, Liu, Xiao, & Shi, 2009b); and (c) the monthly temperature of south Xinjiang from 1951 to 2008 (Zheng, Yan, & Yuan, 2010).

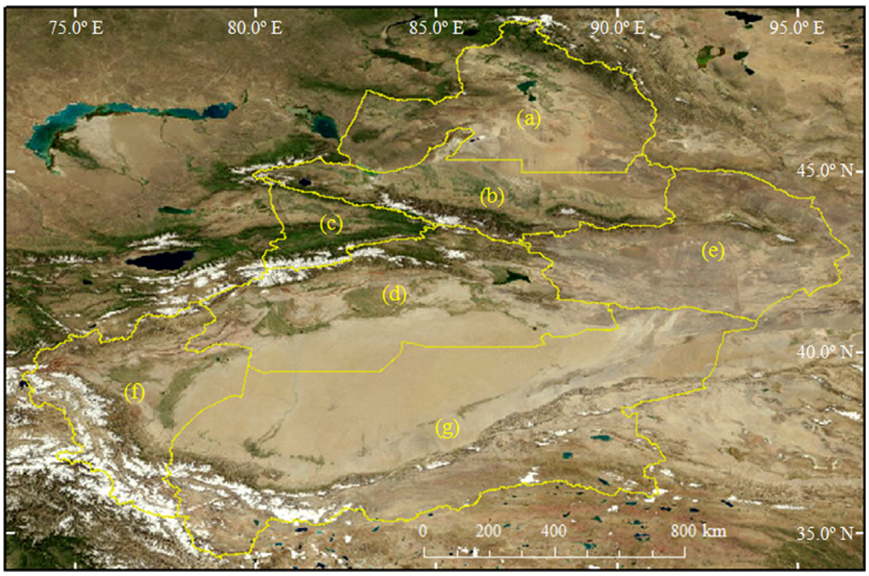

Fig. 2. Sub-regions for soil and water conservation in Xinjiang, China. (a) North part of Junggar basin; (b) North part of Tian Mountain; (c) Ili river valley; (d) North part of Tarim basin; (e) Turpan–Hami basin; (f) West part of Tarim basin; (g) South part of Tarim basin.

Table 1
The soil water erosion area and its proportion of Xinjiang, China.

Year	Soil erosion area ($\times 10^3$ km^2)				Proportion (%)		
	China		Xinjiang		T_X/T_C	W_C/T_C	W_X/T_X
	Total area (T_C)	Water erosion area (W_C)	Total area (T_X)	Water erosion area (W_X)			
1985	3670	1794	950	114	25.9	48.9	12.0
1995	3556	1649	1036	115	29.1	46.4	11.1
2000	3569	1612	1031	117	28.9	45.2	11.3
2011	2949	1293	885	87.6	30.0	43.8	9.90

Liang, Li, Su, and Pan (2009) developed a method to calculate the specific corresponding erosion modulus for each erosion grade:

$$y_i = \frac{x_{1i} + x_{2i}}{2} \tag{1}$$

where y_i is the average erosion modulus, and x_{1i} and x_{2i} are the cut-off values for the *i*th soil erosion grade. Here, *i* equals to1, 2, 3, 4, and 5 for nonevident, slight, moderate, intense, and extremely intense erosion grades, respectively. A correlative equation between the average erosion modulus (y_i) and erosion grade (i) was obtained as:

$$y_i = 560.7i^2 - 569.3i + 180.0\left(R^2 = 0.997, P < 0.01\right) \tag{2}$$

According to Eq. (2), y_i=16950 [t/(km^2 a)] when i=6. Thus, the average erosion modulus for severe erosion (i=6) can be obtained by extrapolation.

The average erosion modulus for any soil erosion sub-region was calculated using Eq. (3)

$$z = \frac{a_i y_i}{\sum_{i=2}^{6} a_i} \tag{3}$$

where z is the average erosion modulus for a certain soil erosion sub-region, and a_i is the area suffering soil erosion for the *i*th soil erosion grade in this soil erosion sub-region.

To specify the harmful aspects and treatment progress of soil water erosion, data on flooding area, direct economic loss caused by geohazards, capacity of small reservoirs, and newly controlled soil erosion area from 2000 to 2010 were retrieved and compiled from the Xinjiang statistical yearbook (Jin, 2011).

3. Results

3.1. Water erosion area

From 1985 to 2011, the total soil erosion area in China was reduced by 721 × 10^3 km^2, from 3670 × 10^3 km^2 to 2949 × 10^3 km^2, while this reduced area for soil water erosion is 501 × 10^3 km^2, accounting for 69.5% of the former (Table 1). Moreover, the proportions of soil water erosion area in both China and Xinjiang were decreased during the past 26 years, illustrating that regions suffering from water erosion were given a priority to overcome the erosion problem. Total soil erosion areas in both China and Xinjiang were reduced from 1985 to 2011. However, the proportion of total soil erosion area in Xinjiang to that of China during this period increased (Table 1). In fact, over 90.1% of the soil erosion area in Xinjiang is affected by wind erosion. Therefore, Xinjiang is one of the regions where it is the most difficult to control soil and water loss in China. The importance of prioritizing the control of soil water erosion in Xinjiang is also shown in Table 1. After using water erosion control measures, surface runoff was reduced and stored in soil through infiltration. The increased soil moisture supported denser vegetation and prevented wind erosion thereafter. This is especially important in areas where dualistic water–wind erosion processes impact a region. For instance, in order to prevent wind erosion, vegetation surrounding the desert areas was irrigated using flood water from Qira county of Xinjiang (Liu, 1994).

Table 2
Soil erosion area for each grade in Xinjiang, China.

Grade	Soil erosion modulus ($t\ km^{-2}\ a^{-1}$)		Soil erosion area ($\times 10^3\ km^2$)			
	Range	Average value	1985	1995	2000	2011
Slight	200–2500	1350	113.8	81.3	83.7	64.9
Moderate	2500–5000	3750	0	33.9	33.3	18.8
Intense	5000–8000	6500	0	0.215	0.23	2.56
Extremely intense	8000–15000	11,500	0	0	0	1.32
Severe	>15,000	16,950	0	0	0	0.098

3.2. Intensity

According to the standards for classification and gradation of soil erosion in China (SL 190–2007), the soil loss tolerance of Xinjiang was 200 t/(km^2 a), equivalent to 0.15 mm/a (The Ministry of Water Resources of China, 2008). The average soil erosion modulus in the water erosion area of Xinjiang increased from 1350 t/(km^2 a) in 1985 to 2184 t/(km^2 a) in 2011. In 2011, the average soil erosion modulus is in the range of slight grade, equivalent to lowering ground surface at the rate of 1.64 mm/a, which is 10.9 times higher than the soil loss tolerance value. Although total soil water erosion area in Xinjiang showed a reducing trend (Table 1), the average soil erosion modulus and the area for grade above intense erosion are still increasing (Table 2), suggesting an ever-worsening trend of soil water erosion in Xinjiang.

3.3. Serious soil water erosion region

The average soil erosion modulus of the northern Tarim basin (Fig. 2d) was 2531 t/(km^2 a), slightly higher than 2500 t/(km^2 a) and is considered moderate erosion [soil erosion modulus: 2500–5000 t/(km^2 a)]. This is mainly attributed to the combined impacts of heavy grazing, vegetation degradation and heavy precipitation in southern Tian Mountain. The six other sub-regions suffered slight erosion [soil erosion modulus: 200–2500 t/(km^2 a)]. Overall, both the total soil water erosion area and the area for grade above intense grade [soil erosion modulus: >5000 t/(km^2 a)] are relatively larger in the Ili river valley, the northern Tian Mountain, and the northern Tarim basin (i.e., southern Tian Mountain), which are serious soil water erosion regions and the key soil and water conservation regions in Xinjiang.

The characteristics of water erosion in Xinjiang can be summarized as follows: the water erosion area is quite large, accounting for $\sim$10.0% of the total soil water erosion area in China (Table 1). However, the water eroded regions are generally dominated by slight erosion. Serious water erosion areas are concentrated in the Tian Mountain region (including the Ili river valley).

4. Discussion

4.1. Driving factors of soil water erosion

4.1.1. Tectonic uplift

Xinjiang is a region dominated by terrestrial deposition since the late Permian period (about 260 million years ago) (Zhang, 2012). During the Triassic period and the Paleogene period, the mountains in the Tian Mountain region were denuded to quasi-plains, and intense tectonic uplifts in the Himalayan movement and neo-tectonics shaped the current condition of the Tian Mountain (Wang & Yang, 2010). Tectonic uplift leads to the change of erosion base level, which affects erosion and deposition. The weathering crust in mountain regions of Xinjiang is mainly detrital weathering crust. The large amount of clastic rocks and deposition resulting from neo-tectonic uplift offered a material source for erosion. Moreover, earthquakes could trigger flooding, landslide, collapse, or even debris flow. For instance, a 6.6 Richter scale earthquake occurred at the edge of Xinyuan county and Hejing county on June 30, 2012, which damaged reservoirs and water channels and increased the chance of flooding.

4.1.2. Topography

The average altitude of Tian Mountain is ~4000 m, which is 3000 m higher than the Junggar basin and the Tarim basin. A large number of basins with varied areas exist in the Tian Mountain region, such as the Ili basin and the Turpan–Hami basin. High precipitation occurs in the middle and low mountain regions. Due to intense flow, the valleys are strongly incised and widely distributed (Wang & Yang, 2010; Guo & Li, 2013). The average slope of the Kahai watershed in western Tian Mountain was 18.5°, with a maximal value of 62.8° (Mu, 2007). The sharp topography enhanced interrill soil erosion and gully erosion, which changed the landforms. The interrill erosion area accounted for 90.7% of the total eroded area in the Ili river valley, while the remaining 9.3% represents gully erosion (An & Chen, 1998). Soil and water loss occurred in farmland and grassland with slopes of 3–8° in the Ili river valley, while in hills with slopes between 30° and 40°, landslides could easily form (Yang, 1983). Soil erosion could also be affected by slope aspect. Because of longer sunlight time, sunny slopes are drier and could support less vegetation than the shady slopes which are moister, encouraging erosion on the former (Fig. 3).

4.1.3. Soil erodibility

According to the Chinese Soil Taxonomy, most parts of Xinjiang are covered by Aridosols and desert (Fig. 4). Soil types in mountain area are mainly Isohumosols and Cambosols (Hu, 2010). Cambosols are soils with a less developed profile and a cambic horizon. These soils are generally too thin to fully infiltrate surface runoff, and therefore are easily eroded. Parent material is mostly loess; widely distributed in the northern Tian Mountain and the Ili river valley (Wang & Yang, 2010). Without well-developed aggregate structure, the porous loess is erosion prone (Yang, 1983). On northern parts of Tian Mountain, soils with vertic features are derived from Tertiary red clay. These soils shrink when dry and swell when wet, which would promote soil creep and erosion. Moreover, soil fertility and the content of >0.25 mm water stable aggregates in Xinjiang lands are generally low (Chai, Wang, Chen, Sun, & Jia, 2009), which exacerbate soil erodibility.

4.1.4. Rainfall

Under the current climate change, both mean annual precipitation and temperature have increased since 1961 in Xinjiang (Zhang, 2013a). The mean annual precipitation of Xinjiang was 164.7 mm from 1991 to 2011. Most of the rainfall events occur in spring and summer (Fig. 1a). The snow is relatively heavy in winter and the surface runoff from melted snow can lead to flooding and erosion in spring. Although precipitation is generally limited in Xinjiang, isolated heavy rains may occur. Moreover, the water resources of Xinjiang are spatially unevenly distributed; more water resources are distributed in mountain areas than in the basin areas. The mean annual precipitation in the Tian Mountain area, western Junggar Mountain area, and the Altay Mountain area are >500 mm. In regions of the Ili river valley with altitude >1500 m, the mean annual precipitation was 840 mm, while for the regions with altitude between 1500 and 2500 m, the mean annual precipitation reached 1000 mm (Mao, Wang, & Hu, 2010). The mountain area is considered the “wet inland” of the otherwise arid area. In Yining city of Ili river valley, the rainfall and runoff factor (R), a numerical value used to quantify the raindrop impact on soil erosion (Wischmeier & Smith, 1978), was estimated as 403.2 MJ mm/(hm h) (Shi, 2008). This value accounts for ~64.5% of that of Lishi, a county located on the Loess Plateau (Zhang, Li, Peng, & Yu, 2004).

4.1.5. Vegetation degradation

Located in the arid region, the ecosystems of Xinjiang are particularly fragile. Climate change, human activity, and plague of locusts may lead to vegetation degradation. Due to deforestation, the forest coverage rate reduced from 2.0% in 1880 to 1.7% in 1930, and even 1.03% in the 1970s (Lu & Yan, 1989). Currently, the forest area in Xinjiang is 66.2×10^3 km^2. However, the natural forest area is only 14.2×10^3 km^2 accounting for 21.4% of the total forest area (Jia, 2009). Soil and water loss might still exist even under economic and secondary forest coverage (Zhang et al., 2011). Heavy grazing is the ultimate reason for grassland degradation. In 1990, the grassland area in Xinjiang was 573×10^3 km^2. This number decreased to 514×10^3 km^2 in 2000 and 511×10^3 km^2 in 2010. The grassland area decreased 10.7% from 1900 to 2010. Cultivated grassland for farming is another reason for grassland area

Fig. 3. The impact of slope aspect on soil erosion.

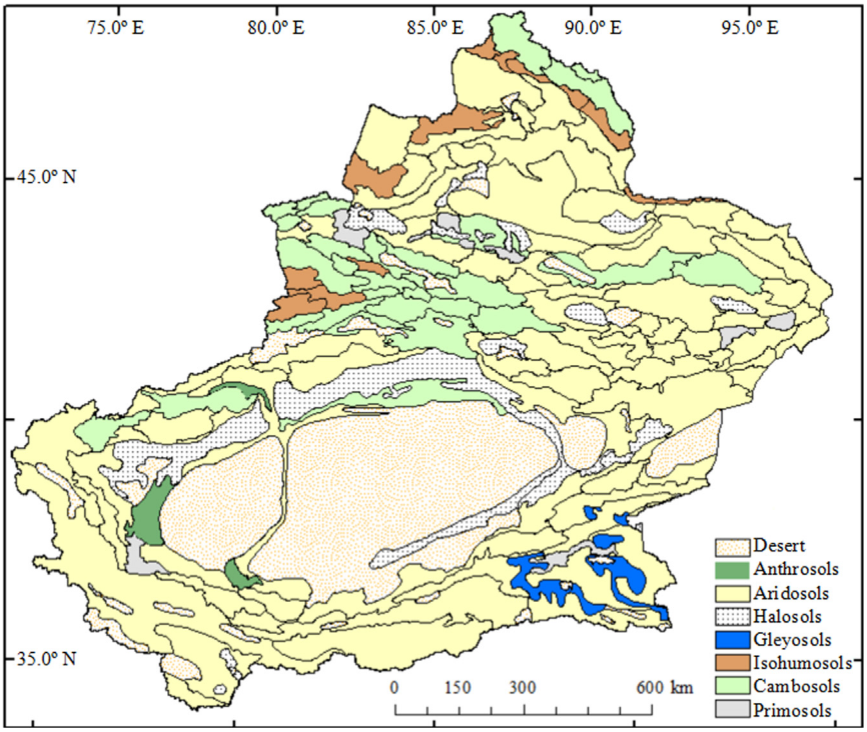

Fig. 4. The main soil orders of Xinjiang, China; modified from Gong, Huang, and Zhang (2014).

reduction. Primary vegetation is destroyed when new farmlands are established on prior grasslands in low mountain and hilly regions. In order to prevent vegetation degradation, approaches such as the establishment of a natural forest protection zone and forbidden grazing areas, rotational grazing, conversion of cropland to forest and grassland, as well as developing forestry and fruit industry are currently being implemented.

4.1.6. Population boom and development activities

The population of Xinjiang in 1950 was 4.44 million, but by 2010 it increased to 21.8 million, about five times higher than the former. Along with the population boom, newly cultivated farmland area is also soaring. From 1950 to 1998, 39.3×10^3 km^2 were cultivated for cropland, and 35.6% of these newly cultivated farmland were later abandoned (Chen, 2004). These abandoned farmlands are prone to erosion. The situation is especially dire when the cultivated farmlands occur on sloped areas. The Chinese government launched the West Development strategy in 1999 (Dong, Li, & Wei, 1999). Massive economic activities, such as road building and exploiting natural gas and mineral products not only destroyed the original vegetation on hill slopes but also disturbed the surface soil and produced large amounts of waste solids, soil, and water loss hence, poor land management (Li, Gao, & Guo, 2012).

Fig. 5. The impact of soil water erosion on grassland in Xinjiang, China.

In the Universal Soil Loss Equation (USLE), five factors influencing soil water erosion are identified: rainfall and runoff, soil erodibility, topography, cover and management, and support practices (Wischmeier & Smith, 1978). When discussing soil erosion in the red soil region of southern China, a geological factor (e.g., neo-tectonics) was also considered (Shi, 1983). Anthropogenically accelerated erosion due to human activity can greatly accelerate soil erosion rate (Montgomery, 2007). Vegetation is the most effective factor for reducing soil and water loss (Wischmeier & Smith, 1978). Heavy precipitation functions as the ultimate force in soil water erosion. Erosion can change the ground surface topography, and the formation of shallow gullies can facilitate soil loss and increase of sediments (e.g., Fig. 5). Tectonic movement should be understood at a large temporal scale, due to its low frequency of occurrence. After analysis of Xinjiang's current condition of soil and water loss, we subjectively surmised the driving factors influencing water erosion from high to low impact are: population boom and human activity > vegetation degradation > rainfall and climate change > topography and soil erodibility > tectonic movement. This order is mostly based on expert knowledge; a similar approach was used to comprehend the order of the five soil-forming factors that influencing the formation and distribution of Vertisols (Coulombe, Wilding, & Dixon, 1996).

4.2. Environmental consequences

4.2.1. Destroyed grassland and farmland and reduced their productivity

Water erosion effectively denudes fertile surface soils and reduces their fertility. Severe gully erosion can alter flat farmland and grassland into several small channels (Fig. 5). Farmland and grassland can also be lost through lateral erosion of a river bank. In Hotan county, 33.3 km^2 of farmland was lost because of the lateral erosion of the Yurunkax and Karakax rivers (An & Chen, 1998). Moreover, bank erosion could directly increase sediment concentration in flood water (Yu, Wei, & Wu, 2015). When the farmlands were irrigated with such flood water, several problems were caused including surface soil hardening, poor tillage properties (tilth), and low fertility. In Qira county, sand enters farmland though irrigation water; as much as 15 cm every year (Zhang et al., 2002). Soil and water loss and irrigation with flood water could lead to desertification and degradation of grassland and farmland, and therefore threaten agricultural sustainability in Xinjiang (Hu, 1996).

4.2.2. Improved the risk of flooding

The soils in Xinjiang mountain areas are generally too thin to restraint surface runoff. Soil erosion not only reduces soil depth, but also damages surface soil structure, which further decreased the soils' ability to adjust mountain runoff. Flooding frequently occurs in mountain areas when it rains, especially following heavy rains. The average flooded area in Xinjiang was 675.4 km^2 per year from 2000 to 2010 (Fig. 6). Generally, the flooded area only accounted for 0.56% of the soil water area in Xinjiang.

4.2.3. Sediment deposition in reservoirs

The number of large, medium, and small reservoirs is 450 in Xinjiang, with a total capacity of 10.3 billion m^3. Due to soil and water loss, a large amount of sediment has been deposited in the reservoirs, hence the reservoirs' capacity to mitigate flooding is reduced. The average sediment concentration of the Ili river ranges from 0.20 to 0.80 kg/

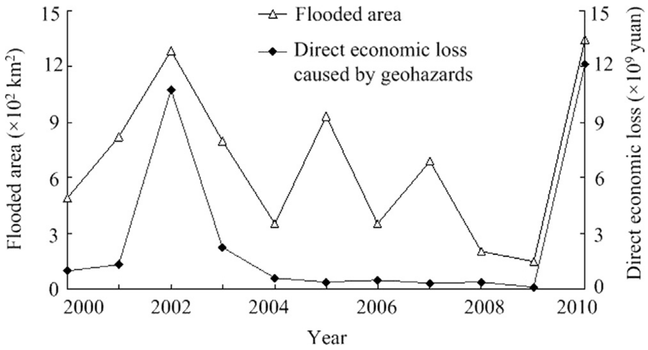

Fig. 6. Annual changes of flooded area and direct economic loss caused by geohazards from 2000 to 2010 in Xinjiang, China.

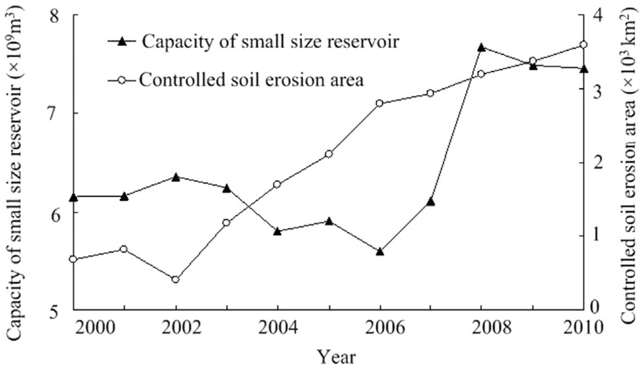

Fig. 7. Annual changes in capacity of small-size reservoir and newly controlled soil erosion area from 2000 to 2010 in Xinjiang, China.

(m^3 a), and the sediment translation modulus ranges from 50 to 600 t/(km^2 a) (He, 1999). The impact of sediment deposition on small reservoirs is especially significant. In 2002, the number of small reservoirs in Xinjiang was 304, which was reduced to 267 in 2006. Small reservoir capacity also reduced by 11.9%, from 0.636 billion m^3 to 0.56 billion m^3 during the same period (Fig. 7). For example, the Nuoya reservoir of Minfeng county, a 20 million m^3 reservoir, was completely filled by sediment after only ten years of use (Hu, 1996).

4.2.4. Damaged transportation and irrigation facilities

Severe geological disasters such as landslides and debris flow can be triggered by soil and water loss, which damages transportation and irrigation facilities thereafter and results in socioeconomic loss (Luo, Jing, & Yu, 1999; Wang, 2002). For example, from June 3 to 5, 2010, continuous heavy rains in Hotan caused mountain flooding and debris flow. In all, 2964 houses, 144.7 km of roadway, 131.8 km of water channel, and 56 bridges were damaged. Also, more than 53.3 km^2 of farmlands were flooded. Direct economic loss caused by geological disasters in Xinjiang from 2000 to 2010 was $\sim 2.70 \times 10^7$ yuan (about 4.35 million US dollar) per year (Fig. 6).

4.2.5. Deteriorated poverty

Xinjiang is an under-developed region in China. The per capita gross domestic product (GDP) of Xinjiang in 2010 was 30,087 yuan (equivalent to 4900 US dollar). Among its 88 counties, 51 of experience both serious soil and water loss and national poverty (Li, 2010). Soil and water loss further exacerbate poverty. For example, in the Hetian region of Xinjiang, the economic loss due to geological disasters consumed $\sim$1% of its annual GDP in 2010 (Zhang, 2013b).

In conclusion, soil and water loss not only influences the ecological water security and ecological fragility of this arid region, but also affects the socioeconomic development of Xinjiang. Areas of serious soil water erosion are also often easily eroded by wind. A series of negative consequences result such as hindering transportation, damaging water resource engineering structures, and affecting local and regional prosperity.

4.3. Integrated controlling measurements

4.3.1. Strategies and planning of water and soil conservation

The water and soil conservation strategies implemented in Xinjiang can aptly be summarized as regional protection combined with local control. Thus, at regional scales the natural ecological rehabilitation should be the main measurement. Detailed approaches such as establishing forbidden areas by fence, implementing rotational grazing, raising livestock in sheep pens, conversion of cropland to forest and grassland, and building cisterns should be taken in order to facilitate the large-area self-rehabilitation of eco-environment. Moreover, at local scales both soil loss prevention methods (e.g., preventing heavy grazing, and prohibiting illegal cropland cultivation) and water and soil conservation methods (e.g., conservation agriculture, planting forest) should be implemented (Yan & Yin, 2004; Guo & Li, 2013).

In 1994, the Shuimo river catchment, Toutun river catchment, and Yining city were selected as demonstration regions of soil and water conservation in Xinjiang. In 2000, critical prevention and reserve zones, important supervision zones, and key control zones for soil and water conservation were clearly labeled in Xinjiang. Unpublished books, such as “Planning of water and soil conservation in Xinjiang” and “Water and soil conservation and ecological restoration in Xinjiang” were also compiled to guide soil and water conservation in each county. To minimize the impact of development projects on soil erosion, any new development and construction project is required to have a water and soil conservation scheme as of October 2013, according to newly enacted regulations in Xinjiang.

4.3.2. Biological measures

The area controlled by soil and water conservation measures in Xinjiang is 9.55×10^3 km^2, of which 9.46×10^3 km^2 (i.e., 99.1% of the total area) is controlled by biological measures (The Ministry of Water Resources of China, 2013). A natural forest protection zone was built in serious soil erosion areas, and deforestation and grassland cultivation are prohibited. Apart from this natural vegetation rehabilitation approach, a series of other measures, such as establishing forbidden areas by fence, implementing rotational grazing, and raising livestock in sheep pens, were taken to restore the damaged grassland ecosystem (Bai, Hong, Song, & Xie, 2005; Zhang & Hua, 2004). When planting forest near the river bank, suitable plants are required according to the specific soilscape and soil erosion conditions (Chen, Li, Wang, & Zhang, 1996). Soil and water conservation areas might also feature fruit trees in order to achieve a win–win situation of both ecological and economic benefits.

4.3.3. Engineering measures

Soil and water conservation measures for development projects mainly involve sediment storage dam, debris blocking projects, slope protection engineering, land treatment projects, river regulation, and drainage ditches (Hong, Qiu, Wang, & Xie, 2003; Xu, 2013). In 2011, the west section of the West–East natural gas transmission project in China was named as the national demonstration project of soil and water conservation by the Ministry of Water Resources of China.

4.3.4. Integrated treatment and demonstration at the small watershed scale

Biological and engineering measures were combined to pursue the highest ecological and economic benefits. Agricultural and engineering measures should also be included in soil and water conservation in Xinjiang, since simply biological measures such as planting forest and grass are usually not effective. Based on the previous successful measures (Tables 3 and 4), the soil and water conservation model of Xinjiang can be summarized as a landscape ecological design model (Fig. 8), i.e., preventing erosion via natural vegetation in high mountain areas in the first place, while impounding surface runoff in low mountain areas to eliminate flooding and develop grassland farming. Moreover, in oasis areas, water-saving measures, such as drip irrigation and rainfall collection, should be used to develop forestry and fruit industry. Without financial incentives for local farmers, soil and water conservation is also not sustainable. Presently, the newly controlled soil erosion area in Xinjiang is averaging 2.07×10^3 km^2/a (Fig. 7). At this speed, at least 42 more years will be needed to completely control water erosion in Xinjiang.

Table 3
The intensity of soil water erosion for each soil and water conservation sub-region in Xinjiang, China.

Sub-region	Soil water erosion area ($\times 10^3$ km^2)		Average soil erosion modulus (t km^{-2} a^{-1})
	Total area	Area for grades above intense erosion	
North part of Junggar basin	9.25	0.179	1566
North part of Tian Mountain	16.0	0.930	2058
Ili river valley	18.6	1.31	2231
Turpan–Hami basin	6.59	0.445	2159
North part of Tarim basin	13.3	1.11	2531
South part of Tarim basin	7.41	0	2115
West part of Tarim basin	16.6	0	2363

Table 4
Integrated measurements of soil and water conservation and ecological restoration at watershed scale in Xinjiang, China.

County (city)	(Small) Watershed	Controlled area (km^2)	Integrated measurements	Reference
Yining	North mountain slope	46	Considering the economic benefits of farmers and planting fruit trees, restoring grassland near river bank, building terrace	Liu, 1998
Urumqi	Shuimo river	250	Restoring forests to retain water, improving soil infiltration capacity, building grassland farmland, rotation grazing	Jiang et al., 1998
Ruoqiang	Middle and downstream of Ruoqiang river	300	Natural vegetation restoration first, then using control measures and water–saving irrigation	An, Zhang, Liu & Bai, 2005
Jimsar	Weihu channel,Liudao channel	1124	Building grassland farmland, planting water-saving vegetation	Zhang & Hua, 2004
Changji	Toutun river	1417	Planting mixed forests, most of them were conservation forest, while the rest were economic forest	Luo, 2007
Jiashi	downstream of Kezi river	3590	Using engineering measures to irrigate natural desert forest with flooding water	Hu, 2004
Korla	Kongque river	7116	Planting economic forest in barren mountains, and planting ornamental trees along the river bank	Cui, 2009

4.3.5. Impacts of water and soil conservation

Soil and water conservation works in Xinjiang began in 1994. After two decades, the soil water erosion area decreased by 23.8%, from 115×10^3 km^2 in 1995 to 87.6×10^3 km^2 in 2011 (Table 1), while the forest area increased from 13.1×10^3 km^2 in 1993 to 69.8×10^3 km^2 in 2013 (State Forestry Administration of China, 2014; Zhang, 2015). Moreover, the planted area of fruits also increased rapidly, from 1.52×10^3 km^2 in 1994 to 9.34×10^3 km^2 in 2013 (Liu, 1995; Chen, 2014). The development of forestry and fruit industry not only increased the income of local farmers, but also changed the barren mountain into a “flower and fruit mountain”. In 2013, the Tian Mountain was named as a world natural heritage site. Therefore, soil and water conservation efforts improved the landscape quality of Xinjiang. Soil and water conservation practice could also yield multiple ecosystem service functions, such as reducing sediment deposition in reservoirs, mitigating flood, drought and geohazards, lessening fertilizer loss and water contamination, as well as benefiting water resource conservation and carbon sequestration (He, Zhang, Li, Gao, & Wang, 2012; Ping, Lin, Bai, Liu, & Lu, 2014).

4.4. Implications for soil and water conservation in Central Asia

Available publications about the magnitude of soil water erosion in the five countries of Central Asia (i.e., Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) are rare. Most parts of the mountain area in these five countries are concentrated in Kyrgyzstan and Tajikistan, where are also the main source region for renewable surface water resource (Abuduwaili, Ayoupu, Liu, Wu, & Tang, 2009; Zhang, Hu, Zhou, Saparov, &

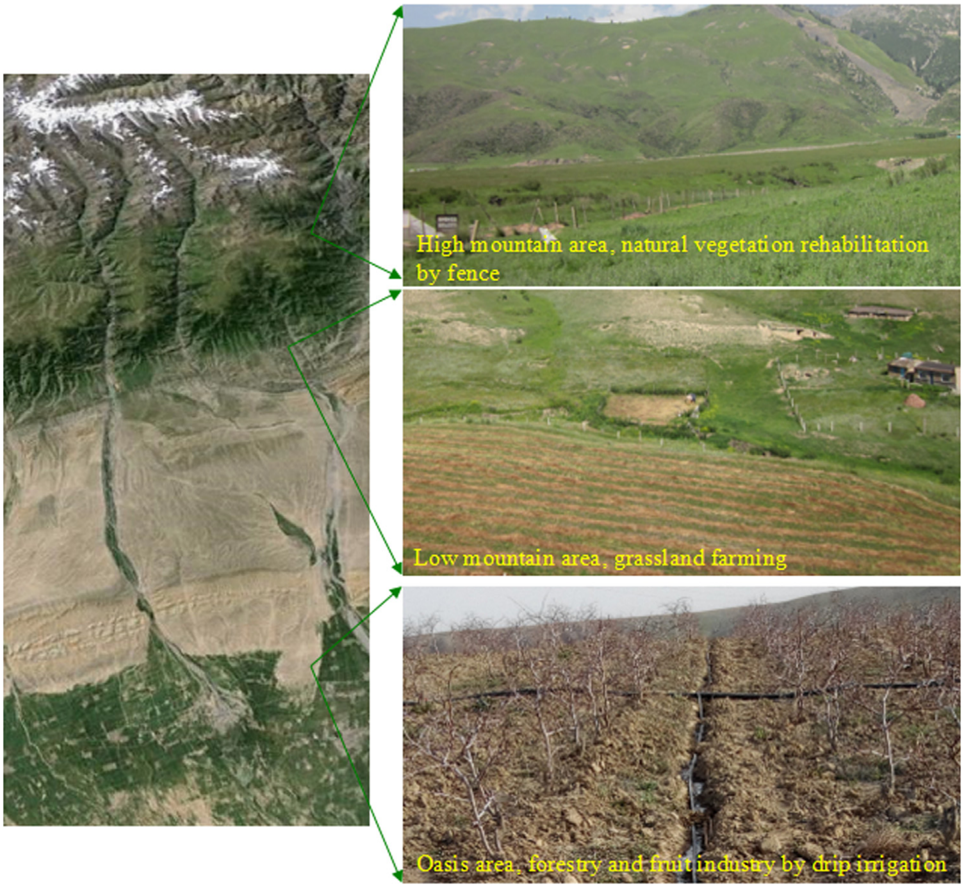

Fig. 8. The landscape ecological design concept model for soil and water conservation in Xinjiang, China.

Kuziev, 2012). The annual mean precipitations in northern and western Kyrgyzstan are as much as 800 mm, and 27.9% area of Kyrgyzstan is affected by desertification (Liu, 2004). For a 60 km^2 catchment in Faizabad of Tajikistan, it was estimated that a third of the catchment was eroded by water at a rate of >3000 t/(km^2 a) (Bühlmann et al., 2010). The percent of area affected by water erosion in Uzbekistan and Turkmenistan is 15.8% and 1.4%, respectively (Rakhmatullaev et al., 2013; Zhang, Liu, Yao, & Wang, 2013). The annual mean precipitation of Kazakhstan ranges from 100 to 300 mm, and the main type of soil erosion is irrigated erosion in cropland (Abuduwaili et al., 2009; Saparov et al., 2013). It can be concluded that serious water erosion areas in the five countries are mainly distributed in the mountain area.

The five countries of Central Asia are important regions for developing prataculture and animal husbandry industry, since the average percentage of grassland there is 63.8% (Fan et al., 2012). However, grassland degradation might be caused due to heavy grazing. In order to protect the ecosystem, grassland farming has been developed in Kazakhstan, and floods are used to irrigate the grassland farmland (Jianati et al., 2013). The strategies of water and soil conservation in Xinjiang as well as the summarized landscape ecological design model are brought out from a geo-system perspective to combat desertification. Since both the characteristic of water erosion and the grassland management approach in the five countries of Central Asia are similar to those of Xinjiang, it is reasonable to extend this model to other regions of Central Asia. For example, in order to reduce erosion, agroforestry and industrial nut-fruit plantation has been adopted in Tajikistan and southern Kyrgyzstan, respectively (Bühlmann et al., 2010; Sakbaeva et al., 2013). This landscape ecological design model might also be useful for protecting mountain–desert ecosystems in other regions of the world, such as the western USA and the southern Latin America.

5. Conclusions

The soil erosion area of Xinjiang constitutes nearly one third of the total soil erosion area in China now, and water erosion shows an ever-deteriorating trend over the last 26 years. Limited precipitation makes vegetation restoration and forest plantation difficult; Xinjiang therefore is one of the regions with the largest difficulty to control soil erosion in China. Both anthropogenic factors, such as population boom and development activities, and natural factors, such as vegetation degradation, climate change, and landforms are influencing soil water erosion. The interaction of these drivers makes water erosion in this fragile ecosystem even worse. Integrated measurements to control soil water erosion not only minimize socioeconomic loss caused by geohazards, but also bring both ecological and economic benefits from a long-term perspective. A landscape ecological design approach, such as developing a forest/fruit industry and building grassland farmland, is suggested for successful long-term soil and water conservation in Xinjiang, as well as in other regions of Central Asia.

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