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Afforestation and the impacts on soil and water conservation at decadal and regional scales in Northwest China

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ABSTRACT

Massive afforestation has been conducted in dryland regions of Northwest China since 1978. With the impending effects of climate change, it is necessary to reconsider the effects of artificial vegetation on soil and water conservation at decadal and regional scales. Using long-term official and synthesized data, the vegetation's impacts on reducing water loss and their ecological water requirement were studied in four provinces (e.g., Inner Mongolia, Gansu, Qinghai, and Xinjiang). Results showed that vegetation of the four provinces was dominated by grass, while artificial forest had taken up 13% of the total forest area. At the plot scale, vegetation could reduce runoff and sediment by 44% and 83%, respectively. At the regional scale, soil erosion areas showed a decreasing trend, especially after the year 2000. In Inner Mongolia and Gansu, both runoff coefficients and water resource amounts showed decreasing trends. As such, future large-scale afforestation might be ecologically unsustainable in these two provinces. However, the runoff coefficients and water resource amounts of Qinghai and Xinjiang showed increases, mainly linked to climate change. This study helps elucidate the paradox of vegetation restoration in arid regions, and gives some suggestions for ecological restoration in other drylands of the world.

1. Introduction

Drylands cover >40% of the earth's land area (Millennium Ecosystem Assessment, 2005). Sustainable development in drylands depends upon techniques such as soil and water conservation (Mortimore et al., 2009). However, this fragile ecosystem can readily result in land degradation and desertification when mismanaged. Designer ecosystem is a coupled natural-human system designed to optimize ecological services and to alleviate adverse conditions that support ecosystem functions, when environmental degradation is extreme and restoration of an ecosystem to the past state is impossible (Martínez and López-barrera, 2008). Applying designer ecosystem and vegetation management to control soil water erosion could achieve the highest ecological, social, and economic benefits (Palmer et al., 2004).

Forest-water interaction is the central topic for most researches on afforestation in dryland ecosystems. Conversion of marginal cropland to fruit forest could save >70% crop water demand in Uzbekistan of Central Asia (Djanibekov et al., 2012). Fog harvesting was demonstrated to provide additional water input for seedling establishment in southeast Spain (Vallejo et al., 2012). For Mediterranean ecosystems in North Africa and West Asia, afforestation could be successful occasionally even when the annual precipitation is < 200 mm, where the species introduced is appropriate (Le Houérou, 2000). Precipitation and evapotranspiration are important climate variables in modelling the impact of afforestation on water yield. Simulated results showed that a 10% increase in tree cover in the headwaters would reduce river flows by 17% in the 7.5×10^4 km^2 Macquarie River catchment of Australia (Herron et al., 2002). However, on the 0.64 million km^2 Loess Plateau of China, it is estimated that the vegetation restoration from 1999 to 2007 had resulted in water yield decreased in 37% and increased in 35% of the study area (Feng et al., 2012).

Areas of Northwest China could be considered the perfect natural laboratory to study the impact of vegetation restoration on regional hydrological processes in earth surface systems. Most parts of Northwest China are drylands (arid and semi-arid regions) and are suffering serious environmental and ecological problems. In order to achieve multiple environmental objectives such as

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combating desertification, restoring groundwater sources, and eliminating dust storm hazards (e.g. haboobs), long term ecological studies are needed. The Three Norths Shelter Forest System Project, a massive afforestation project, has been conducted in Northwest China since 1978 (Cao et al., 2011; UNCCD and World Bank, 2013). Immediately after the beginning of China's Grand Western Development Program in 1999, other great ecological engineering plans (e.g., the Grain for Green Project) were launched.

However, inadvertent negative effects might arise when planting trees in drylands without carefully considering the prevailing ecosystem. On the Loess Plateau, vegetation restoration could exacerbate environmental degradation and soil desiccation caused by ignoring climate, pedological, hydrological, and landscape factors in large-scale afforestation (Cao et al., 2011; Jiao et al., 2012). In fact, local climate conditions (e.g., mean annual precipitation) and plant species should be major considerations in artificial forestation (Jin et al., 2011; Jian et al., 2015). Most previous research on the impact of vegetation restoration in dryland ecosystems of China was located in the semi-arid Loess Plateau, with little attention paid to truly arid regions. Zhou et al. (2015) noted that land cover changes (e.g., afforestation) in non-humid regions can lead to greater hydrological responses than that in humid regions. With deference to climate change, urgent consideration is needed concerning the trade-off between vegetation restoration and soil and water conservation in arid regions (Cao et al., 2010; Yang et al., 2010).

Given the lack of available research on afforestation in truly arid regions of China, the objectives of this study were to: (1) explore the current condition of vegetation restoration in Northwest China, (2) understand the effects of vegetation on soil and water conservation at both plot and regional scales, and (3) discuss the impact of long-term vegetation restoration on water resources in Northwest China.

2. Material and methods

2.1. Study area

Four provinces located in Northwest China (e.g., Inner Mongolia, Gansu, Qinghai, Xinjiang) were chosen for this study (Fig. 1). About 70.5% of the four provinces contributes to the inland rivers watershed (Chen et al., 2004), which is spatially larger than the arid region of China (Li et al., 2013). Furthermore, most part of the four provinces could be classified as drylands (State Forestry Administration of China, 2014). The main geomorphological units in the study area are mountains, plateaus, and basins. Climate of the region is dry with mean annual precipitation <400 mm. Dominant soils of the region include Orthic Aridosols and Gelic Cambosols, as classified by *Chinese Soil Taxonomy* (Gong et al., 2014). The forest types are dominated by shrub, coniferous forest and broad-leaved forest (State Forestry Administration of China, 2014) while the grassland ecosystem is dominated by tempered desert, tempered steppe, and alpine meadow (Meng, 1994). The total soil erosion area of the four provinces is 1.88×10^6 km^2, including 1.57×10^6 km^2 wind erosion area and 0.309×10^6 km^2 water erosion area. Only soil water erosion is considered in this study, since water eroded region should be given a priority to overcome the erosion problem in dryland ecosystems (Zhang et al., 2015). Finally, population densities of Inner Mongolia, Gansu, Qinghai, and Xinjiang are 21.1, 60.6, 8.0, and 13.6 people per km^2, respectively; areas of prime importance for animal husbandry of sheep, beef cattle, and horses.

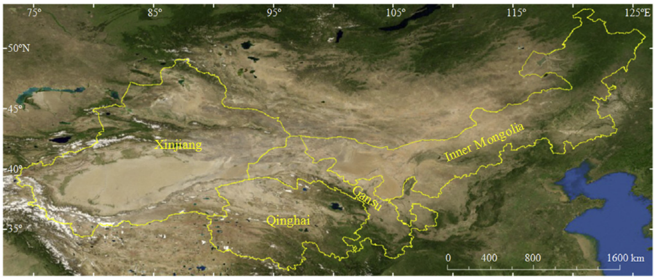

Fig. 1. Sketch map of four studied provinces in Northwest China.

2.2. Data sources, calculation and statistical methods

It is difficult to obtain long-term, large-scale data through field experiments. Thus, the vegetation data compiled in this study were derived from official authorities in China. For example, the forest resources area of China is regularly surveyed every five years. The forest area (including shrub area), artificial forest area, and forest coverage fraction data from 1988 to 2013 were all synthesized from forest survey results (State Forestry Administration of China, 2014; Zhang, 2015). Grassland area data for each province was derived from the Grassland Resources Survey of China (Meng, 1994; National Bureau of Statistics of China, 2011–2014), with the grass coverage fraction calculated thereafter. There was no continuous planting grass area data available. Subsequently, only data from 1990 (Meng, 1994), 1997 (Meng and Liu, 2000), 2000 to 2003 (Liu, 2002, 2003), and 2010 to 2013 (National Bureau of Statistics of China, 2011–2014) were collected.

Field plot approach for studying the impact of vegetation on soil and water conservation is time and labor intensive. Hence, only eight relevant case studies were collected from previous publications. Each plot was constructed with a cement ridge of 30 cm above ground around the borders. A marked H-flume and two volumetric tanks were built at the outlet of each plot for surface runoff and sediments collection (Wei et al., 2007). Plots used by Gao et al. (2007), Wei et al. (2007), and Chen et al. (2010) were 10 m × 10 m and 10 m × 5 m, while plots used by Zhang et al. (2004) and Xu et al. (2007) were 20 m × 5 m. The soil loss rate of two cases was measured using a ^{137}Cs approach (i.e., Zhang et al., 1994; Wu and Tiessen, 2002). Following the formula to calculate a C-factor, an index used to quantitatively express the effect of vegetation on preventing soil erosion in the universal soil loss equation (USLE) (Wischmeier and Smith, 1978), the runoff reduction factor (C_r), and sediment reduction factor (C_s) were calculated as Eq. (1) and (2).

$$C_r = V_r/B_r \tag{1}$$

$$C_s = V_s/B_s \tag{2}$$

where, C_r and C_s are the runoff reduction and sediment reduction factors, V_r and V_s are the amounts of runoff and sediment lost from a vegetated plot, and B_r and B_s are the amounts of runoff and sediment lost from a corresponding barren land plot. All the landscape conditions such as soil, climate and terrain of the vegetated plots are the same with the corresponding barren land plot for each case study. A comparison of different types of vegetation (e.g., forest, shrub, and grass) on reducing runoff and sediment was performed using one-way analysis of variance (ANOVA).

Data of soil water erosion area from 1985 to 2011 were collected from Li (2010) and the Ministry of Water Resources of China (2013), which 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 et al., 2010). However, the same standard for gradation of soil erosion was used in these four surveys, making the comparison among the four surveyed results reasonable.

Data on annual precipitation (mm), natural runoff (mm), and water resource amount (mm) from 2001 to 2013 as well as their normal values (from 1956 to 2000) were collected from the China Water Resources Bulletin (Ministry of Water Resources of China, 2002–2014). Annual precipitation was calculated based on the isohyetal map of annual precipitation in China. Natural runoff was calculated by using runoff of natural rivers to divide the region area. The runoff coefficient and water resource amount were calculated using Eq. (3) and (4):

$$r = Q_1 \,/\, P \times 100\% \tag{3}$$

$$Q = Q_1 + Q_2 - Q_3 \tag{4}$$

where, r, Q_1, P, and Q are runoff coefficient (%), natural runoff, annual precipitation, and water resource amount, respectively. Q_2 is the groundwater resource amount (mm), which refers to the annually renewed dynamic water in saturated aquifer for a certain region. Q_3 is the repeated amount of water (mm) for natural runoff and groundwater resource. It is noteworthy that natural runoff (Q_1) is also the difference between annual precipitation (P) and annual surface evapotranspiration (ET) (Feng et al., 2012).

3. Results and discussion

3.1. Changes in vegetation areas and structure

In 2013, the forest area of Inner Mongolia was 1.54 times larger than the sum of those of the other three provinces. However, the forest of Inner Mongolia is mainly distributed in its northeast part (Fig. 1). The average forest coverage fraction of the four provinces was 10.3% (Table 1), substantively lower than the average value across all of China (21.6%). The forest areas of all four provinces showed rapid increases after 1998 (Fig. 2). Collectively, the total forest area of the four provinces was 2.33 times larger in 2013 than in 1988. Two reasons account for the boom of forestry: Firstly, several major afforestation programs such as the Three Norths Shelter Forest System Project (Phase IV), the Grain for Green Program, and the Natural Forest Conservation Program have been conducted in Northwest China since 2000 (Cao et al., 2011). Secondly, the shelter shrub with a coverage >30% as well as the economic shrub in dryland region (annual mean precipitation < 400 mm) were considered as shrub forest and included in forest area, according to a regulation promulgated by the State Forestry Administration of China in 2004. Shrub areas of the four provinces also experienced ever-increasing trends since 1988 (Fig. 3). Shrubs constitute the main afforestation species in arid and semi-arid regions (Table 1). In 2013, prevalence of shrub forest in the four provinces was Inner Mongolia > Xinjiang > Qinghai > Gansu.

Table 1
Coverage fractions of each type of vegetation and the proportion of artificial vegetation in Northwest China.

	Coverage fractions (%)			Proportion of artificial vegetation (%)		Artificial forest: Artificial grassland
	Forest	Shrub	Grassland	Forest	Grassland	
Inner Mongolia	21.03	6.75	66.61	13.3	5.58	1.00: 1.33
Gansu	11.28	8.48	42.05	20.3	13.3	1.00: 2.30
Qinghai	5.63	5.62	50.35	1.83	3.00	1.00: 14.7
Xinjiang	4.24	2.80	34.39	13.5	2.97	1.00: 1.81
Average	10.34	5.09	47.66	13.1	7.19	1.00: 1.78

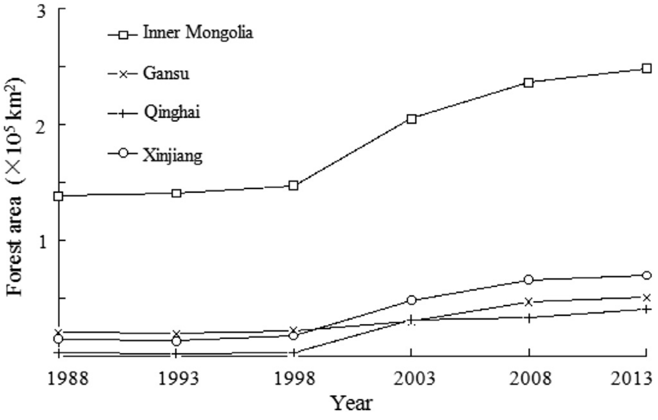

Fig. 2. Changes of forest area of four provinces in Northwest China.

Grassland is the largest terrestrial ecosystem of China, and has multiple ecological functions such as preventing wind erosion, stabilizing sand, and conserving soil and water. All four of the studied provinces are important pastoral areas in China. Statistical data showed that from 1990 to 2013 the grassland areas remained constant for Inner Mongolia, Gansu, Qinghai, and Xinjiang at 7.88×10^5 km^2, 1.79×10^5 km^2, 3.64×10^5 km^2, and 5.73×10^5 km^2, respectively (Meng, 1994; National Bureau of Statistics of China, 2014). The total grassland area of the four studied provinces accounted for 33.9% of the total grassland area in China.

In each of the four studied provinces in Northwest China, the coverage fraction for different vegetation types was grassland >> forest > shrub (Table 1). The artificial forest areas for Inner Mongolia, Gansu, Qinghai, and Xinjiang in 2013 were 33,165 km^2, 10,297 km^2, 744 km^2, and 9400 km^2, respectively. The total artificial forest area of the four provinces was 53,606 km^2, and accounted for 13.1% of the total forest area in the four provinces. Among the four provinces, the proportion of artificial forest in Gansu was the highest, while that in Qinghai was the lowest. Reserved planting grass areas involve those grasslands which have been influenced by anthropogenic activities, such as artificial planting, restoration and amelioration, and aerial seeding. Reserved planting grass areas changed greatly from year to year (Fig. 4), due mainly to rat damage, locusts, and fire damage. Limited rainfall also

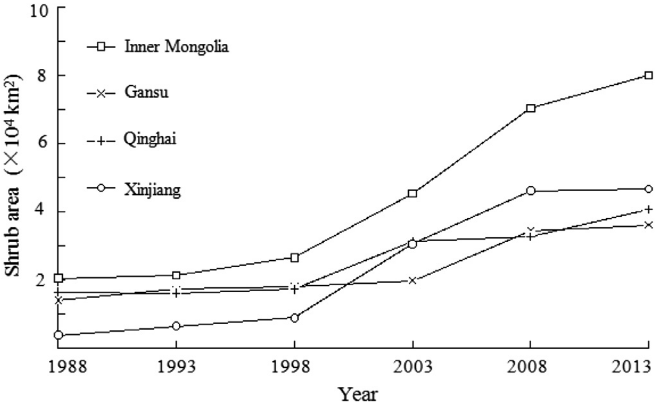

Fig. 3. Changes of shrub area of four provinces in Northwest China.

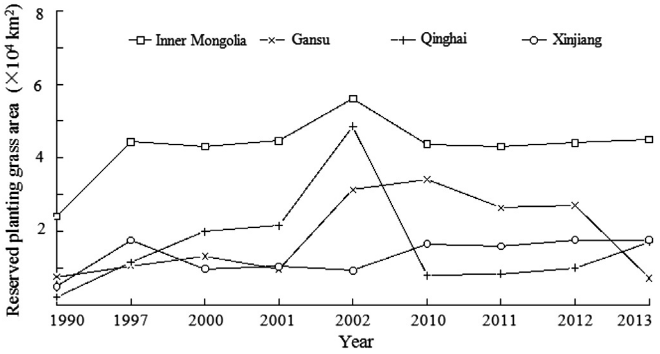

Fig. 4. Annual changes of the reserved planting grass area of four provinces in Northwest China.

contributed artificial grassland degradation. The changes of reserved planting grass areas in Fig. 4 could explain why the grassland areas of the four provinces in 1990 are not different from those in 2013.

3.2. Plot scale vegetation impacts on soil and water conservation

When annual precipitation ranged from 351 to 453 mm, surface runoff of vegetated plots varied from 5.5 to 188 mm (Table 2), suggesting that vegetation could reduce runoff by >50%; even up to 90% sometimes. Notably, antecedent soil moisture is usually low in this dryland ecosystem of Northwest China. Even with no vegetative cover, ~25% of precipitation received could be transferred to groundwater directly through infiltration. Given differential soil conditions and slopes across the case studies, it is not rational to compare the vegetative reduction in runoff using indices such as runoff coefficient or runoff rate. Instead, the runoff reduction factor (C_r) was used to indicate the effect of vegetation on runoff. The C_r value of forest, shrubs, and grass was 0.684, 0.333, and 0.622, respectively (Fig. 5a). However, no significant difference existed among the three vegetation types in reducing runoff. The mean runoff reduction factor for all the studied vegetation was 0.565, suggesting that vegetation restoration measurements such as returning farmland to forestland could effectively improve infiltration by root systems (Zhang et al., 2011). Similarly, the sediment reduction factor (C_s) of forest, shrubs, and grass was 0.115, 0.012, and 0.251, respectively (Fig. 5b). However, the effects of shrubs and grass in reducing sediment were significantly different ($p < 0.05$). This is mainly attributed to the combined effects of vegetation canopy and understory cover (Wei et al., 2007; Chen et al., 2010). The lowest C_s value of shrubs could partly be explained by its lowest C_r value, since surface flow affects sediment variation during the erosion process (Zhang et al., 2010). The mean sediment reduction factor for all the studied vegetation was 0.170. Generally, shrubs were superior for reducing runoff and sediment. However, the intershrub area might still suffer soil and water loss when the shrubs were scattered (Schlesinger et al., 1999).

3.3. Regional scale vegetation impacts on soil and water conservation

At the regional scale, the soil water erosion areas for all the four provinces showed decreasing trends from 1985 to 2011. The deceasing trend was especially distinct after 2000 (Fig. 6). This time coincided with the year that forest and shrub areas started to proliferate (Figs. 2 and 3). From 1985 to 2011, soil water erosion area of the four provinces reduced by 1.11 × 10^5 km^2 (Fig. 6), while their forest area increased by 2.34 × 10^5 km^2 from 1988 to 2013 (Fig. 2). The magnitudes of the two areas are the same, suggesting that reduced water erosion area is mostly attributed to increases in vegetative coverage. In fact, ~84% of the soil and water conservation area in these four provinces was under control by vegetation measurements (Ministry of Water Resources of China, 2013). The deceased annual precipitations of Inner Mongolia and Gansu (Fig. 7) might also contribute to the reduction of soil water erosion areas in these two provinces.

The runoff coefficients of Inner Mongolia and Gansu from 2001 to

Table 2
Effects of different types of vegetation on soil and water conservation in Northwest China.

Province	Period	Rainfall(mm)	Slope (°)	Land use	Soil loss rate(t km^{-2} a^{-1})	Runoff(mm a^{-1})	Reference
Gansu	1986–1999	427	10–20	Cropland/Spring wheat	8599	17.1	Wei et al., 2007; Chen et al., 2010
				Forest/Chine Pine	760	13.5	
				Shrub/Sea buckthorn	131	5.84	
				Grass/Native	534	9.50	
				Grass/Purple Alfalfa	3392	15.0	
Gansu	–	565	33–45	Bare land	3276	–	Zhang et al., 1994
				Forest	246	–	
				Grassland	188	–	
Gansu	1999	416	3–20	Cultivated land	5533	–	Wu and Tiessen, 2002
				Pasture	800	–	
Gansu	2002–2003	351	12–18	Cultivated fallow	–	29.6	Huang et al., 2005
				Forest/Prunus armeniaca var. ansu	–	8.65	
Gansu	2003	453	17	Barren slope	–	26.7	Zhang et al., 2004
				Forest/poplar	–	22.0	
				Shrub/Sea buckthorn	–	19.9	
				Grass/Native	–	23.6	
				Grass/Purple Alfalfa	–	19.0	
Gansu	2005–2006	618	12–15	Cropland	122.2	8.24	Gao et al., 2007
				Forest	22.2	6.84	
Gansu	–	416	17–20	Cropland	104.1	279	Zhao, 2010
				Grass/Native	18.3	58.1	
				Grass/*Festuca ovina* L.	60.3	156	
Qinghai	2001–2005	363	27	Cropland	3750	233	Xu et al., 2007
				Shrub/Caragana intermedia	7.22	24.7	
				Shrub/Sea buckthorn	66.6	32.8	
				Grass/Native	1225	188	
				Grass/Purple Alfalfa	999.8	87.0	

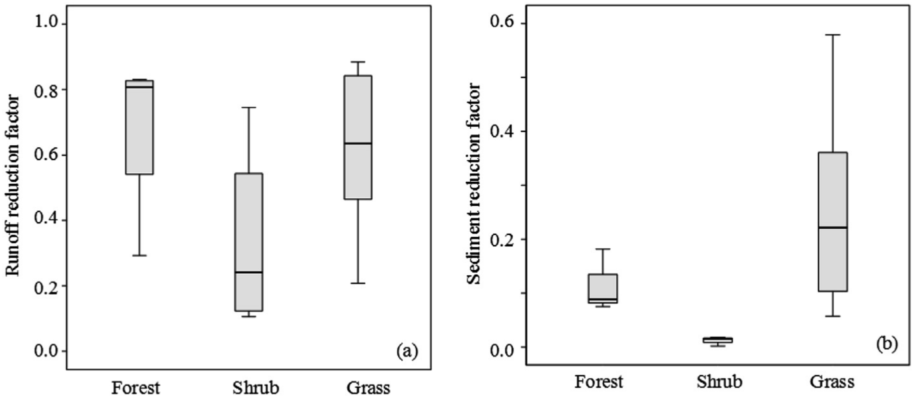

Fig. 5. Effects of the three types of vegetation on soil and water conservation in Northwest China.

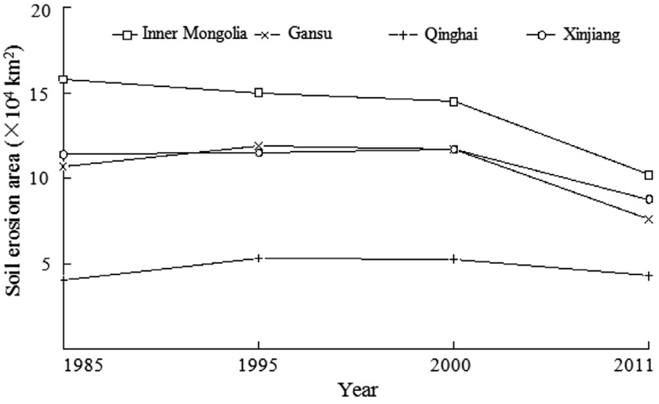

Fig. 6. Changes of soil water erosion area in Northwest China.

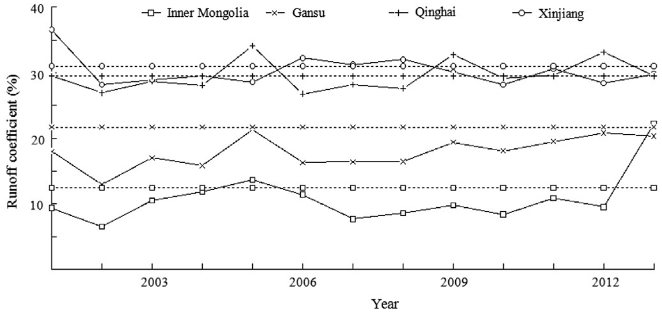

Fig. 8. Changes of runoff coefficient and the comparison with normal values in Northwest China. The normal values are the mean annual values from 1956 to 2000, as illustrated by the dotted straight line.

2013 were generally lower than their normal values (Fig. 8). For some years in Gansu, the runoff coefficient was lower than the normal value even though precipitation was higher than normal (e.g., 2003 and 2007) (Figs. 7 and 8). Forest coverage, shrub coverage, and the proportion of artificial forest in both Inner Mongolia and Gansu were relatively high in the four studied provinces (Table 1). Wang et al. (2011) showed decreasing runoff coefficients with increasing vegetation. Therefore, the decreased runoff coefficients of Inner Mongolia and Gansu were likely caused by large-scale afforestation. However, from 2001 to 2012 the runoff coefficients of Qinghai and Xinjiang did not change appreciably (Fig. 8), suggesting that runoff increased with enhanced precipitation (Fig. 7), and the increases of forest coverage (Fig. 2) did not significantly reduce runoff in these two provinces. This could be explained as follows: To begin with, the forest coverage fractions of the two provinces are still low (Table 1). Furthermore, high precipitation regions of Qinghai and Xinjiang are concentrated in mountain areas, where the soils are generally too thin to fully infiltrate surface runoff (Liu et al., 2013; Zhang et al., 2015). The precipitation of Inner Mongolia increased abruptly in 2012; precipitation in 2013 was similar to 2012 (Fig. 7). Subsequently, the runoff coefficient and water resource amount of Inner Mongolia in 2013 were higher than normal values (Figs. 8 and 9). Long-term data are still needed to confirm the dynamics of precipitation in Inner Mongolia.

3.4. Ecological water requirement and water resource sustainability

Generally, the ecological water requirement (EWR) of vegetation is defined as the water resources used to maintain the natural

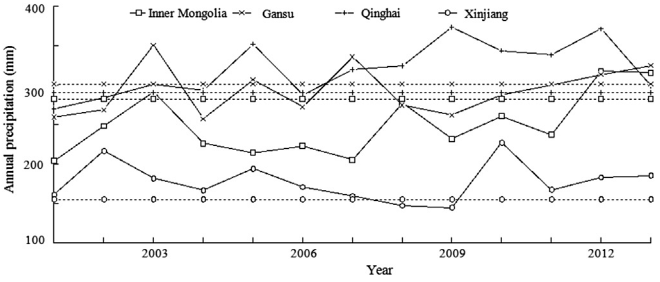

Fig. 7. Changes of annual precipitation and the comparison with normal values in Northwest China. The normal values are the mean annual values from 1956 to 2000, as illustrated by the dotted straight line.

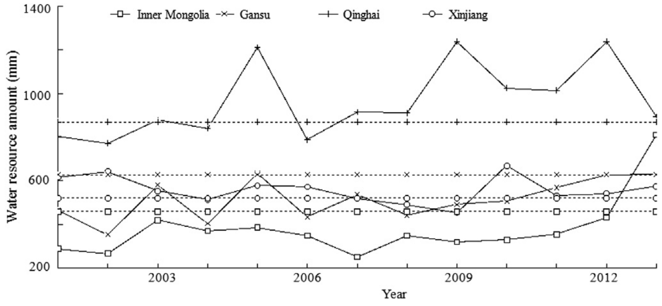

Fig. 9. Changes of water resource amount and the comparison with normal values in Northwest China. The normal values are the mean annual values from 1956 to 2000, as illustrated by the dotted straight line.

Table 3
Ecological water requirement (EWR) of different types of vegetation in Northwest China.

Province	Vegetation	EWR (mm)	Formula	Reference
Inner Mongolia	Forest/*Pinus tabuliformis*	225	EWR = surface evapotranspiration + soil water storage	Bao, 2005
	Forest/Ponulus simonii	391		
	Shrub/Hippophae rhamnoides	261		
	Grass/Stipa bungeana	207		
Inner Mongolia	Forest/Populus euphratica	306	EWR = phreatic evaporation	Guo et al., 2010
	Shrub	410		
	Grass	410		
Inner Mongolia	Forest/Populus euphratica	156	EWR = vegetation productivity × transpiration coefficient	Zhao et al., 2007
	Shrub/Tamarix spp.	134		
	Shrub/Haloxylon ammodendron	20		
Inner Mongolia	Forest/Populus euphratica	527	EWR = transpiration for plant growth + groundwater evaporation	Fu et al., 2008
	Shrub	49		
	Grass	43		
Gansu	Forest	364	EWR = evapotranspiration of reference crop × plant coefficient	Hao et al., 2010
	Shrub	335		
	Grass	254		
Xinjiang	Forest	374	EWR = phreatic evaporation	Fan et al., 2004
	Shrub	234		

balance of vegetation ecosystems, as well as to continue their normal ecosystem service functions (Zhao and Cheng, 2002; He et al., 2006). The EWR of vegetation is not only determined by physiographic factors such as climate, groundwater table, and soil, it is also closely related with plant characteristics such as vegetation species, vegetation fractional coverage, and community types (Fan et al., 2004; Fu et al., 2008). Presently, there is no a uniform formula used to calculate EWR (Table 3). However, EWR is often expressed by evapotranspiration of vegetation. The EWRs for the cases studied in this research were often higher than the corresponding normal value of precipitation for each province in Fig. 7, implying that artificial vegetation might lead to water shortage and soil desiccation due to plant growth. For instance, vegetation construction produced prominent negative effects on soil water below 40 cm in northern China (Li et al., 2014a). A global analysis of 504 annual catchment observations showed that plantation decreased stream flow by 227 mm or 52% per year (Jackson et al., 2005).

The average water resource amounts from 2001 to 2012 of both Inner Mongolia and Gansu were clearly lower than their normal water resource amounts (Fig. 9). Though in 2013 the water resource amount of Gansu was close to the normal value, and that of Inner Mongolia was even higher than normal (Fig. 9), it is still too early to be optimistic. The water resource amount reduction is mostly attributed to decreasing precipitation (Fig. 7). Furthermore, massive afforestation might also result in water resource shrinking through canopy interception. The vegetation restoration approach based on large-scale afforestation should only be attempted with extreme caution in Inner Mongolia and Gansu, considering the limited annual precipitation and the EWR of vegetation. The optimal EWR of Minqin County of Gansu in normal years was 264 mm (Hao et al., 2010), accounting for 87% of the normal annual precipitation of Gansu. To minimize EWR, the maximum coverage thresholds for establishing shrubs and herbs was recommended as 10% and 35% in the Shapotou area of Ningxia, a province adjacent to Inner Mongolia and Gansu (Li et al., 2014b).

By contrast, the water resource amounts of both Qinghai and Xinjiang from 2001 to 2013 were generally higher than their normal water resource amounts (Fig. 9). In fact, the annual precipitation of the two provinces has increased over the last several decades (Fig. 7); a clear benefit for regional ecological restoration and rehabilitation. The EWR of Xinjiang was estimated as 237.9×10^8 m^3 (Jia and Ci, 2000), equivalent to 14.3 mm. The net surface runoff amounts of Qinghai and Xinjiang have also increased (Fig. 8). Surely, this will result in a loss of water resources in the arid region with high evaporation. However, the risk of flooding might also be improved. The effect of shrubs in reducing surface runoff and soil erosion are illustrated in Fig. 5. Moreover, the EWR of shrubs is generally lower compared with that of forest (Table 3). Therefore, the planting of shrubs with suitable coverage should be encouraged in Qinghai and Xinjiang, especially for the places prone to suffer flooding.

Future vegetation restoration strategies in Northwest China rely on integrated landscape engineering and designed ecological solutions, whereby the species and suitable vegetation coverage in afforestation or grass planting should be varied according to specific site conditions such as rainfall amount, soil properties, geomorphological characteristics, and groundwater table. More studies are needed to understand the hydrological impact of vegetation restoration at regional scale from comprehensive perspectives, such as regional hydrological cycling, ecological process dynamics, and landscape heterogeneity.

4. Conclusions

Northwest China is typically a region dominated by arid climate and a desert-grassland ecosystem. Natural vegetation is scattered in this region, and vegetation restoration and ecological rehabilitation are therefore difficult. The past three decades have been characterized by a proliferation of artificial vegetation in Northwest China. Although improving vegetation coverage facilitates reduced soil erosion and surface runoff, massive afforestation and ecological water requirements of the vegetation might lead to water shortage. Under the background of climate change, the annual precipitation and water resources of Inner Mongolia and Gansu in Northwest China during the last ten years have decreased, while those of Qinghai and Xinjiang have increased. The need to identify anthropogenic impacts (such as great ecological engineering project) on the regional sustainability of dryland ecosystems remains critical. In order to simultaneously achieve rational vegetation restoration and sustainable water resource management, integration of knowledge from geomorphology, hydrology, pedology, and biology, as well as applying the concepts of landscape engineering and designer ecosystems are required.

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