

Effects of revegetation on soil moisture under different precipitation gradients in the Loess Plateau, China

Fei Tian, Xiaoming Feng, Lu Zhang, Bojie Fu, Shuai Wang, Yihe Lv and Pei Wang

ABSTRACT

Revegetation can alter catchment water balance and result in soil desiccation. Large-scale revegetation took place in the Loess Plateau of China to control soil erosion and improve environmental conditions. However, the dynamic nature of soil moisture in response to revegetation under different climatic conditions is still unclear mainly due to lack of long-term *in situ* observations. To overcome this challenge, a biophysically based ecohydrological model (WAVES) was used to examine the effects of revegetation on soil moisture. Results showed that trees consume more water (100% of precipitation) than shrub (97.6%) and grass (98.3%), and therefore are more likely to result in soil desiccation. No runoff occurred under the tree scenario, while for shrub and grass, runoff accounted for 2.4% and 1.7% of precipitation, respectively. In areas with mean annual precipitation (MAP) less than 400 mm, tree planting resulted in soil water deficit, while in areas with MAP exceeding 600 mm, no soil water deficit occurred. Within this MAP range (400 < MAP < 600 mm), this could lead to soil water deficit during dry years. Extending this analysis to the entire Loess Plateau, 40% of the region will face reduced soil moisture when converting cropland to trees.

Key words | afforestation, Loess Plateau, mean annual precipitation, revegetation, soil desiccation, WAVES model

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INTRODUCTION

China experienced severe droughts in 1997 and serious floods in 1998, causing serious economic and environmental damage. In the wake of these disasters, the Chinese government took unprecedented conservation measures (Xu & Cao 2001), one of which was the Grain for Green Program (GGP, also known as the Conversion of Cropland to Forest and Grassland Program) introduced in 1999 to protect the

degraded environment (Zhang *et al.* 1999). The objective of this program was to convert cropland to plantations and grassland on steep slopes by compensating farmers with subsidies. The 'Grain for Green' Program aimed to achieve a target of converting 146,700 km² of cropland to plantations by 2010 and total planned investment exceeded US\$40 billion (SFA 2003). Although the project was designed to address environmental issues (e.g. climate change, droughts, water crisis) in China, it could set up a good example for other nations to achieve both socioeconomic and environmental sustainability through revegetation strategies. The success of the 'Grain for Green' Program has important global implications (Liu & Diamond 2005).

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The focus of this research was the Loess Plateau, which is the largest highly erodible area on earth (Peng 2001), where the pilot phases of the GGP were implemented. Many studies have reported positive effects of GGP on the Loess Plateau. For example, Xin *et al.* (2008) and Cao *et al.* (2009) concluded that vegetation cover on the Loess Plateau exhibited an overall ascending tendency during the period 1998–2005. Feng *et al.* (2010) documented that recovery of vegetation was effective in controlling soil erosion. However, recent studies have also raised concerns about the possibility of water scarcity and soil desiccation following revegetation in water limited areas and this can affect the sustainability of further development of GGP (Wang *et al.* 2011a, 2011b). Feng *et al.* (2012) detected that water yield in 38% of the Loess Plateau has decreased as a result of land cover change alone. Deep soil layers in the Loess Plateau are regarded as ‘soil reservoir’ with high water-holding capacity, which could sufficiently mitigate drought and supply the necessary water for plant growth. This function has been threatened by afforestation due to increased evapotranspiration (Chen *et al.* 2008b). Based on *in situ* measurements, studies showed clearly that afforestation can lead to soil desiccation (Li *et al.* 2008; Wang *et al.* 2011a, 2011b; Zhang *et al.* 2012). For example, Yang (2001) discussed the formation of dry soil layer and indicated that soil desiccation is the negative effect of afforestation. Cao *et al.* (2009) indicated that soil water content in an afforestation plot at depths of 0 to 1.0 m and 1.0 to 2.0 m, were 63.2% and 42.8% lower than in the abandoned plots, respectively. Wang *et al.* (2009) showed that plantations had depleted soil moisture below 2 m, as a result they rely on present year precipitation for transpiration. Li *et al.* (2008) reported that average soil moisture in a 0–10 m soil profile of the forestland was lower than that of nearby grassland. Fan *et al.* (2010) conducted a field study of the soil water balance under different land use patterns and discovered that trees may reduce soil moisture, but after trees were removed, soil water was replenished. Yang (2001) detected a response of soil moisture to land use and afforestation at a depth of 2 m, and showed that the deep soil moisture decreased more than 35% after land use conversion, and a soil moisture deficit appeared, and high planting density was found to be the main reason for the severe soil moisture deficit. However, there are few studies about long-term

inter-annual changes in soil moisture under different vegetation types due to the lack of long-term *in situ* observation and simulation, the dynamic mechanism of water consumption of vegetation related to soil desiccation is still unknown. Quantitative analysis is needed for further research especially on a basis of the long term relationship of water supply and demand (Xu 2005; Jung *et al.* 2010). Sankaran *et al.* (2005) reported that trees are unlikely to form closed-canopy woodland with less than 650 mm of precipitation, and afforestation could result in soil moisture deficit especially in water limited semi-arid regions, however it is still not clear how revegetation will affect soil moisture under different precipitation gradients in the Loess Plateau.

In this study, an ecohydrological model (WAVES) was used to evaluate the effect of revegetation on soil moisture dynamics in the Loess Plateau. One advantage of the WAVES model (Zhang *et al.* 1996) is that it properly represents the soil moisture dynamics by dynamically linking hydrological processes with vegetation growth at the spatial scale so that it can accurately simulate development of LAI, canopy transpiration, rooting dynamics and soil water stress on both transpiration and growth at the plot or catchment scale (Cheng *et al.* 2014). The WAVES model has been successfully tested against field observation of soil water content, groundwater, and evapotranspiration especially in Australia and China (Salama *et al.* 1999; Wang *et al.* 2001; Crosbie *et al.* 2010; McCallum *et al.* 2010; Cheng *et al.* 2014). On the Loess Plateau of China, the model also showed good performance in evaluating water use efficiency, and soil water content (Kang *et al.* 2003).

The objective of this study was twofold: (1) to evaluate the effects of revegetation on soil moisture on the Loess Plateau; (2) to investigate whether revegetation in given precipitation conditions could result in long-term soil moisture reduction.

MATERIAL AND METHODS

Study area

The study was in the Yangjuangou catchment (36°42'N, 109°31'E), which is located in the central part of the Loess

Plateau in northern Shannxi Province of China (Figure 1). It covers an area of 2.02 km², and at elevations ranging from 1,000 to 1,300 m. The area has a mean annual precipitation (MAP) of 535 mm with precipitation ranging from 338 to 785 mm, and a mean temperature of 9.7 °C (1980–2010). The peak rainfall occurred in the period of June to September, and a dry season is characterized during spring and early summer, the growing season usually ranges from April to October.

The parent material of the soil is loess with a depth of 50–200 m depending on topography. The loess in this region has a porosity of about 50%, the gravimetric field capacity and wilting percentage of soil water are 20–24%, and 3–6%, respectively (Yang & Shao 2000). Average soil water content in the topsoil (0–100 cm) ranges from 7% to 13% and details of the study catchment can be found in Wang *et al.* (2013).

The catchment experienced major land use change. Before 1999, cropland accounted for 29.6% of the total catchment area. After implementation of the GGP, the cropland on steep slopes were gradually abandoned and

converted to trees, shrubs, and grass with only 0.11% of the cropland remaining (Liu *et al.* 2012).

Field measurements and data collection

Four typical land cover types with similar slope positions (upper position), aspects (west), and slope degrees (25 °) were considered. Soil samples were collected for particle size and bulk density measurements. The plant cover and height were also measured. The planted tree was *R. pseudoacacia*, the shrub was *S. pubescens*, the grass site was dominated by beard *Andropogon*, and the main crop was corn (*Zea mays*).

Soil moisture and weather data were measured with six S-SMC-M005 and six S-SMC-M006 soil moisture and temperature sensors fixed on H21 Soil Moisture and Temp Logger Systems. The soil moisture sensors were installed at six depths: 10, 20, 40, 60, 80 and 100 cm below the ground surface. The soil moisture sensor is capable of measuring volumetric saturation values of 0–100%, with an accuracy of ±1.0% and a resolution of 0.1%. Soil moisture data were collected by a HOBO weather station logger every 10 min,

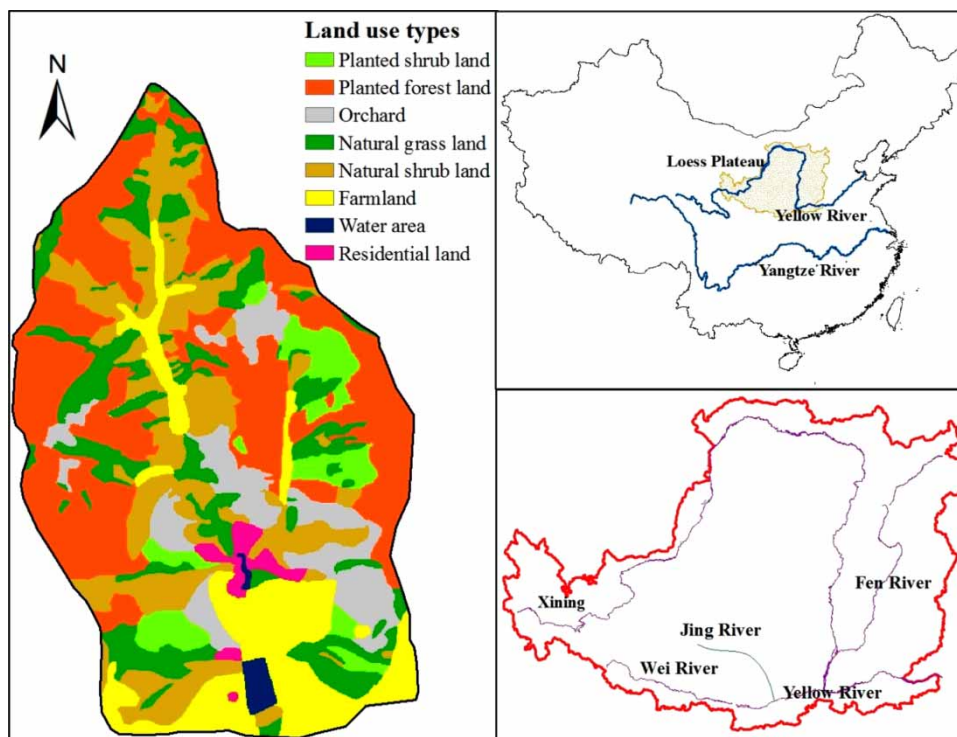


Figure 1 | Land use type and location of Yangjuangou catchment in the Loess Plateau, China. Four different experiment sites are located in the red circle (S1 - tree, S2 - shrub, S3 - grass, and S4 - crop). Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2016.022>.

while other meteorological variables (air temperature, relative humidity, and wind velocity at a height of 2 m above the ground) were recorded every 30 min.

Model application

WAVES (Dawes & Hatton 1993; Zhang et al. 1996) is a one-dimensional process-based model that simulates the process of water, energy, and solute movement in soil–plant–atmosphere continuum on a daily time step. It integrates soil, canopy–atmosphere with a consistent level of process detail, thus the model is well suited to investigations of hydrological and ecological responses to changes in land management and climate variation. It is particularly used in soil water analysis by Yang et al. (2002) and Kang et al. (2003). Detailed descriptions of which can be found in Zhang & Dawes (1998).

WAVES requires three data sets as inputs: meteorological data, soil parameters, and vegetation parameters.

Meteorological data

The meteorological data needed to run the WAVES model included daily maximum and minimum temperature, daily average vapor pressure deficit, daily rainfall, daily rainfall duration, and daily solar radiation. Daily rainfall, maximum and minimum temperature was observed in the field experiment. The daily vapor pressure deficit was calculated from the observed daily relative humidity by using the following equation provided by FAO in report No. 56 (Richard et al. 1998):

$$e^0 = 0.6108 \exp \left[\frac{17.27T}{T + 237.3} \right] \quad (1)$$

where e^0 is the saturated vapor pressure (kpa) and T is the daily average temperature ($^{\circ}\text{C}$). The vapor pressure deficit is calculated by multiplying the saturated vapor pressure by (1 minus the relative humidity). The daily solar radiation was estimated according to daily temperature measurements following Thornthorn & Running (1999).

Soil and vegetation parameters

Soil water movement is simulated with the Richards equation (Richards 1931), and the BW soil model

(Broadbridge & White 1988) was used to generate values of soil water potential, water content, and hydraulic conductivity to allow WAVES model to simulate the movement of soil water with the Richards equation. Table 1 shows the BW soil parameters used in this research, which includes hydraulic conductivity K_s (m/d), saturated water content θ_s (m^3/m^3), water content at the wilting point θ_r (cm^3/cm^3), capillary length scale λ_c (m), and characteristic soil water retention curve, C . Some soil physical parameters were determined from available databases on the basis of soil texture at the field sites. Soil hydraulic conductivity, water content at the wilting point and saturated water content were obtained from Kang et al. (2003). In this research, the soil was divided into three layers of different thickness for all vegetation species, the dominant soil type of each layer was quite different (Table 1). The vegetation parameters were obtained from the WAVES user manual (Dawes et al. 1998). We listed the optimal parameters of different vegetation types, when vegetation conversions occur, we will fix the soil parameters, and then change the vegetation parameters according to Table 2.

Model calibration

Soil and vegetation parameters were adjusted manually in order to achieve good agreement between the simulated and measured soil moisture values in the period of June 25, 2011 to September 15, 2011 (Tables 1 and 2). Analysis was carried out to assess the agreement between simulated and observed values based on the mean error (ME), and relative error (RE). The performance of the WAVES model was assessed on the bases of coefficient of determination (R^2) for simple linear regression between simulated and

Table 1 | Soil layering, texture, depths, and Broadbridge-White parameters for each soil used in the Yangjuangou catchment

Layer	Texture	Depth (cm)	K_s (m/d)	θ_s (m^3/m^3)	θ_r (cm^3/cm^3)	λ_c (m)	C
1	Silt loam	0–40	0.10	0.20	0.07	0.25	1.20
2	Sandy loam	40–80	0.30	0.21	0.08	0.30	1.10
3	Loam	80–300	0.80	0.21	0.11	0.30	1.05

K_s is the saturated hydraulic conductivity; θ_s and θ_r are the saturated and air-dry volumetric water contents, respectively; λ_c is a capillary length scale related to sorptivity; and C is a shape parameter for the soil moisture characteristic.

Table 2 | Vegetation parameters used in the WAVES model in the Yangjuangou catchment

No.	Parameter	Unit	Source references	Vegetation types			
				Tree	Grass	Shrub	Crop
1	1 minus albedo of the canopy	–	Brutsaert (1982)	0.85	0.85	0.85	0.80
2	1 minus albedo of the soil	–	Brutsaert (1982)	0.85	0.85	0.85	0.80
3	Rainfall interception coefficient	m d ⁻¹ LAI ⁻¹	Vertessy <i>et al.</i> (1996)	0.001	0.002	0.001	0.001
4	Light extinction coefficient	–	Monteith & Unsworth (2008)	–0.45	–0.85	–0.45	–0.70
5	Maximum carbon simulation rate	kg C ⁻² d ⁻¹	Collatz <i>et al.</i> (1991)	0.2	0.035	0.04	0.04
6	Slope parameter for the conductance model	–	Leuning (1995)	0.9	0.9	0.9	1.0
7	Maximum plant available soil water potential	m	Hillel (1980)	–200	–150	–200	–300
8	IRM weighting of water	–	Wu <i>et al.</i> (1994)	2.1	2.0	2.1	1.5
9	IRM weighting of nutrients	–	Wu <i>et al.</i> (1994)	0.5	0.5	0.5	0.5
10	Ratio of stomatal to mesophyll conductance	–	–	0.2	0.8	0.8	0.8
11	Temperature when the growth is 1/2 of optimum	°C	Farquhar <i>et al.</i> (1980)	15	20	20	20
12	Temperature when the growth is optimum	°C	Farquhar <i>et al.</i> (1980)	25	30	25	25
13	Year day of germination	D	–	100	100	100	100
14	Degree-daylight hours for growth	°Chr	Charles-Edwards (1982)	30,000	30,000	30,000	30,000
15	Saturation light intensity	μmoles m ⁻² d ⁻¹	Wu <i>et al.</i> (1994)	1,200	1,800	1,800	1,800
16	Maximum rooting depth	M	Hatton <i>et al.</i> (1992)	1.0	1.0	1.0	1.0
17	Specific leaf area	LAI kg C ⁻¹	Charles-Edwards (1982)	50	24	40	30
18	Leaf respiration coefficient	kg C kg C ⁻¹	Running & Coughlan (1988)	0.001	0.0002	0.0001	0.0015
19	Stem respiration coefficient	kg C kg C ⁻¹	Running & Coughlan (1988)	0.0006	–1	–1	–1
20	Root respiration coefficient	kg C kg C ⁻¹	Running & Coughlan (1988)	0.0001	0.0001	0.0001	0.0002
21	Leaf mortality rate	fraction of C d ⁻¹	Running & Coughlan (1988)	0.0005	0.005	0.0065	0.00045
22	Above-ground partitioning factor	–	Running & Gower (1991)	0.3	0.4	0.6	0.6
23	Salt sensitivity factor	–	–	1.0	1.0	1.0	1.0
24	Aerodynamic resistance	s d ⁻¹	Brutsaert (1982)	15	30	20	20
25	Crop harvest index	–	–	0.001	0	0	0
26	Crop harvest factor	–	–	0.001	0	0	0

observed values. Significance was based on a 95% confidence level. ME was evaluated using the following equation:

$$ME = \frac{1}{n} \left(\sum_{i=1}^n sim(i) - \sum_{i=1}^n obs(i) \right) \quad (2)$$

where $sim(i)$ and $obs(i)$ are simulated and observed soil moisture (cm³/cm³) at the i th point, respectively, and n is the number of observations.

Relative error was calculated as:

$$RE = \left[\frac{obs(i) - sim(i)}{obs(i)} \right] \times 100\% \quad (3)$$

where RE is the relative error, and $sim(i)$ and $obs(i)$ are simulated and observed soil moisture (cm³/cm³). The smaller the RE , the better the result.

Scenario design

Effects of vegetation on soil moisture were evaluated by considering different vegetation change scenarios: cropland to shrub, cropland to grass, and cropland to trees. In the simulations, daily meteorological data in the period of 1980 to 2010 were used. Changes in average soil moisture over 3 m soil layer under three scenarios were compared at seasonal and annual scales.

RESULTS

Calibration of the WAVES model

The WAVES model was calibrated against daily soil moisture measurements. Simulated daily soil moisture in the 1.0 m layer under four different vegetation covers showed good agreement with observed values (Figure 2). ME of soil moisture simulation with optimal parameters (see Tables 1 and 2) was 0.005, 0.002, 0.008, and 0.005 cm³/cm³ for trees, grass, shrub, and crop, respectively. Estimates of soil moisture from the WAVES model are also plotted against the field measurements in Figure 3. Most data points were closely distributed around the 1:1 line, with a highly significant ($P < 0.05$) correlation coefficient of 0.92. The average relative error in the soil moisture for the four vegetation types was only 1%, indicating that the WAVES model generally exhibits a good performance in the study

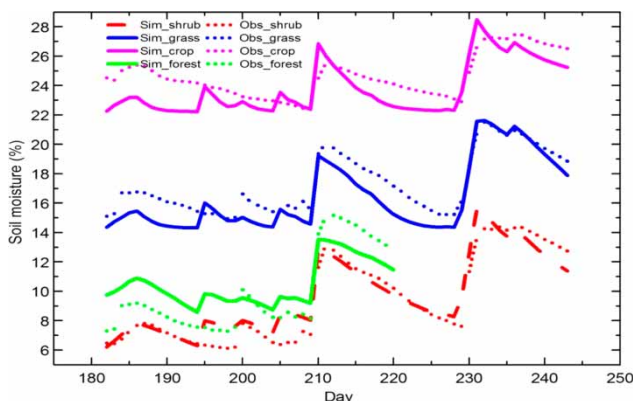


Figure 2 | Comparisons between simulated and observed soil moisture of four different vegetation categories in the 1.0 m layer at Yangjuangou catchment for the period of 25th June to 15th September 2011.

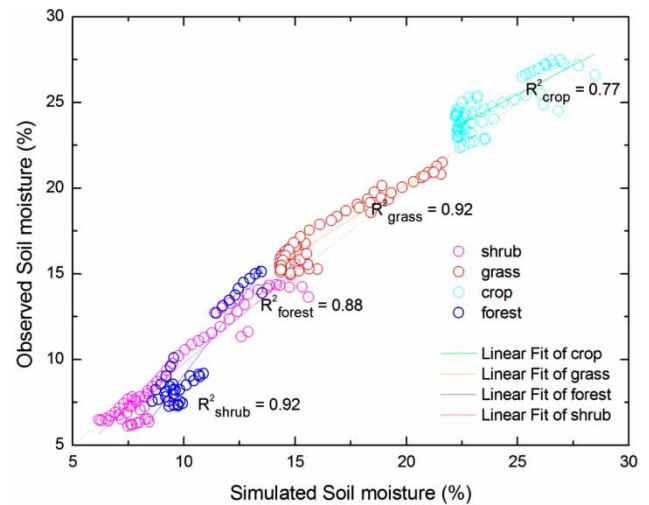


Figure 3 | The scatter plot for the simulated and observed soil moisture under four different vegetation categories in the 1.0 m layer at Yangjuangou catchment for the period of 25th June to 15th September 2011.

area. These results indicate that the WAVES model is capable of estimating soil moisture on the Loess Plateau across different vegetation types.

Changes in seasonal water balance under different vegetation scenarios

Monthly variation of precipitation, simulated interception, evapotranspiration, and runoff under the different vegetation covers are shown in Figure 4. During the winter period and early spring, vegetation coverage was low, interception and evapotranspiration were minimal for all vegetation scenarios. During the growing season (from June to September), under the tree planting scenario, no runoff occurred, evapotranspiration and interception accounted for 88.8% and 19.8% of precipitation, respectively, i.e. the sum of evapotranspiration and interception was greater than precipitation, therefore soil water deficit appeared. However, under the shrub, grass, and crop scenarios, interception accounted for 17%, 14%, and 13% of precipitation, respectively, and evapotranspiration accounted for 68%, 69%, and 68% of precipitation, respectively. Runoff accounted for 2.5%, 1.4%, and 1.0% of precipitation, respectively, and no soil water deficit occurred.

Besides, seasonal changes in interception and evapotranspiration in the four vegetation covers are apparent

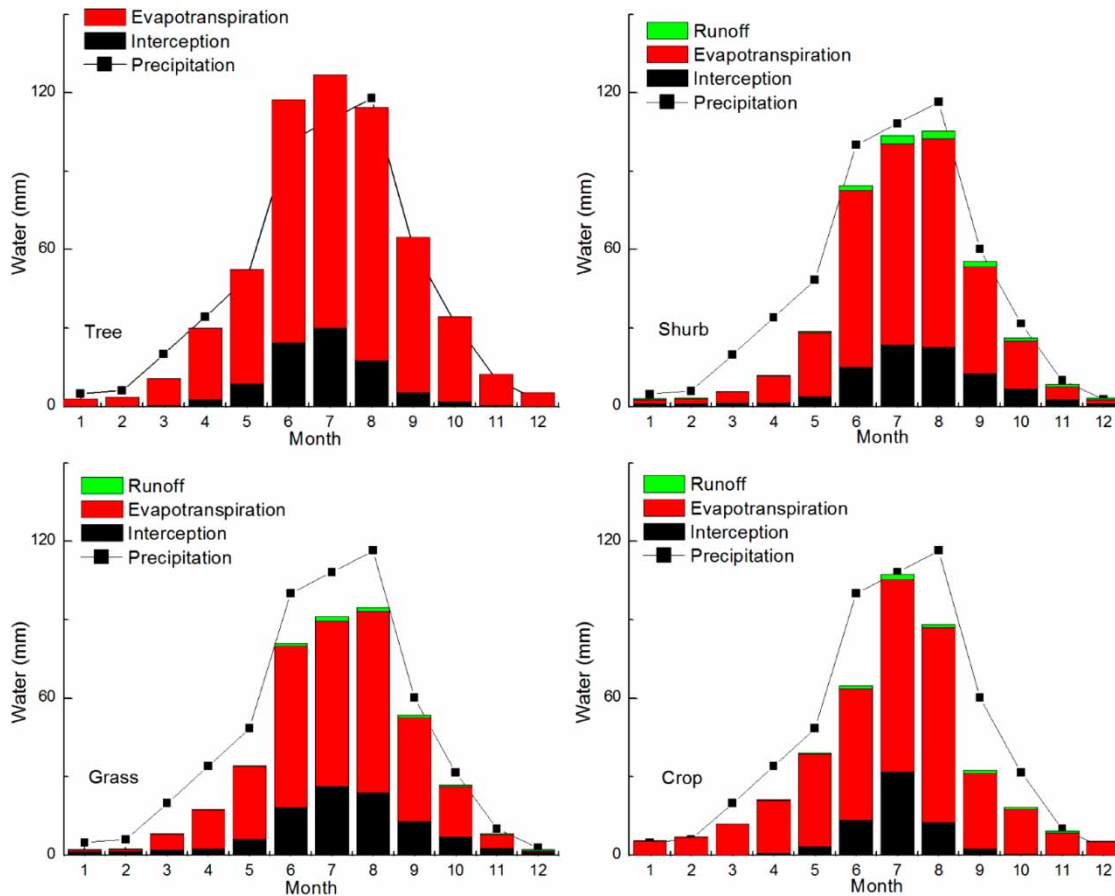


Figure 4 | Monthly variation of interception, evapotranspiration, runoff and precipitation under difference vegetation characteristics at Yangjuangou catchment from 1980 to 2010 based on the WAVES simulation.

and they responded positively to precipitation (Figure 4). When vegetation germination began, monthly interception and transpiration were generally low (0.05 mm–2.4 mm and 0.45 mm–2.6 mm, respectively). Most of interception and transpiration occurred during the growing season (i.e. 77–92% of interception and 73–85% of transpiration).

Average annual water balance under different vegetation scenarios

Variations of annual average interception, evapotranspiration, and runoff under different vegetation scenarios are shown in Figure 5. On average (1980–2010) the simulated annual interception for shrub, grass, crop, and trees was 75, 84, 67, and 85.5, respectively, accounting for 14.2%, 15.9%, 12.7%, and 16.2% of MAP, respectively. The corresponding annual average evapotranspiration was 441, 436, 456, and 443 mm,

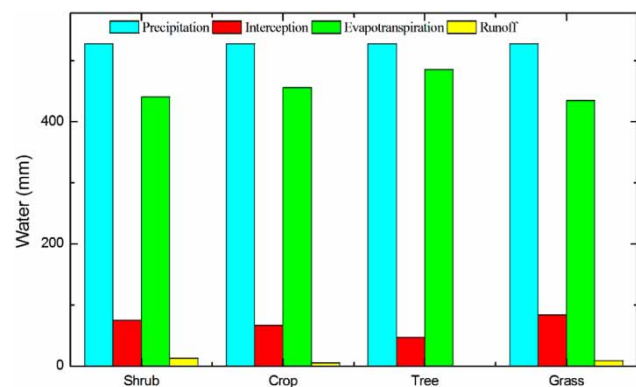


Figure 5 | Variation of annual average interception, evapotranspiration, and runoff under different vegetation characteristics at Yangjuangou catchment from 1980 to 2010 based on the WAVES simulation.

respectively. The ratio of evapotranspiration (ET) to precipitation was 83.4%, 82.4%, 86.3%, and 83.8%, respectively. The sum of ET and interception represents about 97.6–99%

of precipitation for shrub, grass, and crop. Simulated runoff was 12.7, 9.0 and 5.3 mm, accounting for 2.4%, 1.7%, and 1% of precipitation, respectively. Under the forest scenario, the sum of evapotranspiration and interception was equal to precipitation therefore no runoff was generated.

Soil moisture response under different precipitation regime

Annual soil water storage when cropland was planted to trees during 1980–2010 is clearly presented in Figure 6. For the first dry year (in 1980) of tree planting with MAP of 481 mm, soil water deficit occurred and the deficit amount was about 180 mm. In a wet year, rainfall may recharge soil water store, thus the soil water deficit will disappear. The dry years and wet years appeared interactively, therefore the soil water deficit occurred according to the low and high precipitation amount. In Yangjuangou catchment, soil water deficit occurred in 15 of 30 years, and it ranges from 8 mm in 1984 (MAP = 513 mm) to 106 mm in 1995 (MAP = 359 mm), which indicated that soil desiccation was a general problem during the cropland converting to tree stage. Under the scenario of converting cropland to shrub and grass, soil water deficit

occurred some years in the period of the simulation (1980–2010), however, the soil water deficit amount was far less than the forest scenario. Besides, the slope of the linear fit of forest was larger than that of grass and shrub, indicating that soil water deficit was more serious under the forest scenario.

We further evaluated relationships of MAP and the soil water deficit for trees from 1980 to 2010 (Figure 7). Results suggest that in areas with MAP less than 400 mm, tree planting could result in serious soil water deficit and soil desiccation. While in areas with the MAP exceeding 600 mm, no soil water deficit could occur. Availability of soil water seems to be sufficient to sustain tree growth, and soil water surplus was a general phenomenon. Within this MAP range ($400 < \text{MAP} < 600$ mm), tree planting could lead to soil water deficit during dry years.

DISCUSSION

Implication for upscaling

Comparing with other models for investigating the processes of soil water dynamics, the WAVES model strikes a good

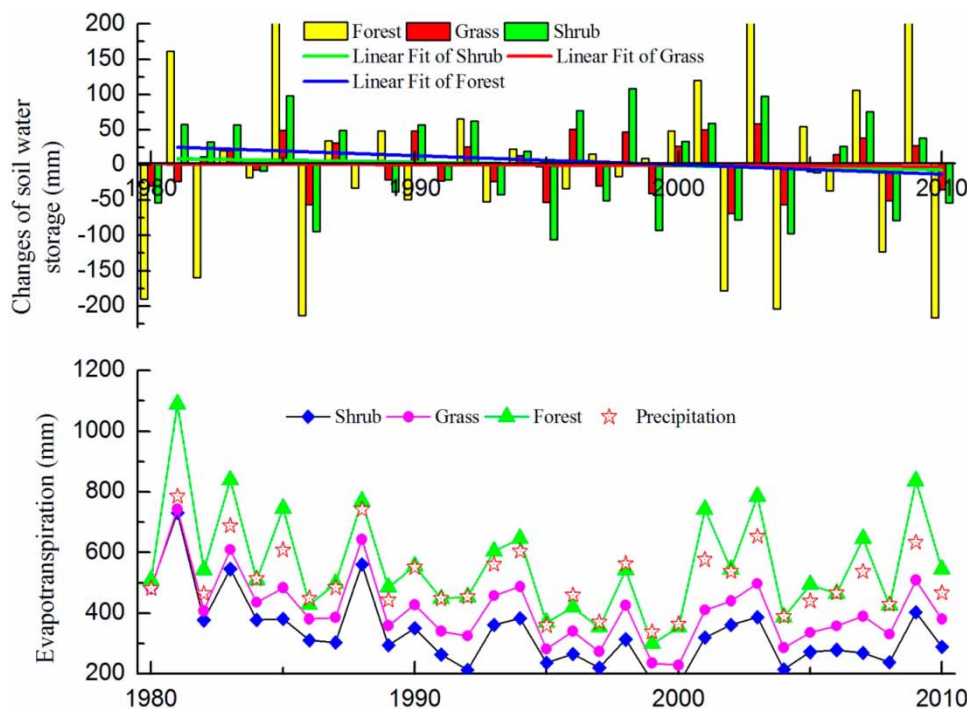


Figure 6 | Annual evapotranspiration and changes of soil water storage (S) in abandoned cropland to three scenarios from 1980 to 2010 based on the WAVES simulation.

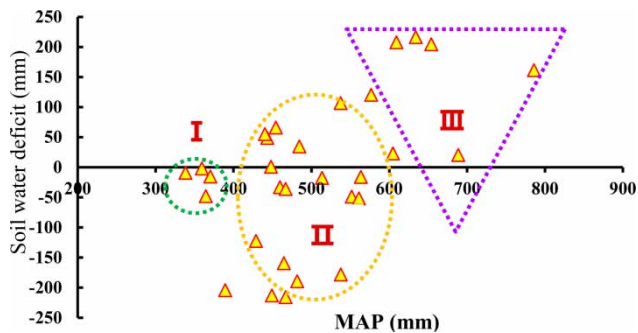


Figure 7 | Changes in soil water deficit as a function of MAP in the last 30 years at Yangjuangou catchment (Roman numerals I, II, and III represent the three precipitation gradients: I: MAP < 400 mm; II: 400 mm < MAP < 600 mm; III: MAP > 600 mm).

balance between complexity and accuracy of prediction in water, energy and carbon processes. This is the first study to evaluate changes in long-term soil water storage under different vegetation scenarios on the Loess Plateau of China.

The successful application of the WAVES model to the Yangjuangou catchment suggests that the model is capable of representing hydrological processes on the Loess Plateau. According to the methodology presented for assessing the average changes in groundwater recharge under a future climate in the Murray-Darling Basin, Australia (Crosbie *et al.* 2010), the output of the WAVES modelling in our research can be used to produce regression equations between average rainfall, average annual evapotranspiration, and soil moisture for each combination of soil type, vegetation, and climate. Using the set of regression equations and the set of annual average rainfall rasters for each climate scenario, a series of annual average evapotranspiration, and soil moisture rasters could be developed to the whole Loess Plateau for historical and different future climate scenarios. Therefore this research could be considered for upscaling to the whole Loess Plateau region, and then the effects of revegetation on soil moisture at regional scale can be examined.

Effects of revegetation on water budget

Miralles *et al.* (2010) detected global canopy interception from satellite observations, and found that interception is responsible for the evaporation of approximately 13% of the total incoming rainfall over broadleaf evergreen forests, 19% in broadleaf deciduous forests, and 22% in needle leaf forests. In arid and semi-arid region where most rainfall

occurs in low frequency, interception by canopy can amount to more than 10% of the annual rainfall. In this research, the simulated interception of shrub, grass, crop, and trees is approximately 14.2%, 15.9%, 12.7%, and 16.2%, respectively. Our results are consistent with previous studies, and falls within the scope (10–23%) of previous calculations for different vegetation interception losses (Wang *et al.* 2011a, 2011b). Clearly rainfall interception is a significant component of the water budget and quantifying the magnitude of rainfall interception is essential if we are to understand the future impact of afforestation on the water budget.

On average the simulated ratio of evapotranspiration to precipitation was 83.4%, 82.4%, 86.3%, and 83.8% for shrub, grass, crop, and trees, respectively. Evapotranspiration loss fell in the scope (62–87%) for the corresponding vegetation type on the Loess Plateau (Wei *et al.* 1998), although our results showed a little higher evapotranspiration for trees compared with other studies showing evapotranspiration loss of 76% (Wang *et al.* 2014). However, both studies indicated that interception and evapotranspiration were the major pathway of water loss, accounting for over 97% of the precipitation for shrub and grass. Therefore interception and evapotranspiration are important in water flux and have the major impact on soil moisture (Good & Caylor 2011). Aligned with Bellot *et al.* (1999) and Kyushik *et al.* (2005) conclusion that evapotranspiration is a main cause of depletion of soil moisture, our research also found that evapotranspiration and interception accounted for 100% of precipitation during cropland abandonment to trees for the last 30 years, which indicates that all water from precipitation evaporated, and the soil water storage was depleted, soil water deficit occurred in this scenario, and no runoff was produced. While for shrub and grass, runoff accounted for 2.4%, and 1.7% of precipitation, respectively. The runoff ratio produced by our WAVES-based simulation was relatively comparable with previous research in the same catchment (Liu *et al.* 2012), which reported a ratio of about 1.55%, and 1.57%. Excluding errors produced in the process of field observation and model simulation, the difference of runoff may be attributed to vegetation morphology and structure, which can change the characteristics of rainfall that reaches the soil surface (Lorens & Domingo 2007).

The characteristics of water loss from the soil profile were also detected in previous studies at Changwu (annual precipitation of 584 mm) and Wuqi County (annual precipitation of 451 mm) of the Loess Plateau (Li 2002). Furthermore, Chen *et al.* (2008a) showed that the soil moisture deficit could become serious in dry and normal years. Our study demonstrated that it is necessary to maintain infiltration or reduce evapotranspiration by, for example, selecting appropriate vegetation types in order to avoid soil water deficit.

Implication for 'Grain for Green' program

Our analysis showed that revegetation could alter water budgets in water-limited areas, thus causing soil water deficit. Furthermore, soil water deficit is highly temporally varied, thus reliable long-term observation and simulation of soil moisture is needed. For the Loess Plateau, the average annual precipitation ranges from 300 mm in the northwest to 750 mm in the southeast. By extending our analysis on the effect of precipitation conditions on soil moisture (Figure 7) to the entire Loess Plateau, it suggested that 40% of the region with MAP of less than 400 mm (Figure 8) will face the reduced soil moisture when converting cropland to trees, and consequently limiting tree growth. About 10% of the region with MAP more than 600 mm showed soil water surplus and soil water seems sufficient to sustain tree growth. While other 50% of Loess Plateau (400 <

MAP < 600 mm) will face reduced soil moisture in the dry years. This is in accordance with previous studies conducted at plot or catchment scale on the Loess Plateau (Zhang *et al.* 2007; Chen *et al.* 2008a).

Revegetation such as afforestation on the Loess Plateau resulted in an increase in vegetation cover (Xin *et al.* 2008), an improvement in soil nutrient levels (Wang *et al.* 2011a, 2011b), and in controlling soil erosion (Feng *et al.* 2012). Implementation of afforestation at large scale throughout the arid and semi-arid region, ignoring differences in climate and hydrology, in the end reduced soil moisture, therefore soil water availability was not sufficient to sustain forests in many areas (Wang *et al.* 2011a, 2011b; Zheng *et al.* 2014), ultimately affecting forest survival (Cao *et al.* 2011). Hydrological response to vegetation restoration varied across the Loess Plateau and, as it has a strong north-south gradient in precipitation and terrain, afforestation remains challenging (Feng *et al.* 2012). There are a number of factors that can affect afforestation and the impact on soil moisture and these include precipitation (Wang *et al.* 2009; Liu & Shao 2015), planting density and productivity (Chen *et al.* 2008a, 2008b; Yang *et al.* 2012). Therefore different vegetation conditions (i.e. structure, density, growth age, and species of vegetation), water balance pattern, ecosystem-carrying capacity must be carefully considered and should be given more attention (Sankaran *et al.* 2005).

CONCLUSIONS

We investigated the effects of vegetation characteristics on soil moisture reduction under different precipitation conditions on the Loess Plateau in North Western China. In order to quantify their long-term effects on soil water dynamics, the WAVES model was applied for the 1980–2010 period, and three revegetation scenarios were considered. The following conclusions can be drawn from this study.

The simulated soil moisture at the daily scale showed good agreement with observed values with relative error of only 1%, indicating that the WAVES model generally exhibits a good performance.

As simulated interception ratios of shrub, grass, crop, and trees are about 14.2%, 15.9%, 12.7%, and 16.2%,

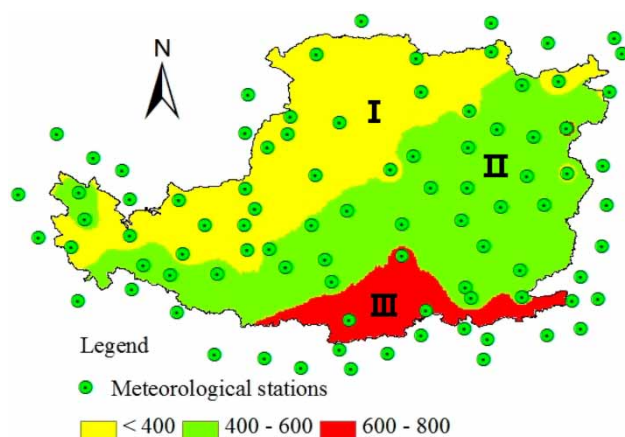


Figure 8 | MAP in the last 30 years on the Loess Plateau (Roman numerals I, II, and III represented the three precipitation gradients: I: MAP < 400 mm; II: 400 mm < MAP < 600 mm; III: MAP > 600 mm).

respectively, clearly rainfall interception is a significant component of the water budget. Quantifying the magnitude of rainfall interception is essential if we are to understand future impact of afforestation on the water budget.

Trees consume more water (100% of precipitation) than grass (97.6%) and shrubs (98.3%), and therefore no runoff is generated, and thus more likely to result in soil desiccation.

Areas with MAP less than 400 mm afforestation could result in serious soil water deficit; in areas with the MAP exceeding 600 mm, no soil water deficit would occur; within this MAP range ($400 < \text{MAP} < 600$ mm), tree planting could lead to soil water deficit during dry years. About 40% of the Loess Plateau has MAP of less than 400 mm where plantation development will face reduced soil moisture. About 10% of Loess Plateau with MAP more than 600 mm showed soil water surplus and soil water seems sufficient to sustain tree growth. The other 50% of Loess Plateau ($400 < \text{MAP} < 600$ mm) will face reduced soil moisture in dry years under the tree planting scenario.

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REFERENCES

- Bellot, J., Sanchez, J. R., Chirino, E., Hernandez, N., Abdelli, F. & Martinez, J. M. 1999 Effect of different vegetation type cover on the soil water balance in semi-arid areas of South Eastern Spain. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* **24**, 353–357.
- Broadbridge, P. & White, I. 1988 Constant rate rainfall infiltration: a versatile nonlinear model 1. Analytic solution. *Water Resources Research* **24**, 145–154.
- Brutsaert, W. 1982 *Evaporation into the Atmosphere: Theory, History, and Applications*. Kluwer Academic Publisher, Dordrecht, The Netherlands, p. 299.
- Cao, S. X., Chen, L. & Yu, X. X. 2009 Impact of China's Grain for Green Project on the landscape of vulnerable arid and semi-arid agricultural regions: a case study in northern Shaanxi Province. *Journal of Applied Ecology* **46**, 536–543.
- Cao, S. X., Chen, L., Shankman, D., Wang, C. M., Wang, X. B. & Zhang, H. 2011 Excessive reliance on afforestation in China's arid and semi-arid regions: lessons in ecological restoration. *Earth-Science Reviews* **104**, 240–245.
- Charles-Edwards, D. A. 1982 *Physiological Determinants of Crop Growth*. Academic Press, North Ryde, Australia, p. 161.
- Chen, H. S., Shao, M. A. & Li, Y. Y. 2008a Soil desiccation in the Loess Plateau of China. *Geoderma* **143**, 91–100.
- Chen, H. S., Shao, M. A. & Li, Y. Y. 2008b The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China. *Journal of Hydrology* **360**, 242–251.
- Cheng, L., Zhang, L., Wang, Y. P., Yu, Q., Eamus, D. & O'Grady, A. 2014 Impacts of elevated CO₂, climate change and their interactions on water budgets in four different catchments in Australia. *Journal of Hydrology* **519**, 1350–1361.
- Collatz, G. J., Ball, J. T., Grivet, C. & Berry, J. A. 1991 Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer. *Agricultural and Forest Meteorology* **54** (2–4), 107–136.
- Crosbie, R. S., McCallum, J. L., Walker, G. R. & Chiew, F. H. S. 2010 Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. *Hydrogeology Journal* **18**, 1639–1656.
- Dawes, W. R. & Hatton, T. J. 1993 *TOPOG_IRM: Model Description*. Technical Memorandum 93/5. CSIRO Division of Water Resources, Canberra, Australia.
- Dawes, W., Zhang, L. & Dyce, P. 1998 *WAVES V3.5 User Manual*, CSIRO Land and Water, Canberra, Australia.
- Fan, J., Shao, M. A., Wang, Q. J., Scott, B. J., Klaus, R., Cheng, X. R. & Fu, X. L. 2010 Toward sustainable soil and water resources use in China's highly erodible semi-arid loess plateau. *Geoderma* **155**, 93–100.
- Farquhar, G. D., Caemmerer, S. & Berry, J. A. 1980 A biochemical model of photosynthetic CO₂ assimilation in leaves of C3 species. *Planta* **149**, 78–90.
- Feng, X. M., Wang, Y. F., Chen, L. D., Fu, B. J. & Bai, G. 2010 Modeling soil erosion and its response to land-use change in hilly catchments of the Chinese Loess Plateau. *Geomorphology* **118**, 239–248.
- Feng, X. M., Sun, G., Fu, B. J., Su, C. H., Liu, Y. & Lamparski, H. 2012 Regional effects of vegetation restoration on water yield across the Loess Plateau, China. *Hydrology and Earth System Sciences* **16**, 2617–2628.
- Good, S. P. & Caylor, K. K. 2011 Climatological determinants of woody cover in Africa. *PNAS* **108**, 4902–4907.
- Hatton, T. J., Walker, J., Dawes, W. R. & Dunin, F. X. 1992 Simulations of hydroecological responses to elevated CO₂ at the catchment scale. *Australian Journal of Botany* **40**, 679–696.
- Hillel, D. 1980 *Fundamentals of Soil Physics*. Academic Press, New York, USA, p. 413.

- Jung, M., Rerichstein, M., Ciais, P., Seneviratne, S. I., Sheffield, J., Goulden, M. L., Bonan, G., Cescatti, A., Chen, J., de Jeu, R., Dolman, A. J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B. E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K., Papale, D., Richardson, A. D., Rouspard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S. & Zhang, K. 2010 Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature* **467**, 951–954.
- Kang, S. Z., Zhang, L., Liang, Y. L. & Dawes, W. 2003 Simulation of winter wheat yield and water use efficiency in the Loess Plateau of China using WAVES. *Agricultural Systems* **78**, 355–367.
- Kyushik, O., Yeunwoo, J., Dongkun, L., Wangkey, L. & Jaeyong, C. 2005 Determining development density using the Urban Carrying Capacity Assessment System. *Landscape Urban Planning* **73**, 1–15.
- Leuning, R. 1995 A critical appraisal of a combined stomatal-photosynthesis model for C3 plants. *Plant, Cell & Environment* **18**, 339–355.
- Li, Y. S. 2002 Productivity dynamic of Alfalfa and its effects on water eco-environment. *Acta Pedologica Sinica* **39**, 404–411 (in Chinese with English abstract).
- Li, J., Chen, B., Li, X. F., Zhao, Y. J., Ciren, Y. J., Jiang, B., Hu, W., Cheng, J. M. & Shao, M. A. 2008 Effects of deep soil desiccation on artificial forestlands in different vegetation zones on the Loess Plateau of China. *Acta Ecologica Sinica* **28**, 1429–1445.
- Liu, B. X. & Shao, M. A. 2015 Modeling soil–water dynamics and soil–water carrying capacity for vegetation on the Loess Plateau, China. *Agricultural Water Management* **159**, 176–184.
- Liu, J. G. & Diamond, J. 2005 China's environment in a globalizing world. *Nature* **435**, 1179–1186.
- Liu, Y., Fu, B. J., Lv, Y. H., Wang, Z. & Gao, G. Y. 2012 Hydrological responses and soil erosion potential of abandoned cropland in the Loess Plateau, China. *Geomorphology* **138**, 404–414.
- Lorens, P. & Domingo, F. 2007 Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. *Journal of Hydrology* **335**, 37–54.
- McCallum, J. L., Crosbie, R. S., Walker, G. R. & Dawes, W. R. 2010 Impacts of climate change on groundwater in Australia: a sensitivity analysis of recharge. *Hydrogeology Journal* **18**, 1625–1638.
- McVicar, T. R., Li, L. T., Van Niel, T. G., Zhang, L., Li, R., Chazdon, Q. K., Zhang, X. P., Mu, X. M., Wen, Z. M., Liu, W. Z., Zhao, Y. A., Liu, Z. H. & Gao, P. 2007 Developing a decision support tool for China's re-vegetation program: simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. *Forest Ecology and Management* **251**, 65–81.
- Miralles, D. G., Gash, J. H., Holmes, T. R. H., Jeu, R. A. M. & Dlooman, A. J. 2010 Global canopy interception from satellite observations. *Journal of Geophysical Research* **115**. Doi:10.1029/2009JD013530.
- Monteith, J. & Unsworth, M. 2008 *Principles of Environmental Physics*, 3rd edn. Elsevier, New York, USA, p. 440.
- Peng, K. 2001 Green mountains and clear water depend on returning agricultural land to forest land or grass land of the west. *Forest Inventory Planning* **26**, 30–34.
- Richard, G. A., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.
- Richards, L. A. 1931 Capillary conduction of liquids through porous media. *Physics* **1**, 318–333.
- Running, S. W. & Coughlan, J. C. 1988 A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling* **42**, 125–154.
- Running, S. W. & Gower, S. T. 1991 FOREST-BGC, a general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiology* **9**, 147–160.
- Salama, R., Hatton, T. & Dawes, W. 1999 Predicting land use impacts on regional scale groundwater recharge and discharge. *Journal of Environmental Quality* **28**, 446–460.
- Sankaran, M., Hanan, N. P., Scholes, R. J., Ratnam, J., Augustine, D. J., Cade, B. S., Gignoux, J., Higgins, S. I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K. K., Coughenour, M. B., Diouf, A., Ekaya, W., Feral, C. J., February, E. C., Frost, P. G. H., Hiernaux, P., Hrabar, H., Metzger, K. L., Prins, H. H. T., Ringrose, S., Sea, W., Tews, J., Worden, J. & Zambatis, N. 2005 Determinants of woody cover in African Savannas. *Nature* **438**, 846–849.
- State Forestry Administration 2003 *Forest Statistics Yearbook 2003*. China Forestry Publ. House, Beijing.
- Thornton, P. E. & Running, S. W. 1999 An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. *Agricultural and Forest Meteorology* **93**, 211–228.
- Vertessy, R. A., Hatton, T. J., Benyon, R. G. & Dawes, W. R. 1996 Long-term growth and water balance predictions for a mountain ash (*Eucalyptus regnans*) forest catchment subject to clear-felling and regeneration. *Tree Physiology* **16**, 221–232.
- Wang, H. X., Zhang, L., Dawes, W. R. & Liu, C. M. 2001 Improving water use efficiency of irrigated crops in the North China Plain-measurements and modelling. *Agricultural Water Management* **48**, 151–167.
- Wang, Z. Q., Liu, B. Y., Liu, G. & Zhang, Y. X. 2009 Soil water depletion depth by planted vegetation on the Loess Plateau. *Science in China* **52**, 835–842.
- Wang, L., Wei, S. P., Horton, R. & Shao, M. A. 2011a Effects of vegetation and slope aspect on water budget in the hill and gully region of the Loess Plateau of China. *Catena* **87**, 90–100.

- Wang, Y. Q., Shao, M. A., Zhu, Y. J. & Liu, Z. P. 2011b Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. *Agricultural and Forest Meteorology* **151**, 437–448.
- Wang, S., Fu, B. J., Gao, G. Y., Liu, Y. & Zhou, J. 2013 Response of soil moisture in different land cover types to rainfall events in a re-vegetation catchment area of the Loess Plateau, China. *Catena* **101**, 122–128.
- Wang, B., Wen, F. X., Wu, J. T., Wang, X. J. & Hu, Y. N. 2014 Vertical profiles of soil water content as influences by environmental factors in a small catchment on the hilly-gully Loess Plateau. *PLoS One* **9**, 109546.
- Wei, T. X., Zhu, J. Z., Zhang, X. P., He, K. N. & Gao, Z. J. 1998 The regularity of water consumption of black locust and Chinese pine on the Loess Plateau in southwest of Shanxi Province. *Journal of Beijing Forestry University* **20**, 36–39 (in Chinese with English abstract).
- Wu, H., Rykiel Jr., E. J., Hatton, T. & Walker, J. 1994 An integrated rate methodology (IRM) for multi-factor growth rate modelling. *Ecological Modelling* **73**, 97–116.
- Xin, Z. B., Xu, J. X. & Zheng, W. 2008 Spatiotemporal variations of vegetation cover on the Chinese Loess Plateau (1981–2006): impacts of climate changes and human activities. *Science in China Series D: Earth Sciences* **51**, 67–78.
- Xu, J. 2005 Precipitation–vegetation coupling and its influence on erosion on the Loess Plateau, China. *Catena* **64**, 103–116.
- Xu, J. T. & Cao, Y. Y. 2001 The socioeconomic impacts and sustainability of the SLCP. In: *Implementing the natural forest protection program and the sloping land conversion program: Lessons and policy recommendations*. CCICED – Task Force on Forests and Grasslands (J. T. Xu, K. Eugenia & A. W. Thomas, eds). China Forestry Publ. House, Beijing, pp. 49–70.
- Yang, W. Z. 2001 Soil water resources and afforestation in Loess Plateau. *Journal of Natural Resources* **16**, 433–438.
- Yang, W. Z. & Shao, M. A. 2000 *Studies on Soil Moisture on the Loess Plateau*. China's Science Press, Beijing, p. 305.
- Yang, Y. H., Watanabe, M., Wang, Z. P., Sakura, Y. S. & Tang, C. Y. 2002 Prediction of changes in soil moisture associated with climatic changes and their implications for vegetation changes: WAVES model simulation on Taihang Mountain, China. *Climate Change* **57**, 163–183.
- Yang, L., Wei, W., Chen, L. D. & Mo, B. R. 2012 Response of deep soil moisture to land use and afforestation in the semi-arid Loess Plateau, China. *Journal of Hydrology* **475**, 111–122.
- Zhang, L. & Dawes, W. 1998 *WAVES: An Integrated Energy and Water Balance Model*, CSIRO Land and Water Technical Report No. 31/98. CSIRO, Canberra, Australia.
- Zhang, L., Dawes, W. R. & Hatton, T. J. 1996 Modelling hydrologic processes using a biophysically based model – application of WAVES to FIFE and HAPEXMOBILHY. *Journal of Hydrology* **185**, 147–169.
- Zhang, P., Zhou, X. & Wang, F. 1999 *Introduction to Natural Forest Conservation Program*. Chinas Forestry Publishing House, Beijing (in Chinese).
- Zhang, B. Q., Wu, P., Zhao, X. N., Wang, Y. B., Wang, J. W. & Shi, Y. G. 2012 Drought variation trends in different subregions of the Chinese Loess Plateau over the past four decades. *Agricultural Water Management* **115**, 167–177.
- Zheng, M. G., Liao, Y. S. & He, J. J. 2014 Sediment delivery ratio single flood events and the influencing factors in a headwater basin of the Chinese Loess Plateau. *PLoS One* **9**, 3112594.

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