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Annual runoff and evapotranspiration of forestlands and non-forestlands in selected basins of the Loess Plateau of China

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ABSTRACT

Large-scale forestation has been undertaken over decades principally to control the serious soil erosion in the Loess Plateau of China. A quantitative assessment of the hydrological effects of forestation, especially on basin water yield, is critical for the sustainable forestry development within this dry region. In this study, we constructed the multi-annual water balances to estimate the respective grand average of annual evapotranspiration (ET) and runoff for forestlands and non-forestlands of 57 basins. The overall annual runoff and corresponding runoff/precipitation ratio were low, with a mean of 33 mm (7%) ranging from 10 (2%) to 56 mm (15%). Taking the grand average of annual precipitation of 463 mm for all basins, the corresponding grand averages of annual ET and runoff were 447 and 16 mm for forestlands, 424 and 39 mm for non-forestlands, respectively. Thus, the corresponding ratios of annual ET and runoff to precipitation were 91·7 and 8·3% for non-forestlands, 96·6 and 3·4% for forestlands, respectively. Although the absolute difference in grand average of annual runoff was only 23 mm, it represents a large difference in relative terms, as it equates up to 58% of annual runoff from non-forestlands. We argue that the large-scale forestation may have serious consequences for water management and sustainable development in the dry region of NW China because of a runoff reduction. This study highlights the importance of quantifying the ET of forests and other land uses and to examine how land cover change may affect the water balances in an arid environment. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS forestation; evapotranspiration; water yield; land use change; Loess Plateau

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INTRODUCTION

The Loess Plateau of China suffers from severe water shortages and soil erosion as a result of several natural and anthropogenic causal factors (Shi and Shao, 2000). Besides the loose soil properties and erosive rainstorms, extensive disturbance and conversion of grasslands and natural forests have been identified as the key causes (Fu, 1989). Therefore, over the past five decades, vegetation restoration, especially forestation, has been encouraged as an effective measure for controlling soil erosion (Li, 2004). Such ecological restoration was also designed to alleviate flash floods, increase forest products and diversify rural incomes. Furthermore, forestation is increasingly viewed as an effective measure of carbon sequestration to partially offset the CO_2 emissions. This policy has brought about an extensive conversion from grass- and shrub-land as well as slope farmland to forest plantation. Taking the example of Shaanxi Province located in the central Loess Plateau, the forest coverage has increased from 30·9% in 1999 to 37·3% in 2009 (http://news.xinmin.cn/rollnews/2009/12/29/3 188 581.html). The forest coverage in the Loess Plateau overall has increased from 11·0% in 1977 to 19·6% in 2008 (http://news.hexun.com/2008-07-01/107 104 628.html).

Indeed, the large-scale forestation over the Loess Plateau has brought major benefits to erosion control (Wang, 1992), but it has also caused serious concerns in soil desiccation (Li *et al.*, 2008) and water yield reduction (Huang *et al.*, 2003a,b; Zhang *et al.*, 2007a,b; Wang *et al.*, 2008; Yu *et al.*, 2009). Elsewhere, there has been growing number of studies focused on this issue worldwide in the last few decades (Farley *et al.*, 2005; Jackson *et al.*, 2005; Sun *et al.*, 2006; Wei *et al.*, 2008; Vanclay, 2009). Quantifying the impacts of forestation on water yield and minimizing its adverse effects to water resources has now become an important part of sustainable forestry strategies in China, particularly with regard to the drier regions such as the Loess Plateau.

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The complex interaction of various environmental factors, such as climate, topography, soil and vegetation, controls the water yield of drainage basins and its spatio-temporal variability. The classic paired catchments approach has been widely used for determining changes in water yield caused by forest change and forest management through excluding the effects of other environmental variables (Brown *et al.*, 2005). Farley *et al.* (2005) produced a global synthesis of average water yield reduction after forestation based on published data of paired catchment studies. But their work was mostly limited to small basins in tropical or humid temperate regions with annual precipitation >1000 mm. Consequently, the conclusions of Farley *et al.* (2005) may not be applicable to areas with lower precipitation, such as the Loess Plateau.

Conversely, there has been only a limited number of paired catchment studies undertaken in China (Wei *et al.*, 2008). Consequently, an alternative approach has to be introduced to evaluate the hydrological impacts of forestation. For example, Zhang *et al.* (2007a,b, 2009) used the water balance model associated with existing data sets of mean annual runoff (MAR) and forest coverage to evaluate the MAR reduction caused by forests in the coarse–sandy hilly area of the Loess Plateau. Their results showed a decrease of MAR by 5·5% if forested on suitable sites (5·8% in area ratio) and by 9·2% if forested on both suitable and less suitable sites (10·1% in area ratio), respectively. They also showed that the rate of MAR reduction decreased with decreasing precipitation.

However, a key issue is that current knowledge about the forestation impacts on annual runoff at large scale within the Loess Plateau remains too limited to support the regional forestry development and other land management. Therefore, we constructed a database of 57 basins in the Loess Plateau for comparing the mean water balances of forestlands and non-forestlands. The main purpose is to quantitatively detect the change in the grand average of annual runoff and evapotranspiration (ET) over the 57 basins with increasing forest coverage. A further objective is to provide a sound ecohydrological basis for improving future forestry development strategies in the Loess Plateau.

STUDY AREA AND METHODS

Geographic characteristics

The study area is the Loess Plateau (34–41 °N, 100–115 °E) which is located in NW China The total area of this feature is 632 520 km^2 and accounts for 6·3% of the entire land area of China.

There are several reasons for selecting the Loess Plateau for this study. The first one is that there are the serious ongoing forest–water conflicts in this region. Second, there are sufficient published hydrological data of the Loess Plateau so that a statistical analysis can be undertaken. Third, the environmental condition (i.e. soil, topography and climate) are comparatively 'uniform'. These circumstances minimize the confounding effects from other variables and so facilitate a better understanding of the hydrological impacts of forestation.

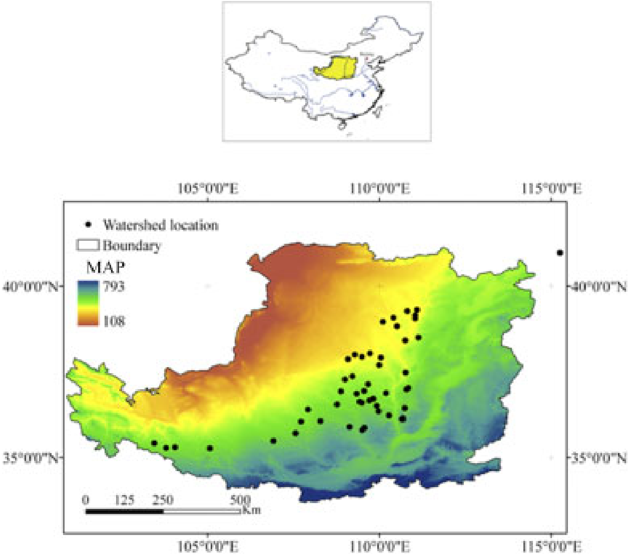

Figure 1. Location of study basins and distribution of MAP (mm) in the Loess Plateau.

The Loess Plateau lies mostly on the transitional border between the monsoon climatic zone and the continental arid climate zone. Details of environmental factors, especially climatic and soil texture features, were described by Wang and Takahashi (1999). The mean annual precipitation (MAP) ranges from 110 to 800 mm (Figure 1) and the mean annual temperature ranges from 5 to 12·5 °C from NW to SE. There are four climatic sub-zones over the plateau, *viz*: (i) arid temperate, (ii) semiarid temperate, (iii) semiarid warm temperate and (iv) sub-humid warm temperate. From northwest to southeast, the net solar radiation receipt at the surface progressively decreases with increasing cloud cover, whereas in contract the temperature, precipitation and humidity increase. There are no apparent differences in mean wind speed over the region.

The Loess Plateau is specially characterized by the huge thickness of loess, generally 100–200 m in depth. The soils vary across a range of textural types which are associated with the climatic gradient. Thus, sand, sandy loam, light loam, medium loam to heavy loam occur which are associated with the shift from the arid to sub-humid zones along this climatic gradient. The corresponding vegetation change along the same gradient is an increase in the area ratio of crops, shrubs and forests from NW to SE. Conversely, there is a decrease in grassland.

Within and around the Loess Plateau, there are several stony mountains, such as the Liupan Mountains and Wutai Mountains. The forest coverage in the stony mountainous basins is generally higher in response to the improved wetness resulted from increasing precipitation and decreasing temperature with rising elevation. The soil type, soil thickness and soil physical parameters are obviously different from those in the typical loess area.

However, the basins we selected for this study are not mountainous basins, but more uniform, loess-dominated basins.

The locations of the basins selected for this study are shown in Figure 1. All of them possess a semiarid climate, with an MAP from 317 to 639 mm (Table I). Except for two river basins located outside, but near the Loess Plateau, all the others which were selected are located within the Loess Plateau. The soil texture for most basins is dominated by light loam, with sand loam or medium loam also occurring within a few basins. The average elevation of these basins lies within a range from 756 to 2148 m asl. By plotting the forest coverage and mean elevation of all basins (not shown here), there is no significant relation between the forest coverage and elevation. This indicates that the forest coverage in the Loess Plateau is less controlled by temperature. Instead, such forest coverage of basins seems to be mostly controlled by the annual precipitation (Figure 2). When the MAP is <450 mm, the forest coverage is generally within 0–10% and increases slowly with MAP, probably because the forests can only grow on limited wet sites such as riparian zones and the adjoining lowest segment of slopes associated with valley bottoms. On the other hand, when the MAP is above a threshold of 450 mm, the forest coverage is higher and increases quickly up to 100% if the MAP reaches 540 mm. Thus, there is an increasing area covered by forests on slopes. Such findings are very similar to the relationship between vegetation and MAP in Loess Plateau, as determined elsewhere by Xu (2005). This implies that the MAP of 450 mm can be used as the threshold for dividing the Loess Plateau or specific basins into two separate groups associated with the climatic precipitation gradient in following analysis.

Data synthesis

From peer-reviewed Chinese and international journals we selected the basin data sets within the Loess Plateau (Table I). We extracted the data of MAP, MAR and forest coverage from the basins with a drainage basin area >10 km^2. The latter area threshold was selected to minimize the possible underestimation of runoff because of potential inter-basin leakage arising from small variations in topography. The mean annual ET (MAET) of each basin equals the difference between MAP and MAR. The length of runoff records, however, remains comparable and ranges from 3 to 21 years, although most of them exceed 10 years. No duplicate data from any basin were used in the analysis. The forests in selected basins are secondary forests with the main tree species being *Quercus liaotungensis, Pinus tabulaeformis* and *Betula platyphylla*, or tree plantations consisting of *Platycladus orientalis, P. tabulaeformis* and *Robinia pseudoacacia*. The MAR changes in both depth (mm) and ratio (%) to MAP were used to assess the forest impacts on water yield.

The method for estimating the aerial average of MAP of 42 basins cited from Zhang *et al.* (2007b) and Liu and Chung (1978) was based on the area-weighted average of the weather station records within and surrounding the basins, but no details were available on how the MAP was calculated for the other 15 basins. Most important, there was no information available from the literature to obtain the errors in estimating the aerial average of MAP for each basin. Furthermore, the data obtained from the literature were not available for estimating this error. These circumstances will introduce an uncertainty into the quantification of the change of annual runoff and ET because of a corresponding change in forest coverage within individual basins, especially the larger basins. To partly offset such concerns, we deliberately selected records of longer duration in an attempt to minimize the inherent errors in precipitation which likely will be larger for shorter term records, but smaller for longer term records. We simply cited the MAP provided from the literature. We believe this is the best one can do within the current constraints of existing published information. On the other hand, this study is the first attempt at trying to condense the state-of-knowledge from existing data sets available in the Chinese scientific literature. The impact of possible errors linked with MAP on the results will be further discussed later.

Estimating ET for forestlands and non-forestlands

Owing to the limited precipitation and soil water in the Loess Plateau, forests have a low area ratio and are mostly scattered within a basin. A direct measurement of the ET over such forests using for example micrometeorological and sap flow methods (Gash and Shuttleworth, 2007) in a river basin scale is very limited or non-existent. Thus, the separate estimation of annual ET of forestlands and non-forestlands from hydrological records is a step towards a more process-based interpretation of forest impacts on water yield.

We assumed that the MAP is used as forestland ET, non-forestland ET and runoff within a basin. The change in soil water and groundwater storage is assumed to be negligible over a long period of many years. The Water Balance Equation (1) below can be used for calculating the regional average of annual ET from forestlands and non-forestlands, as follows:

$$\mathrm{ET} = P - R = \mathrm{ET_f} \cdot f + \mathrm{ET_{nf}} \cdot (1 - f) \qquad (1)$$

where ET is the mean annual ET of a basin (mm), P (mm) is MAP, R (mm) is MAR, $\mathrm{ET_f}$ (mm) and $\mathrm{ET_{nf}}$ (mm) are the regional average of annual ET in forestlands and non-forestlands, f is the forest coverage (decimal) and $(1 - f)$ is the area ratio of non-forestlands in a basin. The difference between $\mathrm{ET_f}$ and $\mathrm{ET_{nf}}$ $(\mathrm{ET_f} - \mathrm{ET_{nf}})$ is viewed as the regional average of water yield change caused by forests. The regional averages of annual runoff from forestlands and non-forestlands are $P - \mathrm{ET_f}$ and $P - \mathrm{ET_{nf}}$, respectively.

Table I. Collected data sets of MAP, MAR and forest coverage from the basins in Loess Plateau.

Source	Name of the river (site)	Forest coverage (%)	Basin area (km^2)	Data period	MAP (mm)	MAR ratio (%)	MAR (mm)	MAET (mm)	Remarks
Hu (2000)	Xiaodian, Gansu Province	15·0	272	>10 years	531	8·9	47	484	
	Caijiamiao, Gansu Province	15·0	270	>10 years	530	6·0	32	498	
	Yaofengtou, Gansu Province	20·0	219	>10 years	511	7·8	40	471	
	Hejiapo, Gansu Province	20·0	100	>10 years	489	6·1	30	459	
Li and Xu (2006)	Nanxiao, Gansu Province	0·0	28	1959–1962	500	2·4	12	488	
	Wangjia, Gansu Province	90·0	48	1959–1962	639	1·6	10	629	
Liu and Chung (1978)	Qingjian (Zichang)	0·0	916	1951–1963	509	6·7	34	475	MAP as area–weighted average of surrounding weather station data
	Xiangu (Anmingou)	0·0	24	1951–1963	624	5·9	37	587	
	Beiluo (Liujia River)	18·3	7315	1951–1963	475	6·1	29	446	
	Fenchuan (Linzhen)	94·4	1121	1951–1963	555	3·2	18	537	
	Beiluo (Zhangcunyi)	97·0	5400	1951–1963	568	3·3	19	549	
	Xiangu (Hongmiaogou)	98·5	42	1951–1963	636	4·6	29	607	
Min and Yuan (2001)	West Branch of Qingshui River, Hebei Province	4·1	706	1963–1981	439	8·2	36	403	
	East Branch of Qingshui River, Hebei Province	39·8	775	1963–1981	500	8·8	44	456	
Wang and Zhang (2001)	Qingshui, Shanxi Province	25·3	435	1960–1969	589	9·3	55	534	
		55·3	435	1970–1979	551	8·3	46	505	
		57·9	435	1980–1989	516	4·5	23	493	
Xu *et al.* (2003)	Yan (Ganguyi)	8·0	5981	1959–1970	536	7·8	42	494	
	Liujia (Beiluo River)	9·0	7325	1959–1970	462	8·2	38	424	
	Xinshui (Daning)	10·0	3992	1959–1970	527	9·5	50	477	
	Zhouchuan (Jixian)	10·0	436	1959–1970	436	12·2	53	383	
	Hulu (Beiluo River, Zhangcunyi)	100·0	4715	1959–1970	569	5·1	29	540	
	Fenchun (Linzhen)	100·0	1121	1959–1970	539	4·3	23	516	
Zhang *et al.* (2007b)	Wudinghe (Dingshi)	0·0	327	1980–2000	375	9·6	36	339	MAP as area–weighted average of surrounding weather station data
	Wudinghe (Hanjiamao)	0·0	2452	1980–2000	317	9·8	31	286	
	Huangpuchaun (Huangpu)	0·0	3175	1980–2000	366	9·0	33	333	
	Wudinghe (Hengshan)	0·0	2415	1980–2000	378	5·6	21	357	
	Wudinghe (Lijiahe)	0·1	807	1980–2000	392	7·9	31	361	
	Wudinghe (Caoping)	0·1	187	1980–2000	403	9·4	38	365	
	Wudinghe (Mahuyu)	0·1	371	1980–2000	391	9·7	38	353	

Zhang *et al*. (2007b)	Kuyehe (Wangdaohengta)	0·2	3839	1980–2000	346	11·6	40	306	MAP as area–weighted average of surrounding weather station data
	Jialuhe (Shenjiawan)	0·6	1121	1980–2000	386	9·8	38	348	
	Wudinghe (Qingyangcha)	0·6	662	1980–2000	413	8·2	34	379	
	Kuyehe (Xinmiao)	0·8	1527	1980–2000	357	14·8	53	304	
	Kuyehe (Shenmu)	0·9	7298	1980–2000	356	15·4	55	301	
	Kuyehe (Weijiachuan)	0·9	8645	1980–2000	361	15·5	56	305	
	Gushanchuan (Gaoshiya)	1·0	1263	1980–2000	385	10·6	41	344	
	Wudinghe (Dingjiagou)	1·0	23 422	1980–2000	348	9·5	33	315	
	Wudinghe (Baijiachuan)	1·1	29 662	1980–2000	362	9·1	33	329	
	Wudinghe (Zhaoshiku)	1·3	15 325	1980–2000	342	8·5	29	313	
	Yanhe (Ansai)	3·8	1334	1980–2000	446	9·0	40	406	
	Qingjianhe (Zichang)	4·0	913	1980–2000	444	9·2	41	403	
	Yanhe (Yanan)	4·2	3208	1980–2000	456	8·6	39	417	
	Qingliangshigou (Yangjiapo)	4·3	283	1980–2000	431	7·4	32	399	
	Xianchuanhe (Jiuxian)	4·4	1562	1980–2000	412	2·7	11	401	
	Qingjianhe (Yanchuan)	5·0	3468	1980–2000	455	8·6	39	416	
	Quchanhe (Peigou)	6·4	1023	1980-2000	478	5·4	26	452	
	Yanhe (Xinghe)	7·7	479	1980–2000	439	8·4	37	402	
	Yanhe (Ganguyi)	9·7	5891	1980–2000	470	7·2	34	436	
	Zhujiachuan (Xialiuji)	10·3	2881	1980–2000	424	2·6	11	413	
	Qiushuihe (Linjiaping)	11·0	1873	1980–2000	448	5·6	25	423	
	Sanchuanhe (Houdacheng)	21·1	4102	1980–2000	471	9·1	43	428	
	Yanhe (Zaoyuan)	24·8	719	1980–2000	488	7·2	35	453	
	xinshuihe (Daning)	28·2	3992	1980–2000	484	4·8	23	461	
	Weifenhe (Xinxian)	34·0	650	1980-2000	446	6·3	28	418	
	Zhouchuanhe (Jixian)	37·9	436	1980–2000	493	4·3	21	472	
	Yunyanhe (Xinshihe)	48·0	1662	1980–2000	507	3·9	20	487	
	Yunyanhe (Linzhen)	65·3	1121	1980–2000	508	3·1	16	492	
	Shiwanghe (Dacun)	72·7	2141	1980–2000	528	5·3	28	500	
Standard deviation (mm)		30·8			78	3·1	11	81	
Average (range)		22 (0–100)			463(317–639)	7·5(1·6–15·5)	33 (10–56)	430 (286–629)	

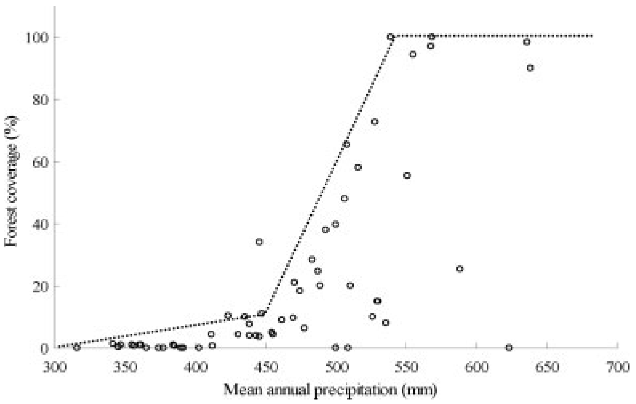

Figure 2. Relation between the potential forest coverage and MAP of basins in the Loess Plateau.

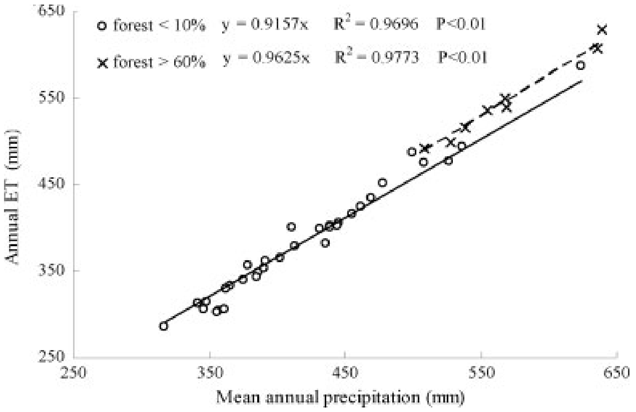

Figure 3. Linear relationship between the MAET and MAP from basins with forest coverage <10% or >60% in the Loess Plateau.

In dry regions like the Loess Plateau where water is the limiting factor for ET, the annual ET of both forestlands and non-forestlands is mainly determined by the amount of annual precipitation. As shown in Figure 3, the MAET and MAP of the loess basins appeared a linear relationship. Therefore, Equation (1) can be expanded into the following Equation (2) in order to consider the linear MAET–MAP relationship:

$$\mathrm{ET} = P - R = P \cdot a_{\mathrm{f}} \cdot f + P \cdot a_{\mathrm{nf}} \cdot (1 - f)$$

or

$$\frac{\mathrm{ET}}{P} = a_{\mathrm{f}} f + a_{\mathrm{nf}}(1 - f) \qquad (2)$$

where:

- a_{f} and a_{nf} are the ratios of annual ET to precipitation in forestlands and non-forestlands, respectively. These ratios can be used to calculate the annual ET with changing annual precipitation.
- The difference between $P \cdot a_{\mathrm{f}}$ and $P \cdot a_{\mathrm{nf}}$ ($P \cdot a_{\mathrm{f}} - P \cdot a_{\mathrm{nf}}$) is the annual runoff (i.e. water yield) change caused by forests.
- The annual runoff from forestlands and non-forestlands is $P(1 - a_{\mathrm{f}})$ and $P(1 - a_{\mathrm{nf}})$, respectively.

The coefficients in Equation (2) (as shown in Table II) were determined by the linear regression analysis using SPSS 12·0 by keeping the constant as zero. This equation can be used for assessing the change of MAR from basins with changing forest coverage and also for determining the maximum forest coverage to maintain certain levels of water yield under a given annual precipitation. The latter is critical to determining the most optimal practice of integrated forest–water management.

In the following analysis, the regional characteristics of MAP and MAR of the basins in the Loess Plateau were first evaluated. Thereafter, Equation (2) was fitted by using the collected data sets of all basins and then by stratifying the two basin groups with MAP below or above 450 mm. Subsequently, the respective grand averages of annual ET and runoff from forestlands and non-forestlands were estimated. The difference of the annual ET or runoff between forestlands and non-forestlands was used to assess the forestation impact on water yield from loess basins.

RESULTS

The regional characteristics of MAP and MAR

The collected data are presented in Table I. The MAP showed a large variation among basins, with a grand average of 463 (±78) mm, ranging from 317 to 639 mm. The MAR in the basins is very low, ranging from 10 to 56 mm. The grand average of MAR of all studied basins is only 33 (±11) mm. This figure is very close to the average of 36·7 mm for the entire Yellow River basin reported by Chang and Wang (2005).

Besides precipitation, many other environmental factors affect the MAR and MAR ratio (MAR/MAP) of basins in the Loess Plateau. Thus, there is a very weak dependency of MAR on MAP, as shown in Figure 4. Even more surprising is the negative relation as presented by the regression equation ($R = 47{\cdot}66 - 0{\cdot}0311P$, $R^2 = 0{\cdot}0466$, $P < 0{\cdot}1$), suggesting a decrease in MAR with increasing MAP. The MAR ratio (*Rr*, %) is very low and varies in the range of 1·6–15·5%, with a mean

Table II. Regression coefficients in Equation (2) showing the regional average of annual ET ratio and runoff from forestlands and non-forestlands for all study basins in the Loess Plateau and for two basin groups with MAP below or above 450 mm.

P (mm)	a_{f}	a_{nf}	$P \times a_{\mathrm{f}}$ (mm)	$P \times a_{\mathrm{nf}}$ (mm)	R^2	$P \times (a_{\mathrm{f}} - a_{\mathrm{nf}})$ (mm)	$P \times (1 - a_{\mathrm{f}})$ (mm)	$P \times (1 - a_{\mathrm{nf}})$ (mm)	$a_{\mathrm{f}} - a_{\mathrm{nf}}$
463 (317–639)	0·966	0·917	447 (306–617)	424 (291–586)	0·9804	23 (16–31)	16 (11–22)	39 (26–53)	0·049
394 (317–448)	1·064	0·903	419 (337–477)	356 (286–405)	0·9098	63 (51–72)	−25–(20–29)	38 (31–44)	0·161
522 (455–639)	0·962	0·925	502 (438–618)	483 (421–591)	0·9647	19 (17–24)	20 (17–24)	39 (34–48)	0·037

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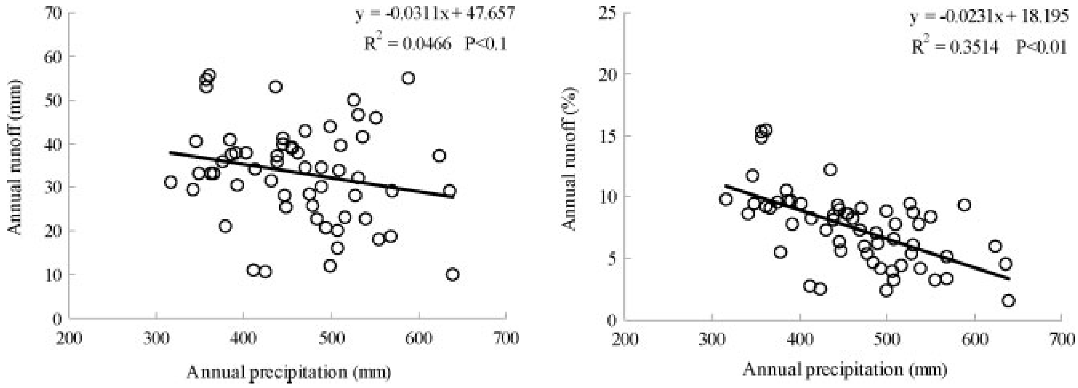

Figure 4. Decreasing trends in MAR (left) and MAR ration (right) with MAP for the studied basins in the Loess Plateau.

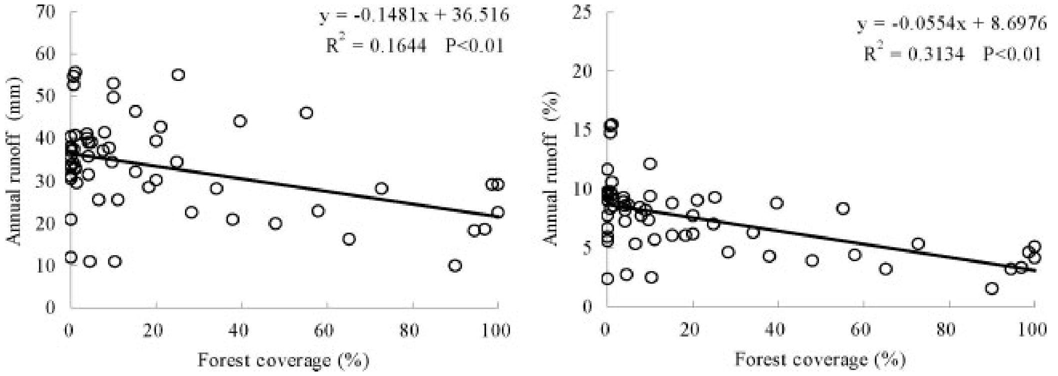

Figure 5. Decreasing trends in MAR (left) and MAR ration (right) with forest coverage for the studied basins in the Loess Plateau.

of 7·5%. It also decreases with increasing MAP ($Rr = 18{\cdot}195 - 0{\cdot}0231P$, $R^2 = 0{\cdot}3514$, $P < 0{\cdot}01$).

There is a wide scattering of data points when comparing the MAR with the forest coverage of basins (Figure 5). However, the relation between the MAR ratio and forest coverage is somewhat better. The MAR ratio decreased at a rate of merely 0·55% per 10% forest coverage increase, ranging from around 8·7% for basins without any forests to 3·2% with full forestation.

The regional average of annual ET and runoff from forestlands and non-forestlands

Two basin groups were selected from the data sets to show the variation of annual ET with MAP from the basins of different forest coverage (Figure 3); the first group is composed of 34 basins with forest coverage <10% to represent poorly forested basins, while the other group is composed of eight basins with forest coverage >60% to represent highly forested basins. The ratios of MAET to MAP were 91·6 and 96·2% for the poorly and highly forested basins, respectively. This clearly shows the increase of water consumption by forests.

To secure a more accurate estimation of the ratio of annual ET to MAP from forestlands and non-forestlands, all the data were fitted into Equation (2). This is necessary to understand and interpret the forest impacts on basin runoff where the effects of varying MAP and forest coverage are minimized. The regression results are presented in Table II. The coefficient of determination between measured and calculated MAET is very high ($R^2 = 0{\cdot}9804$, $P < 0{\cdot}01$).

The regression results of all the basins in Table II suggest that the regional average of annual ET/MAP ratio for forestlands (a_f) was 96·6%, while it was 91·7% for non-forestlands (a_{nf}). These estimations were very close to the regression coefficients in Figure 3. Under the regional average of MAP of 463 mm, the corresponding annual ET was 447 mm for forestlands and 424 mm for non-forestlands, respectively. The implication of these results is that the regional average of MAR ratio was decreased from 8·3% in non-forestlands ($1 - a_{nf}$) to 3·4% in fully forested lands ($1 - a_f$) This is a reduction of 4·9% which is very close to that estimated from the regression analysis shown in Figure 3. The corresponding MAR decreased from 39 mm in non-forestlands ($P \times (1 - a_{nf})$) to 16 mm in forestlands ($P \times (1 - a_f)$). The MAR reduction of 23 mm may not seem to be significant in absolute terms, but its proportion to MAR from non-forestlands amounted to 58%. Moreover, such an MAR reduction is also much higher than the standard deviation of MAR (11 mm, see Table I) between individual basins.

A comparison of the forest effect on annual ET and runoff between dry and wet basin groups

Generally, more forests grow in basins with higher annual precipitation. An analysis in sub-regions or basin groups with different MAP may be helpful in further improving our understanding as to how forestation may affect annual ET and runoff within the Loess Plateau. Therefore, in line with the previous mention, the study basins were stratified into two groups using the 450 mm threshold of MAP, as presented by Figure 2 showing the relation between forest coverage and MAP.

The statistical results in Table II indicate that the annual ET ratio of forestlands (a_f) for the less-precipitation basin group (i.e. MAP <450 mm) is higher than that for the more-precipitation basin group (i.e. MAP >450 mm), whereas the contrary applies to the annual ET ratio of non-forestlands (a_{nf}). When the averaged MAP increases from 394 mm in the less-precipitation basin group to 522 mm in the more-precipitation basin group, the annual ET from both forestlands ($P \times a_f$) and non-forestlands ($P \times a_{nf}$) increases. On the other hand, the non-forestland ET increases faster than the forestland ET. Consequently, the annual ET difference between forestlands and non-forestlands decreases from 63 mm in the less-precipitation basin group to 19 mm in the more-precipitation basin group.

DISCUSSION

The water yield change caused by forestation is usually assessed by the paired catchment approach (Brown *et al.*, 2005). Because of the limited number of paired catchment studies in the Loess Plateau and facing the fact that most basins were only partly forested (Table I), we had to adopt an alternative strategy by using a regional water balance approach to assess the impacts of forestation on water yield. This was achieved by the estimation and comparison of the averages of annual ET and runoff from forestlands and non-forestlands

The above approach has already been shown to be a simple and effective one which requires minimum inputs (Zhang *et al.*, 2001, 2007a,b, 2009). By using this methodology, the actual ET is expressed as an empirical and non-linear function of the annual precipitation and potential evaporation. However, in the dry Loess Plateau with low annual precipitation and very high annual potential ET, the annual actual ET of both forestlands and non-forestlands is mainly controlled by the amount of annual precipitation. Thus, the MAET of basins increases nearly linearly with MAP, as shown in Figure 3. Therefore, we simplified this non-linear ET model into a linear one with annual precipitation as the only one input parameter. Nonetheless, this simple model will be less applicable to more humid regions with higher annual precipitation.

In our study, the regional average of annual runoff was 16 mm in forestlands and 39 mm in non-forestlands in the Loess Plateau basins and thus suggests a grand average of annual runoff reduction of 23 mm after forestation. However, the forestation impact on water yield varies with the MAP of basins. This was shown by the annual ET difference between forestlands and non-forestlands of 63 mm in the less-precipitation basin group and 19 mm in the more-precipitation basin group (Table II).

The forestation impact on runoff is also influenced by the study scale. In the study by Huang *et al.* (2003b) with small paired catchments in the Loess Plateau, the treated catchment with an area of 0·87 km^2 was afforested up to 80% with deciduous species, while the controlled catchment with an area of 1·15 km^2 was maintained as natural grassland. The MAR reduction was 4·6 mm (1960–1980). Elsewhere, Chang and Wang (2005) summarized the findings from plot-scale studies on hillslopes in the Loess Plateau, all of which have been undertaken since the 1950s. Such work has mostly monitored the occurrence of infiltration-excess overland flow generated during high intensity rainstorms (Bruijnzeel, 2004) and is the dominant storm flow pathway over the Loess Plateau landscape (Chang and Wang, 2005). From that synthesis, the average of annual overland flow reduction after forestation was 7·7 mm at the plot scale for the entire loess region, and more specifically 9·4 mm for the hilly area, and 5·9 mm for the hilly-gully area of the Loess Plateau. Both the above respective estimates of MAR and overland flow reduction (i.e. of Huang *et al.*, 2003b; Chang and Wang, 2005) are lower than that in our study. There could be two possible reasons for this. At the plot scale, first is not all water flows leaving the plots could be captured and the second may be because of the young age of forests (i.e. average age of 9 years, ranging from 2 to 25 years) in these plot-scale studies. Certainly in the paired catchment study (Huang *et al.*, 2003b), these writers did note a progressive reduction in annual runoff with tree age. The maximum reduction of about 50% of annual runoff, when compared with controlled catchment, occurred about 15 years after planting. Furthermore, there are obvious differences between the respective study scales, i.e. the paired catchments and runoff plots on the one hand as against on the other, the much larger river basins in our study. However, the potential water yield reduction calculated mainly based on climatic conditions by Sun *et al.* (2006) was about 50 mm (50%), more than double our result. This means that the characteristics of forest ecosystems such as the leaf area index (LAI), root depth and soil properties can also play an important role in the water yield reduction. Young or poorly growing forests with low LAI, shallow root system and less permeable soil may result in more drainage basin runoff and less ET, while more mature and fast growing forests with high LAI, deeper root systems and more permeable soil may lead to less runoff and more ET. In support, Zhang *et al.* (2008) reported an increasing annual ET of plantations in the Loess Plateau with increasing tree age. So far, it seems that the forests in Loess Plateau have not yet attained their climatic optimum rates of ET.

The regional average of annual ET from forestlands is lower than annual precipitation based on the data of all basins. However, for specific basins with low precipitation and low forest coverage (e.g. the less-precipitation basin group with MAP <450 mm, see Table II), it is possible that the annual ET from forestlands can exceed the annual precipitation. Such a possibility could happen especially at smaller scales with annual precipitation at the lowest end of the spectrum. This phenomenon was observed in many plot-scale studies in the Loess Plateau (Yu and Chen, 1996; Wang *et al.*, 2008; Zhang *et al.*, 2008), suggesting that there may be several kinds of extra water sources besides precipitation to be consumed by trees. The first extra water source is the capture of 'runon' (i.e. infiltration-excess overland flow) which has been generated from upslope over more sparsely vegetated areas of comparatively low infiltration. Such flow then penetrates into the floor of scattered forests which, in return, subsequently infiltrates into the soil (Bonell and Williams, 1986). The infiltration-excess overland flow generated during high intensity rainstorms (Bruijnzeel, 2004) is the dominant mechanism of runoff formation in the loess areas. Forests with improved soil infiltration ability (as discussed by Yang *et al.*, 2006) can intercept and then use the overland flow. The second extra water source is the water stored in the thick loess, which can be taken up by deep-rooting trees. The latter is evident by the widely existing phenomenon of soil desiccation in the Loess Plateau (Li *et al.*, 2008). The third extra water source may be groundwater or stream water from the upper reaches of basins (Domingo *et al.*, 2001), which can be subsequently used by forests growing in valleys.

The key to predict and understand the forest impact is to know which water balance component is 'the winner' in affecting runoff. For example, forests can enhance the ET and then lead to less runoff. Paradoxically, forests can also enhance the soil infiltration which leads to greater percolation to groundwater and thus later could contribute towards low flow discharges (Bruijnzeel, 2004). The final impact of forestation on MAR depends on the synthetic effect of these positively or negatively influencing processes. Based on our study and others in the loess region (Zhang *et al.*, 2007a,b), it is not surprising that ET is 'the winner' as the absolute dominant component of the water balance of the drainage basins after forestation in the dry Loess Plateau. With the existence of very thick soils, trees are allowed to develop deep rooting networks and so tap deeper sources of soil water. This leads to a runoff reduction after forestation within the whole Loess Plateau.

Controlling soil erosion is the highest environmental policy for the ecological restoration of the Loess Plateau (Fu, 1989) and this can be effectively attained by forestation (Wang, 1992). Thus, a large-scale forestation programme is currently being implemented (Li, 2004) as one of the most effective measures to control soil erosion and to improve the environment. However, a small absolute reduction of water yield after forestation may cause its high relative decrease in view of the water scarcity in this dry region. Major socio-economic consequences are then the result. Therefore, the maintenance of acceptable basin water yields for community needs is as equally important as soil erosion control. Consequently, the noted reduction in water yield is now an emerging critical issue, which also needs to be seriously incorporated into the design of future forestry development. Forest ecohydrology studies should try to contribute towards this forestland management dilemma by attempting to balance the 'green water' used by forests and 'blue water' for mankind (Falkenmark and Rockstrom, 2006).

According to the results of this study (Table II), we can roughly estimate the grand average of annual runoff and its change under certain MAP as well as forest coverage based on the fitted equation ($R = P(1 - a_f f - a_{nf}(1 - f))$). For example, the annual runoff under a MAP of 500 mm is 41·7, 34·3, 24·4, 17·1 mm for a given respective forest coverage of 0, 30, 70 and 100%. Another application of our results is to calculate the maximum forest coverage ($f = (1 - R/P - a_{nf})/(a_f - a_{nf})$) under a given MAP and stipulated annual water yields that need to be maintained. For example, the maximum forest coverage is 20, 60 and 80% under the MAP of 460 mm in this region if water managers want to maintain the annual runoff at 33·8, 24·7 and 20·2 mm, respectively. However, the determination of optimal forest coverage in basins has to be linked with other considerations. The longer term goal for specific basins is to determine the optimal 'trade-off' by balancing the various environmental requirements involved in forestation, e.g. to arrest the soil erosion by increasing forest coverage on the one hand, but on the other by attempting to minimize the adverse impacts on society through the inevitable runoff reductions. To achieve this goal of a balanced reduction in erosion as against only smaller reduction in water yields to acceptable levels for community water supply, it requires the determination of the most optimal forest coverage by area and spatial location as well as some necessary forest management activities (e.g. reducing tree density, selecting water-saving species).

It is important to highlight that there remains a lot of uncertainty in this statistical assessment of forestation impacts on water yield. The unknown errors in estimating the aerial average of MAP in individual basins can affect the accuracy of fitted parameters in the water balance equations. Furthermore, other factors were not able to be included in this study, e.g. the location and spatial arrangements of forests and related effects. Moreover, the assumption that precipitation is uniformly distributed in forested and non-forested areas within a basin is not entirely valid in Equation (2), especially in larger basins with greater differences in topographic elevations. In addition, other causes for the spatial variability in rainfall at larger scales are well-known phenomena in meteorology such as the spatial–temporal changes in the structure (convective, stratiform) of rain fields at the mesoscale (Houze, 1989; Browning, 1999, 2003). These factors can lead to an error in the estimation of annual ET difference between forestlands and non-forestlands.

CONCLUSION

This study provided a simplified analysis of the water balance of basins in the Loess Plateau of China by using published literature data in the past 50 years. This dry region produced low MAR of only 33 mm on average across all 57 basins studied. Here, ET is the dominant component in water balance (91·7% of MAP for non-forestlands and 96·6% for forestlands) and is strongly controlled by the amount of MAP with a nearly linear positive relationship. Our results can be used to assess the annual runoff change from basins under varying annual precipitation and forestation area ratio and to calculate the proper forest coverage for maintaining a certain water yield.

This study suggests that the regional average of annual runoff for forestlands is only 16 mm, 58% lower than that of 39 mm for non-forestlands. The outcome is that large-scale forestation will likely reduce the water yield and consequently threaten the regional water supply and sustainable development. Thus, a trade-off between the forestation for erosion control and the maintenance of suitable water yield for water supply must be carefully balanced. An integrated management of water and forest/vegetation should be an important aspect of forestry policy in dry regions.

In the dry regions like the Loess Plateau, the changes in climate and land use, especially forestation, can 'tip' the water balance resulting in serious social and ecological consequences (Jackson *et al.*, 2009). Thus, understanding and quantifying the water yield response to increasing forest coverage in basins with varying annual precipitation is critical for improving the forestry development in the dry Loess Plateau region. Process-based models and decision tools (McVicar *et al.*, 2007; Yu *et al.*, 2009) are necessary to solve complex forest–water conflicts. This needs a clear understanding of the forest/vegetation impacts on processes connected with ET. Future ecohydrological studies should focus on ecohydrological processes at multiple scales from the individual plant to paired experimental basins at the headwater and sub-basin scales and then up through to the large basin scale by adopting a nested basin approach. Such an approach will incorporate the influence of factors other than precipitation and forest coverage, such as LAI, slope gradient, slope aspect, soil porosity and soil texture. Moreover, the influences of natural climate variability, varying soil properties and dynamic vegetation structure were not examined here. The quantification of annual runoff and ET response to forestation in our study is just a first step towards a better understanding of such impacts of land cover change on water resources.

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REFERENCES

Bonell M, Williams J. 1986. The generation and redistribution of overland flow on a massive oxic soil in a eucalypt woodland within the semi-arid tropics of Australia. *Hydrological Processes* **1**: 31–46.

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**: 28–61. DOI: 10.1016/j.jhydrol.2004.12.010.

Browning KA. 1999. Mesoscale aspects of extratropical cyclones: an observational perspective. In: *The Life Cycles of Extratropical Cyclones*, Shapiro MA, Grønås S (eds). American Meteorological Society: Boston, MA; 265–283.

Browning KA. 2003. Mesoscale substructure of extratropical cyclones observed by radar. *Meteorological Monographs* **30**: 7–32. DOI: 10.1175/0065-9401(2003)030<0007:MSOECO>2.0.CO;2.

Bruijnzeel LA. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture Ecosystems & Environment* **104**: 185–228. DOI: 10.1016/j.agee.2004.01.015.

Chang DD, Wang LX. 2005. Influences of artificial afforestation on annual runoff amount in upper and middle reaches of Yellow River. *Journal of Mountain Science* **23**(6): 678–686 (in Chinese).

Domingo F, Villagarcía L, Boer MM, Alados-Arboledas L, Puigdefábregas J. 2001. Evaluating the long-term water balance of arid zone stream bed vegetation using evapotranspiration modeling and hillslope runoff measurements. *Journal of Hydrology* **243**: 17–30. DOI: 10.1016/S0022-1694(00)00398-X.

Falkenmark M, Rockstrom J. 2006. The new blue and green water paradigm—breaking new ground for water resources planning and management. *Journal of Water Resources Planning and Management-Asce* **132**: 129–132.

Farley KA, Jobbágy EG, Jackson RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* **11**: 1565–1576. DOI: 10.1111/j.1365-2486.2005.01011.x.

Fu BJ. 1989. Soil erosion and its control in the loess plateau of China. *Soil Use and Management* **5**(2): 76–82. DOI: 10.1111/j.1475-2743.1989.tb00765.x.

Gash JHC, Shuttleworth JW. 2007. *Evaporation—Selection, Introduction and Commentary*, *IAHS Benchmark Papers in Hydrology No. 2*, McDonnell J (ed.). International Association of Hydrological Sciences: Wallingford; 526.

Houze RA. 1989. Observed structure of mesoscale convective systems and implications for large-scale heating. *Quarterly Journal of the Royal Meteorological Society* **115**(487): 425–461.

Hu XL. 2000. Influence of forest cover on the water resources in Loess Hill Region of Gansu Province. *Advances in Water Science* **11**(2): 199–202 (in Chinese).

Huang MB, Gallichand J, Zhang PC. 2003a. Runoff and sediment responses to conservation practices: Loess Plateau of China. *Journal of the American Water Resources Association* **39**(5): 1197–1207. DOI: 10.1111/j.1752-1688.2003.tb03702.x.

Huang MB, Zhang L, Gallichand J. 2003b. Runoff responses to afforestation in a watershed of the Loess Plateau, China. *Hydrological Processes* **17**(13): 2599–2609. DOI: 10.1002/hyp.1454.

Jackson RB, Jobbágy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC. 2005. Trading water for carbon with biological carbon sequestration. *Science* **310**: 1944–1947.

Jackson RB, Jobbágy EG, Nosetto MD. 2009. Ecohydrology in a human-dominated landscape. *Ecohydrology* **2**: 383–389.

Li WH. 2004. Degradation and restoration of forest ecosystems in China. *Forest Ecology and Management* **201**(1): 33–41. DOI: 10.1016/j.foreco.2004.06.010.

Li J, Chen B, Li XF, Zhao YJ, Ciren YJ, Jiang B, Hu W, Cheng JM, Shao MA. 2008. Effects of deep soil desiccation on artificial forestlands in different vegetation zones on the Loess Plateau of China. *Acta Ecologica Sinica* **28**(4): 1429–1445. DOI:10.1016/S1872-2032(08)60052-9.

Li GY, Xu XX. 2006. Rediscussion about the effects of forests on precipitation and annual runoff. *Journal of Northwest Forestry University* **26**(1): 1–611 (in Chinese).

Liu CM, Chung CH. 1978. The influence of forest cover upon annual runoff in the Loess Plateau of China. *Acta Geographica Sinica* **33**(2): 112–127 (in Chinese).

McVicar TR, Li LT, Van Niel TG, Zhang L, Li R, Yang QK, Zhang XP, Mu XM, Wen ZM, Liu WZ, Zhao YA, Liu ZH, 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. DOI: 10.1016/j.foreco.2007.06.025.

Min QW, Yuan JZ. 2001. Effects of forest on regional precipitation: results from some different analyses and their comparisons. *Journal of Natural Resources* **16**(5): 467–473 (in Chinese).

Shi H, Shao MA. 2000. Soil and water loss from the Loess Plateau in China. *Journal of Arid Environments* **45**(1): 9–20. DOI:10.1006/jare.1999.0618.

Sun G, Zhou GY, Zhang ZQ, Wei XH, McNulty SG, Vose JM. 2006. Potential water yield reduction due to forestation across China. *Journal of Hydrology* **328**: 548–558. DOI:10.1016/j.jhydrol.2005.12.013.

Vanclay JK. 2009. Managing water use from forest plantations. *Forest Ecology and Management* **257**: 385–389. DOI: 10.1016/j.foreco.2008.09.003.

Wang YH. 1992. The hydrological influence of black locust plantation in the loess area of Northwest China. *Hydrological Processes* **6**: 241–251. DOI: 10.1002/hyp.3360060211.

Wang QX, Takahashi H. 1999. A land surface water deficit model for an arid and semiarid region: Impact of desertification on the water deficit status in the Loess Plateau, China. *Journal of Climate* **12**: 244–257.

Wang YH, Yu PT, Xiong W, Shen ZX, Guo MC, Shi ZJ, Du AP, Wang LM. 2008. Water yield reduction after afforestation and related processes in the semiarid Liupan Mountains, Northwest China. *Journal of the American Water Resources Association* **44**(5): 1086–1097. DOI: 10.1111/j.1752-1688.2008.00238.x.

Wang LX, Zhang ZQ. 2001. Impacts of forest vegetation on watershed runoff in dryland areas. *Journal of Natural Resources* **16**(5): 439–444 (in Chinese).

Wei XH, Sun G, Liu SR, Jiang H, Zhou GY, Dai LM. 2008. The forest-streamflow relationship in China: A 40-year retrospect. *Journal of the American Water Resources Association* **44**(5): 1076–1085. DOI: 10.1111/j.1752-1688.2008.00237.x.

Xu JX. 2005. Thresholds in vegetation-precipitation relationship and the implications in restoration of vegetation on the Loess Plateau, China. *Acta Ecologica Sinica* **25**(6): 1233–1239 (in Chinese).

Xu JH, Wang L, Wang J. 2003. Analysis of water requirement for vegetation restoration in the Loess Platreau. *Yellow River* **25**(1): 13–15. (in Chinese).

Yang G, Ding GD, Chang GL, Yang L. 2006. Study on improving soil properties of forest vegetation in different land where returning farmland to forests in Loess Plateau. *Research of Soil and Water Conservation* **13**(3): 204–210 (in Chinese).

Yu XX, Chen LH. 1996. A study on water balance of protective forest ecosystem in loess area. *Acta Ecologica Sinica* **16**(3): 238–245 (in Chinese).

Yu PT, Krysanova V, Wang YH, Xiong W, Mo F, Shi ZJ, Liu HL, Vetter T, Huang SC. 2009. Quantitative estimate of water yield reduction caused by forestation in a water-limited area in Northwest China. *Geophysical Research Letters* **36**: L02406. DOI: 10.1029/2008GL036744.

Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**: 701–708. DOI: 10.1029/2000WR900325.

Zhang XM, Yu XX, Wu SH, Chen LH. 2008. Calculation and analysis of quota of water requirement of main afforestation species in Loess Plateau. *Research of Soil and Water Conservation* **15**(1): 36–40 (in Chinese).

Zhang XP, Zhang L, Li R, Yang QK. 2009. DEM-based modeling of the impact of vegetation restoration on annual streamflow in the Loess Plateau of China. *Chinese Journal of Plant Ecology* **33**(6): 1056–1064 (in Chinese).

Zhang XP, Zhang L, McVicar TR, Van Niel TG, Li LT, Li R, Yang QK, Wei L. 2007a. Modelling the impact of afforestation on average annual streamflow in the Loess Plateau, China. *Hydrological Processes* **22**(12): 1996–2004. DOI: 10.1002/hyp.6784.

Zhang XP, Zhang L, Mu XM, Li R. 2007b. The mean annual water balance in the Hekou-Longmen Section of the middle Yellow River: Testing of the regional scale water balance model and its calibration. *Acta Geographica Sinica* **62**(7): 753–763 (in Chinese).