



# The ecological consequences of the large quantities of trees planted in Northwest China by the Government of China

Yang Xiao<sup>1</sup> · Qiang Xiao<sup>2</sup>

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## Abstract

Rapid economic and population growth exacerbates water resource shortages and various associative ecological factors. Additionally, climate change makes it difficult to predict potential eco-environmental risks. The Government of China enacted a large-scale forestation campaign in the northwest to cope with the region's increasingly severe eco-environmental problems. This study applied GIS software to analyze areas where water resource changes have occurred and the reasons behind water shortages. Notwithstanding fluctuations, there was a general increase in water resource trends between 1980 and 2015. On a regional scale, we observed an increasing trend for provinces with large water resources, including Xinjiang, Qinghai, and Xizang, which accounted for 84.58% of the total increases observed between 1980 and 2015. The water resource trend for the region as a whole increased exponentially with increasing rainfall and decreasing evapotranspiration. Furthermore, water consumed by artificial forests in Northwest China reached 14 billion cubic meters, which is equivalent to 5.22% of its total annual water resources. In contrast, this study determined that under natural vegetation conservation practices, water consumed would have decreased to 10.13 billion cubic meters in 2015. Accordingly, this study concluded that the Government of China should change its policy from planting more trees to protecting natural vegetation.

**Keywords** Vegetation cover · Afforestation · Arid and semi-arid areas · Northwest China · Environmental restoration

## Introduction

Due to a combination of factors, both anthropogenic and natural, the environment of Northwest China has suffered from severe degradation (Kong et al. 2015; Miao et al. 2016). Climate change has exacerbated changes and uncertainty of river and stream systems primarily supplied by the rainfall and snowmelt in northwest arid areas. Water systems in arid areas of Northwest China are vulnerable and the stability of water resources are low (Cao et al. 2016; Zhong et al. 2013). Having been affected by climate change, especially by the impact of changes in temperature, for some large rivers within northwest arid areas that are primarily supplied by glacier or snowmelt,

glacier and snow ablation seasons have lagged and now occur earlier under an increase in the amount of ablation during flood periods (Cao 2014). However, in the long run, under further temperature increases, rivers primarily supplied by ice and snowmelt will exhibit a glacier ablation inflection point resulting from glacial recession and reduced glacial water storages. At that time, the amount of water will decrease in summer and, consequently, available surface water resources will decrease sharply (Liu et al. 2015; Zhang et al. 2016).

In the past 50 years, strengthening socioeconomic activities accompanied by growing artificial oasis area was gradually shifting from downstream to mid and upper reaches in northwest arid areas of China, which is resulting in the shrinkage of downstream terminal lakes and the rapid degradation of riparian forest ecosystems in arid/desert systems (Sun et al. 2015). Although vegetation cover in the northwest region has improved in recent years, few studies have taken the effects of the government's ecological restoration program on the ecosystem into account in this region (Fahey and Payne 2017; Gao et al. 2017).

Many countries have confronted increasingly serious problems in water scarcity. For example, 25% of the world's

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✉ Qiang Xiao  
xiaoqiang7598@126.com

<sup>1</sup> College of Biology and Environmental Sciences, Jishou University, Jishou 416000, China

<sup>2</sup> Intangible Cultural Heritage Center, Chongqing university of Arts and Science, Chongqing, China

population is predicted to experience severe water scarcity within the first quarter of the twenty-first century (Li et al. 2017a, b). For example, global warming has led to the shrinkage of glaciers in the northwest region of China and the generation of increasing amounts of meltwater (Li et al. 2017a, b).

The arid region of Northwest China is located in the mid-latitude region of the hinterlands of Eurasia, and it is considered one of the most sensitive regions to global climate changes. Under a background of global warming, water resources based on ice and snowmelt are extremely fragile in this arid region (Noelia Jimenez et al. 2016). Changes in the volume of water resources and its spatiotemporal distribution caused by climate change will further highlight the disparity in water resources for arid areas and the spatial distribution of productivity. Coupled with increasing population pressure and the unreasonable exploitation of water and soil resources, the discrepancy between the supply and demand of water resources between the oasis economy and the desert ecology in northwest arid areas will become more acute (Guo and Shen 2016). Moreover, much of water in northwest arid areas is used inefficiently, decreasing available water for downstream regions and leading to severe constraints on water consumption by local inhabitants (Buendia et al. 2016). In recent years, the government committed to conserve water resources on the Northwest China, which will have significant impacts on the availability of water for local people who depend on these river systems (Deng et al. 2016). But restrictions on water resource availability often result in competition for available water between natural ecosystems and anthropogenic needs.

River systems in China's northwest arid areas originate from mountains, which mainly include melt water of glaciers from high-mountain elevations, precipitation within the forest belt from mid-mountain elevations, and bedrock fissure-derived water from low-mountain elevations. Owing to their complex constituents, such water sources flow conjointly in mountainous areas, which constitute the surface water resources available for arid areas. For a long time, water resources in arid areas of Northwest China have maintained a fragile balance by relying on Nature's unique water cycling processes. Under global warming, however, water system vulnerability has increased, thereby increasing water resource uncertainty. In arid areas of Northwest China, each link in the water cycle is significantly affected by land surface and climate conditions. The components that constitute water resources are complex, and runoff and water resources are highly flexible. Precipitation resulting from climate change and slight changes in temperature will both greatly affect runoff and significantly impact eco-hydrological processes in arid areas. Moreover, changes in the constituents of the water cycle in mountainous areas via climate change will exacerbate water system instability (Asner and Heidebrecht 2002).

To develop its frontier and to reduce regional poverty, the Government of China instituted the "One Belt And One

Road" initiative in 2013 (World Bank 2019). Some have compared this campaign to the Marshall Plan (the European Recovery Program; ERP) by which to make Northwest China a gateway for central Asia, southern Asia, and western Asia (Shen and Chan 2018), as well as a trade and logistics hub and an important industry and cultural exchange center. However, the Northwest China, where water is severely scarce, may not be able to sustain this policy in the long term. Especially, recently rapid population growth and urban expansion have intensified the demand for water, food, housing, and commercial products in this region, resulting in a series of environmental issues. To achieve its economic development goals while also protecting regional water resources reducing ecological degradation, the Government of China has also conducted large-scale afforestation initiatives (including the Sloping Land Conversion Program, the Natural Forest Protection Program) in the northwest region of the country (Liang et al. 2015).

Under a background of global warming and enhancing human activity, water resources in arid areas of Northwest China, based on the supply of precipitation and Glacial melting from mountainous areas, are more fragile, and anthropogenic activities are significantly changing natural water cycling processes in the basin. In this study, we demonstrate the potential impacts of afforestation initiatives on water availability for local inhabitants in Northwest China. To support our analysis, we quantified the impact on regional water balances by comparing water consumption of afforestation with natural vegetation restoration. Important scientific problems are being addressed by current research, such as how to use the principle of ecology to modify traditional water resource structures, how to form a new cyclic symbiotic model through ecological reorganization and design, and how to establish ecological management mechanisms of ecosystem water resources to promote the efficient use of water resources and to reduce impacts on ecological environments.

## Materials and methods

### Study area

The study region is located within Northwest China (26° 51'–53° 20' N; 73° 30'–126° 05' E), which is characterized by an arid to semiarid climate (Fig. 1). Mean annual precipitation is lower than ~400 mm. High mountain elevations under high precipitation, such as the Altai, Tian Shan, Kunlun, and Qilian Mountains, block atmospheric circulation and create vast desert basins within a rain shadow. Altitude is higher in the west and lower in the east. Grassland is the dominant land use and land cover (LULC) types in Northwest China, and they account for 79.24% of the total area of grassland in China according to the LULC 2010 dataset.

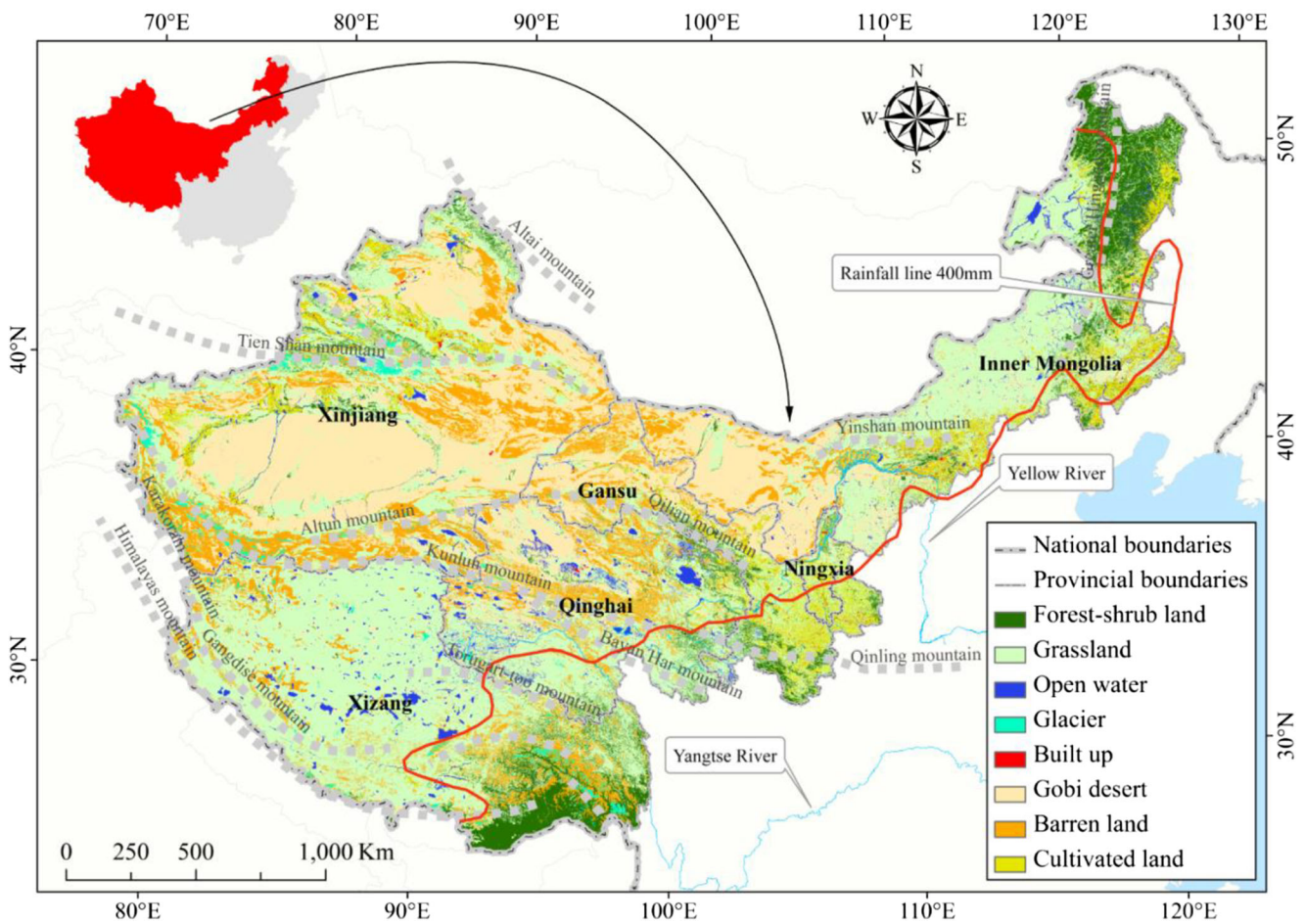


Fig. 1 Location of Northwest China with land use and land cover type distributions

Northwest China mainly includes the Inner Mongolia Autonomous Region, the Xinjiang Uygur Autonomous Region, the Tibet Autonomous Region, Qinghai and Gansu provinces, and the Ningxia Hui Autonomous Region. The Inner Mongolia and Ningxia regions comprise of the largest grassland area in China, which includes meadows, plain grassland, and desert grassland. The region is strongly impacted by Asian monsoon climate factors where most rainfall coincides with high temperatures during the summer season. The dominant LULC in Gansu Province are desert and barren land. The Xinjiang Uygur Autonomous Region is China’s largest administrative division, accounting for more than one-sixth of China’s total territory. Xinjiang is mostly covered by uninhabitable deserts and dry grassland, with dotted oases at the foot of the Tian Shan, Kunlun, and Altai mountains. Inhabitable oases accounted for 9.7% of the total area of Xinjiang in 2010. The Tibetan Plateau (Qinghai and Tibet) is the highest contiguous plateau in the world, with a land area of approximately 1.4 million square kilometers, perched 4500 m AMSL. According to China’s climate classification system, the Tibetan Plateau has a “plateau climate” that is characterized by a subtropical to temperate mountain climate unique to the Qinghai–Tibet Plateau.

The Northwest China is also the source of numerous major rivers in southeastern and eastern Asia, including the Yellow River, the Yangtze River, the Mekong River, and the Salween River. However, it has undergone serious desertification and grassland degradation due to global warming, LULC changes, and overgrazing, which aggravated the scarcity of water resources in arid and semi-arid region.

**Data sources**

We obtained Chinese LULC data from 1980 to 2015 from the National Earth System Science Data Sharing Infrastructure of the Chinese Academy of Science (<http://www.geodata.cn>). These data were produced at a resolution of 1 km, using visual interpretation of Landsat Thematic Mapper (TM) images, with an average overall accuracy greater than 94%. We obtained meteorological data from 1980 to 2015 from the Chinese National Meteorological Information Center of the China Meteorological Administration (<http://data.cma.cn>). Digital elevation model (DEM) data originated from the Shuttle Radar Topography Mission (SRTM), with a resolution of 90 m. Administrative divisions were provided by the Satellite Environment Center, the Ministry of Environmental

Protection of the People's Republic of China. We obtained socioeconomic data in China from 1980 and 2015, including total population and gross domestic production (GDP), from the China Statistical Yearbook (State Statistics Bureau; from 1980 to 2015; <http://tongji.cnki.net>). We obtained afforestation data across China from annually released China forestry statistical yearbooks (from 1949 to 2015) (State Forestry Agency, 1949 to 2015). All cartographic data were converted to the same coordinate system (Albers equal-area conic projection) and the same spatial resolution (1 km).

## Methods

### Water resource quantification

To quantitatively analyze water resources, we applied a water balance equation based the Budyko model to the hydro series from 1980 to 2015 (Zhao et al. 2014). In this case, we assumed that surface water and groundwater interactions were negligible. The water balance for a catchment can be described as follows (Fensham et al. 2005):

$$Q = P - ET_a - \Delta S \quad (1)$$

where  $Q$  is the runoff (mm) as a proxy of the water resource;  $P$  and  $ET_a$  represent precipitation (mm) and actual evapotranspiration (mm); and  $\Delta S$  denotes the changes in catchment water storage capacity (mm), which is usually assumed to be 0 over a long period.

### Evapotranspiration factor

Following an assumption similar to that made by Budyko, actual evapotranspiration can be estimated as follows (Yang et al. 2014):

$$ET = \frac{P \times ET_p}{(P^n + ET_p^n)^{1/n}} \quad (2)$$

where evapotranspiration (ET) is the actual evapotranspiration (mm);  $n$  is the model controlling parameter that determines the shape of the Budyko curve, which primarily represents the integrated effects of catchment land cover characteristics on the water balance (Yang et al. 2014).  $ET_p$  is the potential evapotranspiration, and it can be estimated by the Priestley–Taylor (PT) equation as follows (Priestley and Taylor 1972):

$$ET_p = \alpha \times \frac{\Delta}{\Delta + \gamma} \times (R_n - G) \quad (3)$$

$$\Delta = \frac{4098 \times \left( 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \right)}{(T + 237.3)^2} \quad (4)$$

$$\gamma = 0.665 \times 10^{-3} \times 101.3 \times \left( \frac{293 - 0.0065H}{293} \right)^{5.26} \quad (5)$$

where  $\alpha$  is the PT coefficient of 1.26 for open water and saturated land (Priestley and Taylor 1972),  $\Delta$  is the slope of the saturated vapor pressure curve (kPa, °C<sup>-1</sup>), and  $\gamma$  is the psychrometric constant (kPa; °C<sup>-1</sup>).  $R_n$  is the net absorbed radiation at the surface in megajoule per square meter, which can be estimated using the calibrated radiation part of the FAO56-PM model.  $G$  is the downward soil heat flux in megajoule per square meter, where  $G = 0.26R_n$ .  $T$  is mean air temperature (°C).  $H$  is elevation AMSL (m).

### Trends and abrupt change analyses

To detect variation in trends of water resources during the study period (1980–2015), we used a least squares linear regression model, which is one of the commonly used methods in trend analysis of variation, to obtain the trend of every pixel change (Xiao and Xiao 2019). It can be described as follows:

$$y = a + b \times t + \varepsilon \quad (6)$$

where  $y$  represents water resource variables,  $t$  is year,  $a$  and  $b$  are fitted variables ( $a$  is the intercept and  $b$  is the slope as a proxy of trend), and  $\varepsilon$  is the residual error. If  $b > 0$ , there is an increasing trend in water resources. Conversely, if  $b < 0$ , there is a decreasing trend. We estimated the significance of trends in the annual water resource time series using a  $t$  test, where a  $P$  value  $< 0.05$  was considered significant.

We mainly conducted the analysis of abrupt changes in water resources using the Mann–Kendall method (Yue and Wang 2004). For the Mann–Kendall test of abrupt change, under the premise that the positive sequence curve ( $UF_k$ ) crosses the critical ratio reliability line, if the positive sequence (UF) and the inverse sequence (UB, generated with the reverse data series of UF) have only one obvious crossing point located between the reliability lines, this denotes the catastrophe point and is statistically significant; on the other hand, if the crossing point is located outside the reliability line or there are several obvious crossing points between the lines, we could not establish a definite catastrophe point. In the latter case, we subsequently applied the non-parametric Pettitt's test to detect the abrupt change point (Pettitt 1979).

### Correlation and regression

To investigate the relationship between water resource change and its driving force, we conducted Pearson's correlation analyses. All statistical analyses were performed on a province level using SPSS 20.0 (IBM Corp., Armonk, NY, USA).

## Validation

To verify the reliability of simulated water resources, we validated the simulated results against observed data, which are available from the China Water Resources Bulletin from 1998 to 2015 (Ministry of Water Resources of the People’s Republic of China, 1998–2015). Water resource simulations agreed well with corresponding estimates ( $r = 0.63$ ;  $p < 0.01$ ; Fig. 2). Therefore, this confirmed that the simulated water resources could also be considered reasonable.

## Results

### Change trends derived from water resources in Northwest China

In recent years, water resources in Northwest China fluctuated but showed a general increasing trend from 1980 to 2015 (an increase of 1.27 billion cubic meters per year); however, not all regions exhibited a positive trend. On a regional scale, almost the entire western region has experienced water growth, but the water shortages mainly happened on the eastern region. The provinces with high water resource increases mainly included Xinjiang, Qinghai, and Xizang, accounting for 84.58% of the total increases from 1980 to 2015 (Fig. 3a). In total, water resources increased significantly in the west of the Qinghai–Tibet Plateau and the Tien Shan Mountains. By contrast, total water resources decreased significantly in the Qinling Mountains, the Loess Plateau, and the Horqin Sandy Land. To evaluate long-term changes in water resources, we calculated trend turning points using the Mann–Kendall trend test. As shown in Fig. 3b, we identified three distinctly different trends during 1980–1986, 1986–2004, and 2004–2015. Given that there were several crossing points between the lines, the Pettitt’s test was further applied to detect change

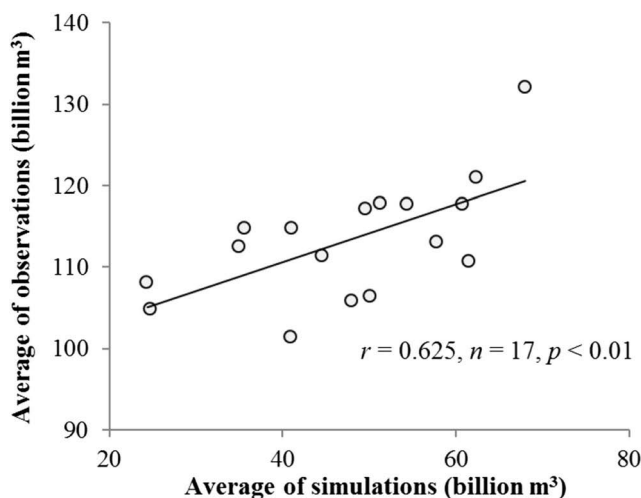


Fig. 2 Validation of water resource results from 1998 to 2015

points or transition years. Periods of abrupt changes were mainly concentrated in 1980–2004 and 2004–2015. Water resources clearly fluctuated (slope =  $-0.64$  billion cubic meters per year) prior to the year 2004. Subsequently, water resources were advanced (slope =  $4.01$  billion cubic meters per year) until the year 2015. Moreover, we found a close relationship between water resource anomalies and precipitation anomalies. Additionally, we observed continuous significant increasing trends for water resource anomalies throughout the whole study period (Fig. 3c).

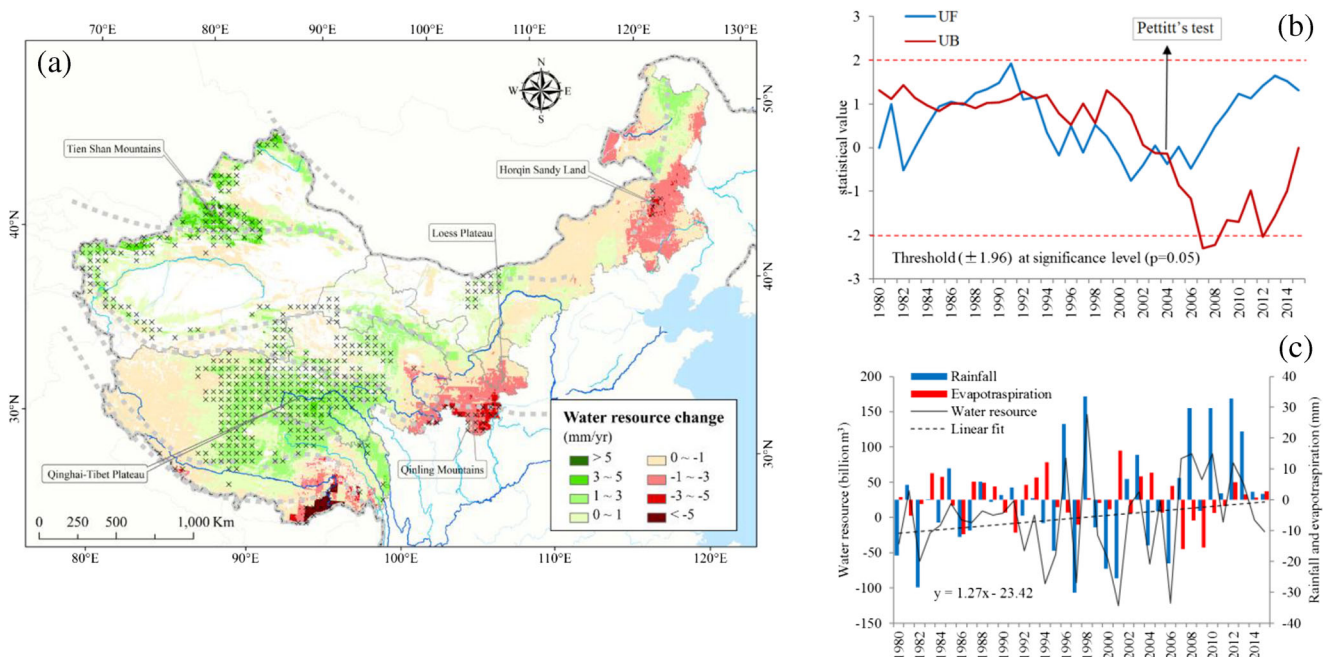
Characteristics of water resources during different decades in Northwest China are provided in Table 1. Annual average runoff depths for Inner Mongolia, Ningxia, Xinjiang, Gansu, Xizang, and Qinghai were 36.33 mm, 31.93 mm, 44.69 mm, 54.60 mm, 64.52 mm, and 78.83 mm, respectively, and the mean coefficient of variation (CV) was 0.72, 1.16, 0.33, 0.46, 0.30, and 0.45 respectively, in China, throughout 1980–2015. It can therefore be determined that CV was larger in Inner Mongolia and Ningxia, indicating that water resources in Inner Mongolia varied greatly.

### Causes for changes in water resources in Northwest China

Water resource trends throughout the entire region of Northwest China increased exponentially with increasing rainfall and decreasing evapotranspiration (Fig. 4a;  $R^2 = 0.72$ ;  $n = 2022$ ;  $p < 0.001$ ) (Fig. 4b;  $R^2 = 0.27$ ;  $n = 2022$ ;  $p < 0.001$ ). However, as Fig. 4 illustrates, relationships differed for each provincial region. Rainfall accounted for more spatial variation in water resources in Gansu, Xizang, and Qinghai (85%, 82%, and 68%, respectively; i.e.,  $R^2$ ) than in Inner Mongolia (60%), Xinjiang (53%), and Ningxia (17%). Evapotranspiration also accounted for more spatial variation in water resources in Ningxia, Gansu, and Qinghai (93%, 72%, and 55%, respectively; i.e.,  $R^2$ ) than in Xinjiang (35%), Inner Mongolia (24%), and Xizang (11%). Moreover, most data points for Gansu, Inner Mongolia, and Ningxia were mainly distributed in the lower-left corner of Fig. 4a, and they were also primarily located in the lower-right corner of Fig. 4b, which implied that a decline in water resources at these locations mainly corresponded to a decrease in rainfall and an increase in evapotranspiration. On the contrary, an increase in water resources in Xinjiang, Qinghai, and Xizang likely predominantly resulted from an increase in rainfall and a decrease in evapotranspiration.

### The appropriateness of the government in planting large quantities of trees under the context of increasing water resources

To address devastating environmental crises and to improve human well-being, since 2000, China has implemented a



**Fig. 3** Temporal patterns, change trends, and abrupt change tests (c) of water resources in Northwest China. **a** Temporal patterns of water resources from 1980 to 2015, with cross marks indicating areas of

significant change ( $p < 0.05$ ). **b** The trend turning point determined by the Mann–Kendall test and the Pettitt’s test. **b** Trends in annual changes of water resources, rainfall, and evapotranspiration from 1980 to 2015

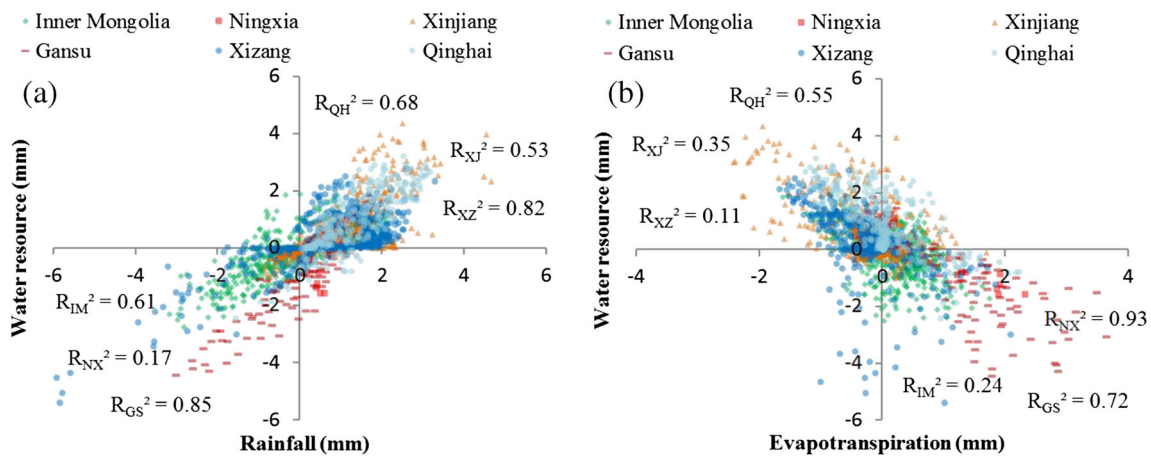
number of national afforestation policies on payments for ecosystem services, especially in arid and semiarid areas of China. Although Northwest China having only 16.43% of China’s total water resources, areas under plantations and mountain closures increased rapidly over time and expanded to roughly 274.29 km<sup>2</sup> by 2015, accounting for 31.86% of the total national afforested area. Afforestation is the planting of trees to improve vegetation cover by increasing forest area under various primary purposes of the government (such as sandstorm prevention and soil retention). Planted areas in the shelterbelt forest accounted for 85.05% of total afforested area in Northwest China (Fig. 5a) and almost half of the shelterbelt forest distributed throughout Inner Mongolia (Table 2).

Furthermore, non-native species (such as poplar) have generally been encouraged in these regions, even though the

actual survival rate is less than 15%. In this study, we found that the water consumed by artificial forests in Northwest China reached 14 billion cubic meters, which is equivalent to 5.22% of annual water resources (Fig. 5b). In contrast, under natural vegetation conservation practices (i.e., where native vegetation is the dominant vegetation type in most afforested areas), water consumed would have decreased to 10.13 billion cubic meters in 2015, which is equivalent to 3.73% of annual water resources. On a regional scale, due to large-scale afforestation activities in Inner Mongolia (the highest ecological risk), water consumption of planted and natural forests in this study reached 7.51 billion cubic meters and 5.57 billion cubic meters, respectively, which is equivalent to 18.08% and 13.41%, respectively, of annual water resources (Table 3).

**Table 1** Characteristics of water resources during different decades in Northwest China

Runoff depth Series	Inner Mongolia		Ningxia		Xinjiang		Gansu		Xizang		Qinghai	
	Average	CV	Average	CV	Average	CV	Average	CV	Average	CV	Average	CV
1980s	35.46	0.41	35.71	1.19	37.43	0.39	63.57	0.35	63.98	0.20	82.94	0.41
1990s	50.04	0.71	30.83	1.16	44.83	0.30	45.41	0.50	62.20	0.32	55.50	0.27
2000s	18.49	0.77	31.40	1.38	46.73	0.26	53.74	0.67	69.90	0.34	88.76	0.53
2010s	44.67	0.55	28.32	0.87	53.15	0.33	56.40	0.11	60.30	0.35	94.32	0.30
1980–2015	36.33	0.72	31.93	1.16	44.69	0.33	54.60	0.46	64.52	0.30	78.83	0.45



**Fig. 4** Relationships between water resource trends and changes in rainfall (a) and evapotranspiration (b) for all provinces investigated. Each data point represents a 35-year trend value throughout 2000–

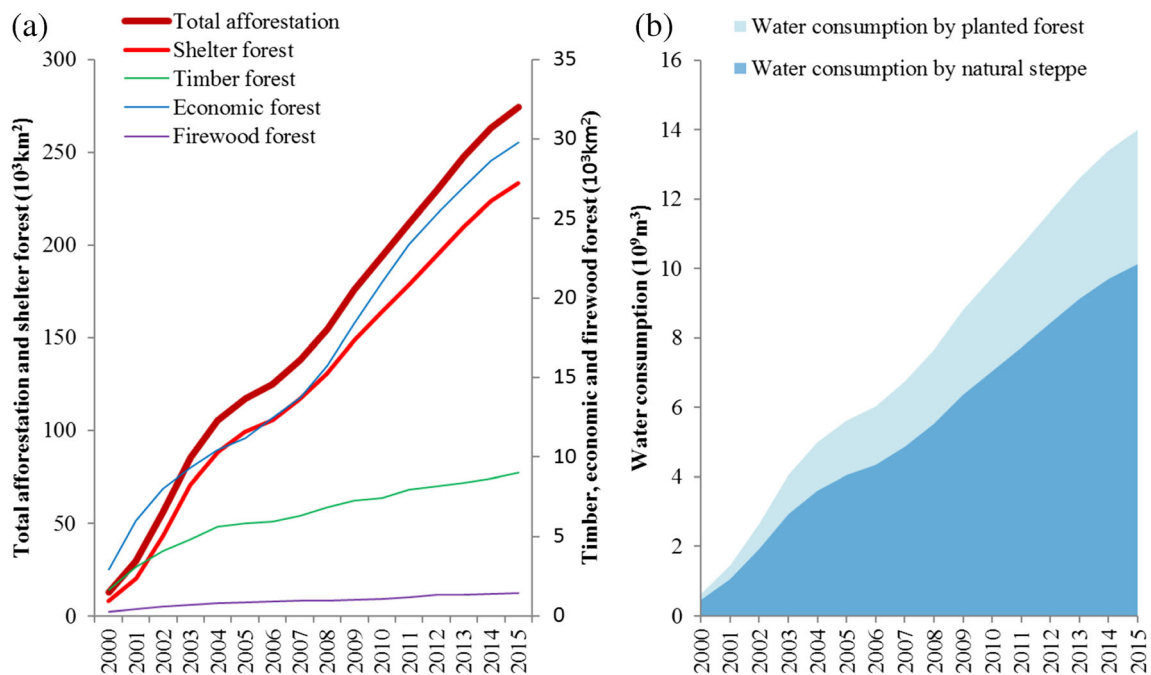
2015.  $R^2$  is the coefficient of determination of the linear functions between water resources and rainfall and evapotranspiration for each province

## Discussion

### Differences in evapotranspiration for different areas in Northwest China

The arid area located in central Northwest China is one of the most undeveloped areas in the mountainous region of China. It is characterized by mountain and basin landform patterns, and it is very sensitive to global climate change (Noelia Jimenez et al. 2016). Global warming has exacerbated changes in the water cycle, making the climate in this area more complex and prone to change. Recent studies have found that changes in temperature and precipitation have important impacts on surface water resources. For example, we clearly

observed an increasing trend in precipitation for northwest arid areas in recent years. Some scholars believe that this phenomenon is the area effectively signaling that the climate has changed to warm and wet (Miao et al. 2016), while other scholars propose that this is the result of intense human activity. The key to this problem is how to cope with a series of ecological impacts caused by an increase in rainfall. Results from this study have shown that increases in precipitation in some northwest areas that surpass the capacity of evapotranspiration will lead to a series of potential ecological risks (Wang et al. 2013). Since 1990, precipitation in northwest arid areas has been relatively high, resulting in many oases springing up in Northwest China. That is to say, with the change in climate, vegetation in Northwest China (i.e., forest, grassland,



**Fig. 5** Afforested areas in Northwest China from 2000 to 2015 (a) and estimated water consumption by planted forests and natural steppe vegetation (b)

**Table 2** Area ratios of planted forests for different provinces in Northwest China (unit: %)

Province	Planted forest	Timber forest	Economic forest	Shelter forest	Firewood forest
Inner Mongolia	48.70	62.86	12.70	50.76	55.91
Xizang	2.83	8.66	1.68	2.79	9.00
Gansu	17.98	14.02	15.99	17.77	14.93
Qinghai	6.77	0.49	0.51	7.19	3.34
Ningxia	8.37	1.25	9.10	8.55	1.87
Xinjiang	15.35	12.72	60.01	12.95	14.95

and oasis) has undergone an evolutionary process. At present, increases in precipitation have emerged alongside a large number of oases, resulting in an increase in transpiration, evaporation, and other water consumption factors. Thus, the vegetation of the region is subsequently facing changes once again, that is, oasis vegetation will evolve into grassland, and parts of desert areas will evolve into oasis vegetation. Therefore, an explicit vegetation scheme should be designed in Northwest China according to the resultant influencing mechanisms, that is, the water cycle and the water resource system (Zhang et al. 2013; Miao et al. 2016).

### The Government of China's tree planting campaign

Although forests can provide a wide range of ecological services, such as air purification and soil condition improvements, forests also reduce the water content of soil in arid areas, especially in Inner Mongolia, Ningxia, and Gansu provinces (see photo: withered trees). The excessive depletion of water resources will eventually disrupt the regional ecological balance that anthropogenic and natural ecosystems survive on (Cao et al. 2016). We found that water consumed by artificial forests in Northwest China reached 14 billion cubic meters, which is equivalent to 5.22% of annual water resources since 2000. Results from this study showed that evapotranspiration from trees in Inner Mongolia, Ningxia, and Gansu is clearly increasing and that too much vegetation will reduce the water content of soils in these areas, thereby reducing available water for local residents. This trend has been observed in the expansion of desertification in Inner Mongolia and Ningxia, which will further reduce the ecological services of the regions (Cao et al. 2016). By analyzing afforestation data from each province, we found that more trees are planted in Inner Mongolia, Ningxia, and Gansu at lower altitudes, which may lead to an increase in evapotranspiration in areas year after year and subsequently more serious water shortages. This will pose a serious threat to sustainable water use in arid and semiarid areas.

Although tree planting programmes in Inner Mongolia, Ningxia, and Xinjiang have clearly led to an improvement in vegetation cover in China, the evidences in reference to the low survival rate of plantation in arid areas suggests that large-

scale afforestation in arid and semiarid areas is inappropriate. This is due to the fact that a decline in water resources in this region mainly corresponds to a decrease in rainfall and an increase in evapotranspiration. In other words, the implementation of large-scale afforestation initiatives has created potentially serious environmental damage. For example, inappropriate afforestation in some areas of Northern China will result in a long-term decrease in soil moisture rates, and inappropriate species selection seems unlikely to produce a stable and balanced source for available water (Stow et al. 2004). This will lead to the further depletion of deep soil water. Moreover, manmade forests could reduce groundwater levels via transpiration, making the survival of native grasses more difficult, which would ultimately reduce the survival of trees. As a result, the tree survival rate of the Three-North Shelterbelt Program accounts for only 15% of afforestation projects. Soil conservation by means of less vegetation may lead to the enlargement of degraded land area, exacerbating the severity of local land desertification and potentially increasing dust storm frequency (Matthews et al. 2004). Therefore, there is strong evidence that suggests that the government should reassess its massive tree planting policy in arid areas. Otherwise, the outcome of the government's policy will be to destroy rather than protect vulnerable ecosystems. When total evapotranspiration of an area is greater than total precipitation, surface soil moisture cannot sustain forest vegetation, shrubs, or herbaceous species, ultimately forming natural ecosystems under unsustainable development and an unstable source of available water (Lambin and Ehrlich 1997).

### Greening movement at the expense of glaciers

China's glaciers are mainly distributed in the north-western region of Xinjiang, Tibet, Qinghai, and Gansu. Among these regions, Xinjiang has the largest proportion of glaciers (55.69%). Regression analysis (Fig. 6) has shown that increasing runoff depths have been negatively correlated to glacier area decline during the past 30 year, especially in Xinjiang Province where significant negative correlations have been observed ( $p = 0.01$ ). There is a negative correlation between a decrease in glacier area and an increase in regional water resources, which shows that the melting of plateau glaciers



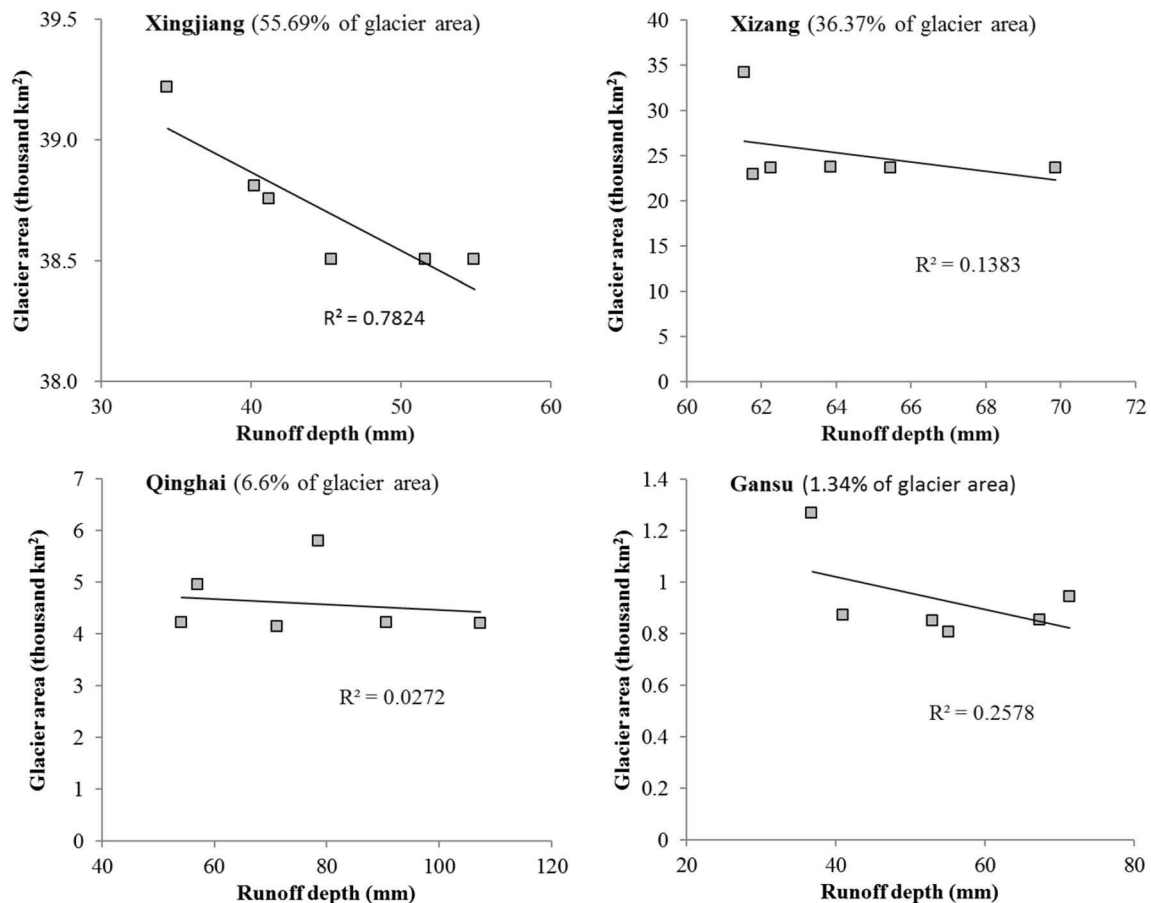
**Table 3** Water consumption of planted and natural forests for different provinces in Northwest China

Province	Planted forest		Natural steppe vegetation		Save water Volume (10 <sup>9</sup> m <sup>3</sup> )
	Consumption (10 <sup>9</sup> m <sup>3</sup> )	Percentage (%)	Consumption (10 <sup>9</sup> m <sup>3</sup> )	Percentage (%)	
Inner Mongolia	7.52	53.70	5.58	55.03	1.94
Xizang	0.61	4.38	0.40	3.98	0.21
Gansu	2.54	18.16	1.71	16.89	0.83
Qinghai	0.33	2.33	0.28	2.72	0.05
Ningxia	0.61	4.35	0.38	3.73	0.23
Xinjiang	2.39	17.08	1.79	17.65	0.6

also leads to an increase in regional water resources under the context of global warming.

Many studies have reported that due to the melting of glaciers under a warming climate, the runoff of the main rivers in Xinjiang, such as the Tarim River, the Brahmaputra River, and some other rivers originating from the northwest region of China, have risen, and in the short term, this will increase the amount of available water for species survival, economic development, and environmental protection. However, this increase in runoff will start to disappear as glaciers completely

ablate. By taking into account the fact that glaciers are shrinking at a steady rate (Fig. 6), any plan based on the assumption that glacier melt water will continue is careless and imprudent. In recent years, with global warming and intensified anthropogenic activities, the glacier area in Northwest China has been decreasing year by year, from 80.13 × 103 km<sup>2</sup> in 1980 to 67.17 × 103 km<sup>2</sup> in 2010. Compared to 1980, glacier area decreased by approximately 16.17%. This study has for the first time reported on quantitative water resource data in the northwest region of China, which will be crucial in supporting



**Fig. 6** Regression analysis depicting the relationships between water resources and glacier area in 1980, 1990, 1995, 2000, 2005, and 2010

future decisions related to water resource management on the plateau. In addition, our results have clearly shown that water consumption of manmade forests is much higher compared to natural vegetation. Restoring the ecological environment of Xinjiang and the Tibetan Plateau by means of afforestation may deteriorate already depleted water resources. Moreover, extensive reclamation of farmland and tree planting in Xinjiang and overgrazing and tree planting in Tibet pose a serious threat to the sustainable use of water resources in the future. The further deterioration of already depleted water resources will have an impact on both population and ecosystems, and it will seriously restrict economic development (Zeng et al. 2000).

Recent studies have shown that the emergence of oases in Northwest China is the result of the interaction of climate change and large-scale afforestation. Although increased evapotranspiration resulting from afforestation may increase the relative humidity of the atmosphere and may increase rainfall in downwind areas of manmade forests, it has yet to be confirmed whether this will actually happen as it has yet to be confirmed whether increased rainfall will positively influence other aspects of the environment (Carlson and Ripley 1997). The principle of prudence tells us that we should stringently review the influence of large-scale afforestation, and before afforestation is proved to be a safe option, we should try our best to protect and reconstruct natural vegetation in Xinjiang and on the Tibetan Plateau. This prudent approach in protecting the ecological environment in the northwest region of China will reduce many potential ecological risks. In reducing these risks, it is necessary to promote a scientific understanding of water cycling processes in Xinjiang and on the Tibetan Plateau and to formulate the rules that support this more comprehensive scientific understanding. Even without achieving expectations, ecological risks will increase (i.e., the relationships between ecological engineering and water resources). Questions must be raised, such as will increases in rainfall ultimately maintain moisture levels of the existing restoration programmes? This is important because the excessive consumption of water resources in advance of answering such questions is like quenching the thirst of a person with poison; thus, in the long run, there are real ecological risks.

## Conclusions

Our results have shown that there is not enough moisture to support tree planting initiatives in Northwest China, and this has been true for the past 35 years, a period that witnessed increases in rainfall in the northwest region of China. The climate of Northwest China appears unsuitable for afforestation restoration practices, and this is due to its limited rainfall. Moreover, planting trees in Inner Mongolia, Tibet, and

Xinjiang also result in higher total evapotranspiration levels than total precipitation rates, which will consume local soil water resources. Research has shown that this is related to too much attention being paid to short-term behavior and not enough attention being paid to consequences of ecological influences. Tree withering in Inner Mongolia is believed to demonstrate water shortages in the region, which indicates that the best way to protect the ecological environment is to maintain its original state.

Restrictions on anthropogenic activities (tree planting, grazing, land reclamation, etc.) in Northwest China would be of great significance in protecting glaciers from vanishing in China. Moreover, water resources in Northwest China are affected by climate, which helps to alleviate the lack of local water resources. These factors in turn increase the amount of available water. Strict control over water resources should be conducted to safeguard glaciers. This study sheds some light on the fact that afforestation in Northwest China should take into consideration local water resource cycling and climate change. It also presents a strong argument for the use of water resources to enhance vegetation reconstruction in Northwest China while avoiding potential ecological risks.

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