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Effects of terracing on soil water and canopy transpiration of Chinese pine plantation in the Loess Plateau, China

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Abstract

Terracing has long been considered one of the most effective measures for soil water conservation and site improvement. However, the quantitative effects of terracing on soil water dynamics and vegetation water use have not been reported. To fill these knowledge gaps, in this study, soil water content and canopy transpiration were monitored in both terrace and slope environments in the semiarid Loess Plateau of China in 2014 and 2015. Results showed that terracing increased soil water content of different soil layers. Mean soil water content of the terrace site was 25.4% and 13.7% higher than that in the slope site in 2014 and 2015, and canopy transpiration at the terrace site increased by 9.1% and 4.8%, respectively. Canopy conductance at the terrace site was 3.9% higher than that at the slope site and it decreased logarithmically with vapor pressure deficit. This study highlighted the critical role of terracing in increasing the soil water content and mitigating water stress in semiarid environments. Thus, terracing has the potential to enhance sustainable vegetation restoration in water-limited regions.

Keywords: terracing; sap flux density; canopy conductance; water stress; Loess Plateau

1 Introduction

Terraces constitute a crucial engineering measure to control erosion, raise crop yields, and maintain sustainable agroforestry. By leveling hillslopes, terraces seek to create better planting surfaces for mitigating water loss and conserving soil (LaFevor, 2014; Zhang et al., 2014). Terracing has been established as the main measure for soil and water conservation for fields with gradients under 25 degrees (Li et al., 2011; Li et al., 2012b). It has been determined that terracing in such locations can reduce both flood runoff and the sediment transport modulus (Bai et al., 2015; Li et al., 2014a), and that the soil water conditions can be improved noticeably (Courtwright and Findlay, 2011; Huo and Zhu, 2013).

Transpiration as an important role part of the soil-plant-atmosphere continuum (Newman et al., 2010) has considerable implications regarding forest management and water yields (Bosch et al., 2014; Brito et al., 2015; Chang et al., 2014b), especially in regions where transpiration is a fundamental datum for understanding the ecophysiology of planted forests (Wang et al., 2012a). It is also central to the construction of an ecosystem-level water balance (Yang et al., 2009). Sap flow measurement can provide insights on environmental limitations and it yields results comparable with the estimates of water use for entire forest ecosystems (Chen et al., 2014b; Chirino et al., 2011; Du et al., 2011; Kim et al., 2014). Previous studies have shown that sap flow characteristics vary with species and growth status, as well as with meteorological, environmental, and edaphic features (Brito et al., 2015; Du et al., 2011). In areas with insufficient water, soil water conditions can restrict many physiological processes (Li et al., 2014b). Plants in these areas tend to deepen and extend their root systems to exploit substantial quantities of soil water for transpiration (Chen et al., 2014c; Limousin et al., 2009). Stomatal closure as an important physiological process was employed by plants to regulate water use and to prevent their hydraulic system from irreversible damage (Chirino et al., 2011). Sap flow reduction caused by stomatal closure is considered to be the preliminary response of canopy transpiration to water stress. Under water-sufficient conditions, differences in vapor pressure deficit (VPD) determine the transpiration amount (Chen et al., 2014b). However, transpiration is restricted by the plant’s hydraulic conductance capacity and cannot exceed the amount of water that can be obtained from the soil. Soil water influences stand transpiration through the water fluxes within the root zone and the percolation of soil profile caused by different rainfall regimes (Chen et al., 2014c). Based on pot experiments, Cui (2012) concluded that sap flow rates dropped 84.7% under severe water stress (5.33%) compared with that under non-stress (19.78%)

conditions. Under saturated conditions, sap flow rates were found to reach 10 times of those in the dry season (Nie et al., 2005).

The semiarid Loess Plateau region of China has experienced long-term serious soil erosion, vegetation degradation, and water loss (Zhang et al., 2008). Intense soil erosion has resulted in the decline of land productivity (under traditional agriculture) and environmental degradation (Wang et al., 2010). Because of the depletion of soil moisture and water shortages, there are many "dwarf and aged" trees in this region (Li et al., 2013). Hence, with the objectives of controlling erosion and conserving water resources, many investigations have been conducted into a wide range of soil management practices, including structural, agronomic, and biological measures (Jin et al., 2014; Yuan et al., 2016). Among these, terraces are a well-developed structural practice. Unlike native plants, many introduced species of vegetation usually have higher water demands (Chen et al., 2008; Yang et al., 2009). Thus, local soils have become extremely dry in both deep and shallow layers, diminishing the expected positive effects of afforestation in controlling soil erosion and improving the regional environment (Wang et al., 2012b; Yang et al., 2012). By analyzing four introduced plant species (*Pinus tabulaeformis*, *Robinia pseudoacacia*, *Caragana korshinskill* and *Hippophae rhamnoides*), Jian et al. (2015) drew the conclusion that in semiarid loess hilly areas, precipitation cannot meet the water loss caused by evapotranspiration in slope-scale. However, few studies have considered the effects of terracing on plant growth, nor its implications for regional ecological restoration.

This paired-site study focused on a small catchment in the western Loess Plateau of China to examine the effects of terracing on the soil water content and canopy transpiration. Similarly aged specimens of Chinese pine (*P. tabulaeformis*), being one of the main artificial plants in the area, were planted in both terrace and slope plots. The specific aims of this study were to (1)

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examine the effects of terracing on soil moisture dynamics; (2) identify the effect of terracing on canopy transpiration.

2 Materials and methods

2.1 Site description

The study area was located in Anjiapo catchment in Dingxi County of Gansu Province, in the western part of the Loess Plateau in China (35°33′–35°35′N, 104°38′–104°41′E). This region has a continental arid temperate climate with mean annual temperature and mean annual rainfall of 6.3 ℃ and 421 mm, respectively (1956–2010 period). Most of the rain falls during the summer months in the form of thunderstorms. The mean annual pan evaporation reaches 1515 mm. The soil type belongs to calcic Cambisol (FAO, 1990), developed from loess material, with the average soil depth varying from 40 to 60 m. In this area, deep percolation can be neglected and groundwater is unavailable for vegetation growth and restoration. Therefore, rainfall is the only water source available for plants. The predominant vegetation types in the study area are native grasses and introduced plants. In this study, two adjacent stands were chosen for the experiment: one with natural sloping topography and the other that has been terraced for over 30 years (Fig. 1). Both sites were planted with specimens of *P. tabulaeformis*, a planted tree species typical of the region (Chen et al., 2010; Wei et al., 2015).

2.2 Environmental observation

Micrometeorological data such as air temperature (T, ℃), solar radiation (R_a, W • m^{-2}), relative humidity (RH, %), and precipitation (P, mm) were obtained using a Vantage Pro2 automatic weather station (Davis Company, USA) located in an open space about 500 m from the site. Vapor pressure deficit (VPD, kPa) was calculated based on the air temperature and relative humidity as:

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$$VPD = 0.611 \times \exp\left(\frac{17.27T}{237.3+T}\right)(1-\mathrm{RH}) \quad (1)$$

Soil water content was monitored continuously using a HOBO U30 (Onset Computer Corporation, Bourne, USA) from 2014 to 2015 within the upper 100 cm of the soil profile. There were five probes in each instrument set to depths of 10, 30, 50, 70, and 90 cm, respectively. Relative extractable water (REW) was calculated as:

$$REW = (\theta - \theta_{\min}) / (\theta_{\max} - \theta_{\min}) \quad (2)$$

where $\theta_{\max}$ and $\theta_{\min}$ are the maximum and minimum soil water content, respectively. The value of REW varies between 0 and 1. Following Bréda et al. (2006), soil water conditions were classified into severely stressed (REW = [0, 0.1]), moderately stressed (REW= [0.1, 0.4]), and non-stressed (REW = [0.4, 1]).

2.3 Sap flux and transpiration measurements

Sap flux was monitored continuously from June 5, 2014 to October 10, 2015. At each studied site, six individuals of *P. tabulaeformis* with different diameters at breast height (DBH, cm) were selected, which represent the size classes within the site (Table 1). Sap flow was measured with the improved Granier's thermal dissipation probe technique (Granier, 1985). The detailed procedure for measuring sap flow was described in Zhang et al. (2015).

Sap flux density (SF_d) was calculated by an empirical calibration equation:

$$SF_d = 0.714 \times \left(\frac{\Delta T_{\max} - \Delta T - (\Delta T_{R1} + \Delta T_{R2})/2}{\Delta T - (\Delta T_{R1} + \Delta T_{R2})/2} \right)^{1.231} \quad (3)$$

where SF_d is sap flux density (mL cm^{-2} min^{-1}); ΔT, ΔT_{R1}, and ΔT_{R2} each represent the temperature difference between probes (Zhang et al., 2015); and $\Delta T_{\max}$ is the maximum value

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of ΔT in cases when the tree was saturated, i.e., no radial tree-trunk increment, air humidity of 100%, and transpiration near zero.

Sap flux (*SF*, kg day^{-1}) was obtained by the multiplication of sap flux density and sapwood area (A_s, cm^2), neglecting the differences in radial profile (Chang et al., 2014a). It was calculated as:

$$SF = 1.44 SF_d A_s \quad (4)$$

Canopy transpiration (E_c, mm day^{-1}) was obtained from the *SF* and crown projected area (A_c, m^2) (Chang et al., 2014a) as:

$$E_c = SF / A_c \quad (5)$$

Mean daily canopy conductance (g_c, mm s^{-1}) was estimated from canopy transpiration (E_c, mm h^{-1}) by using a simplified inverted Penman-Monteith equation (Luis et al., 2005):

$$g_c = \gamma \lambda E_c / \rho c_p VPD \quad (6)$$

where γ is the psychometric constant (kPa ·℃$^{-1}$), λ is the latent heat for vaporizing (MJ kg^{-1}), ρ is the air density (kg m^{-3}), c_p is the specific heat capacity of air (MJ kg^{-1} ·℃$^{-1}$), and the VPD (kPa) is calculated from the air temperature and relative humidity. The value of g_c was assumed as approximate average stomatal conductance and considered to reflect the physiological control of tree transpiration.

2.4 Statistical analysis

DBH, sapwood area, and crown projected area were compared using the student *t* test. For the comparison of soil water content and canopy transpiration dynamics, non-parametric tests of significance were used because of the autocorrelations in the time series data. The Wilcoxon rank sum test, also known as the Mann-Whitney *U* test, was used to test the differences in soil water content and canopy transpiration between the terrace and slope sites. Curve fitting was

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performed using the OriginPro Version 8.0 software (OriginLab Corporation, USA) to establish the relationship between canopy transpiration and soil water content, and between canopy conductance and VPD. Statistical analyses were run using the SPSS version 17.0 software (SPSS Inc., Chicago, IL, USA), for which, the significance level was set at 0.05.

3 Results

3.1 Soil water content

Under the same climatic conditions, soil water content showed differences between the natural slope and terraces (Fig. 2). Data from the shallow layer (0–20 cm) were not analyzed because of anthropogenic disturbance. In both years, statistically significant ($p < 0.05$) higher soil water content was observed at the terrace site than that at the slope site (Fig. 2 a and b). Depth-averaged soil water content of the terrace site was approximately 25.4% and 13.7% higher than that at the slope site in 2014 and 2015, respectively. Moreover, the mean soil water contents at both sites were higher in 2015 than that in 2014. Temporal variations of REW between 20–100 cm (Fig. 2 c and d) indicated that soil water conditions were stressed (REW < 0.4) in both sites during the two consecutive growing seasons. However, REW was 113.1% more at the terrace site compared with that at the slope site during the two years. It was noted that soil water was severely stressed (REW < 0.1) in the slope site, whereas terracing improved the conditions significantly.

3.2 Canopy transpiration

The diurnal variations of sap flux density (SF_d) are shown in Fig. 3. In the growing season, *P. tabulaeformis* had similar trends of variation at both sites, i.e., high flux density in the daytime and low flux density at night. It varied between 0.02 and 0.23 mL cm^{-2} min^{-1} at the terrace site and between 0.02 and 0.18 mL cm^{-2} min^{-1} at the slope site. *P. tabulaeformis* had 20.2% higher maximum sap flux density at the terrace site compared with that at the slope site. Canopy transpiration was found to be 9.1% and 4.8% higher ($p < 0.05$) at the terrace site than that at the slope site in 2014 and 2015, respectively. Annual variation analysis showed that the cumulative canopy transpiration at both sites was higher in 2014 than that in 2015 (Fig. 4). In the naturally sloping site, the cumulative canopy transpiration was 138.6 mm (32.9% of potential evapotranspiration (PET)) in 2014 and 107.6 mm (24.9% of PET) in 2015. The corresponding proportions at the terrace site were 35.7% and 26.0% in 2014 and 2015, respectively. Variation in canopy transpiration between the slope and terrace sites increased with soil water content variation ($p < 0.0001$, $R^2 = 0.20$; Fig. 5).

3.3 Canopy conductance

We classified canopy conductance into two levels based on soil water conditions: REW > 0.1 (Fig. 6 a and b) and REW < 0.1 (Fig. 6 c and d). The relationships between canopy conductance and solar radiation, between canopy conductance and VPD under corresponding soil water conditions are shown in Figure 6. It exhibits that canopy conductance declined logarithmically with VPD (Fig. 6 b and d), and there is no significant relationship between canopy conductance and solar radiation (Fig. 6 a and c). When soil water conditions changed from wet (REW > 0.1) to dry (REW < 0.1), canopy conductance reduced by 12.3% and 24.7% at the slope and terrace sites, respectively. Meanwhile, canopy conductance of *P. tabulaeformis* at the terrace site was up to 3.9% higher than that at the slope site. The frequency of the SF_d peak time suggested that *P. tabulaeformis* suppressed SF_d under high VPD conditions at both slope and terrace sites (Fig. 7). The maximum SF_d ($SF_{d,\,max}$) was relatively similarly distributed before 14:00 local time (LT), i.e., 61.1% at the slope site and 59.2% at the terrace site. However, around 16:00 LT, closer to the most frequent peak time of VPD, the proportion of $SF_{d,\,max}$ at the slope site was 33.3% less than that at the terrace site. Therefore, under the same conditions, terracing was found to alleviate the sensitivity of stomatal response to ambient air humidity.

4 Discussion

4.1 Effects of terracing on soil water recharge

A statistically significant ($p < 0.05$) higher soil water content was found at the terrace site compared with that at the slope site (Fig. 2). Terraces, which interrupt natural slopes with a series of gentle benches, can decrease the connectivity and integrity of overland flow, prolong the residence time of water, and increase the infiltration (Molina et al., 2014). According to Zhang et al. (2005), the soil profile in a terrace can be divided into three layers: the fast changing layer, activity layer, and relatively stable layer. Water storage in the fast changing layer of a terrace can be 7.2% higher than that in sloping land (Huo and Zhu, 2013). Similar to Wang et al. (2014a), soil water content of the terrace site in this study was significantly higher ($p < 0.05$) than that at the slope site within 100 cm in each layer. The depth-averaged soil water content in the terrace site was up to 25.4% higher than that at the slope site (Fig. 2). Similar results have been obtained in studies that compared the effects of contour bench terrace systems in the semiarid Negev in Israel (Stavi et al., 2015), examined terrace characteristics (Engdawork and Bork, 2014), and detected the impact of restoring degraded terraces (LaFevor, 2014). Previous works have reported that approximately 20% (to a potential 200%) of total surface rainwater could infiltrate into underground soil layers after terracing (Courtwright and Findlay, 2011), and that 1.13 times more rainfall can be stored in a terraced system than that in sloping land (Li et al., 2012a). The low REW indicated that the study area is under severe water stress, whereas the large difference between the two sites (113.1 % more REW in the terrace site) suggested that the construction of terraces could help increase soil water content.

4.2 Effects of terracing on canopy transpiration

According to the results, the maximum sap flux density of *P. tabulaeformis* at the terrace site was 20.2% higher than that at the slope site under the same climatic conditions (Fig. 3). During the growing seasons, mean daily canopy transpiration was up to 9.1% ($p < 0.05$) higher at the terrace site than that at the slope site (Fig. 4). Similarly, Pataki et al. (2000) found an observed decrease in maximum sap flow for *Pinus contorta*, *Abies lasiocarpa*, *Populus tremuloides*, and *Pinus flexilis* when soil moisture declined by 31.4%. Under the conditions of a saturated shallow water table, forest transpiration could equal PET (Čermák and Prax, 2001). Brito et al. (2015) found that the total canopy transpiration of *Pinus canariensis* increased by 133% in a wet year than that in a normal year. Canopy transpiration variation showed significant correlation with soil water content variation (Fig. 5). In addition to soil moisture, the low regression coefficient can be attributed to the influence of various environmental factors (Bosch et al., 2014; Brito et al., 2015; Chen et al., 2014c). Among these factors, VPD and solar radiation can trigger a timely response in transpiration, while the influence of soil water is reflected over a longer temporal scale (Chen et al., 2014a; Shen et al., 2015).

As Chen et al. (2014c) indicated that the sensitivity of stomatal response to drought stress can be expressed by the frequency distribution of maxmimum sap flux density. The increased frequency of maximum sap flux density earlier in the day (before 14:00 LT) suggested an enhanced stomatal sensitivity to avoid high VPD (Fig. 7). Studies have shown that the effectiveness of stomatal conductance induced by VPD fluctuation could result in the variation of transpiration rate (Addington et al., 2004; Igarashi et al., 2015), and a decline in canopy conductance with increasing VPD is an indicator of physiological restrictions to transpiration (Chang et al., 2014a; Shen et al., 2015). This occurred to avoid any negative leaf water potential and xylem cavitation (Addington et al., 2004; Wang et al., 2014b). When soil conditions are severely stressed or in a

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prolonged period of VPD tension, it is inevitable that the varying degrees of embolisms can be caused by runaway cavitation (Vergeynst et al., 2015), which could trigger a series consequences, such as reducing water transport, and stomatal closure (Pataki et al., 2000). This would explain why canopy conductance decreased logarithmically with VPD and reduced sharply when soil water condition changed from wet to dry (Fig. 6). In time and space, soil moisture plays an important role in connecting environmental fluctuations and vegetation transpiration (Brito et al., 2015; Chen et al., 2014a). Similar to the conclusions drawn by Shen et al. (2015), our results showed that canopy transpiration and canopy conductance of *P. tabulaeformis* were 6.9% and 3.9% higher at terrace site than that at slope site. Our results suggested that the impact of terracing on transpiration could be explained by the response of canopy transpiration to other environmental factors under different soil water conditions.

4.3 Implications of this study

Under water stress, species tend to adjust their water consumption to avoid reaching water potential values that could produce irreversible damage (Chirino et al., 2011). Depending on their drought avoidance mechanisms, species can be classified into water-spender or water-saver types (Chirino et al., 2011). In this context, *P. tabulaeformis* showed lower sap flux density under drier water conditions (Fig. 3) and reduced canopy conductance with an increasing VPD (Fig. 6 b and d). Therefore, *P. tabulaeformis* can be classified as a water-saver species (Heilmeier et al., 2002). Yang et al. (2008) indicated that in the semiarid Loess Plateau, *P. tabulaeformis* uses water more efficiently than *Robinia pseudoacacia*, and *Malus pumila*. Similar results were found in mixed forests of different ages (Chang et al., 2013) and different species (Chen et al., 2014b; Nie et al., 2005). In dry regions, *P. tabulaeformis* might be a good drought-resistance species that could help control soil loss and improve the ecological

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environment. In this study, it was found that terracing significantly improved soil water conditions. It captured 113.1% more REW than that at the slope site (Fig. 2), and it increased canopy transpiration significantly (Fig. 4). Meanwhile, the average DBH, sapwood area, and crown projected area were 12.0%, 18.8%, and 63.5% higher, respectively, at the terrace site than that at the slope site, and the crown projected area showed statistical significance ($p < 0.05$) (Table 1). Just as Wang et al. (2012a) have indicated, in drylands, the most efficient use of water is to maximize the productive water loss (T) and minimize the unproductive water loss (E). Terracing increases the accumulation of the limited water supply, making more water available for transpiration and growth and thus, improving the efficiency of water use.

5 Conclusions

In this study, the soil water content variation and daily canopy transpiration of *Pinus tabulaeformis* were studied over two consecutive growing seasons (2014–2015) in a typical semiarid area of the Loess Plateau in China. The effects of terracing on soil water content, canopy transpiration, and canopy conductance were investigated. Terracing was found to have a statistically significant positive effect on soil water content. *P. tabulaeformis* in the terrace site showed significantly higher canopy transpiration than that in the slope site ($p < 0.05$), and the variation between the terrace and slope sites increased with soil water content variation ($p < 0.0001$, $R^2 = 0.20$). The impact of terracing on transpiration could be expressed through the response of canopy transpiration to other environmental factors. Terracing increased the accumulation of the limited water supply, providing a greater amount of water for transpiration and growth. For sustainable vegetation restoration in semiarid regions, the adoption of terracing could be a technique worthy of consideration.

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Tables

Table 1. Description of the study sites in Anjiapo catchment.

	Parameter	Type: Slope	Type: Terrace
Geographical parameters	Plot area (m^2)	100	100
	Slope aspect	N	N
	Slope position	Middle	Middle
Biological parameters	Dominant plant	Chinese pine	Chinese pine
	Sample/total number	6/14	6/21
	DBH (cm)	$12.90^a \pm 3.66$	$14.45^a \pm 2.40$
	Sapwood area (A_s,cm^2)	$99.09^a \pm 44.87$	$117.74^a \pm 33.16$
	Crown projected area (A_c, m^2)	$9.55^a \pm 3.56$	$15.61^b \pm 5.11$

Note: slope aspect and slope position were measured by compass; DBH is the diameter at breast height for trees, each parameter was measured from 2014 to 2015. Means without common letters are significantly different at $p < 0.05$ according to t-test.

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Figure Legends

Slope site Terrace site

Fig. 1 Site photographs of the slope and terrace sites.

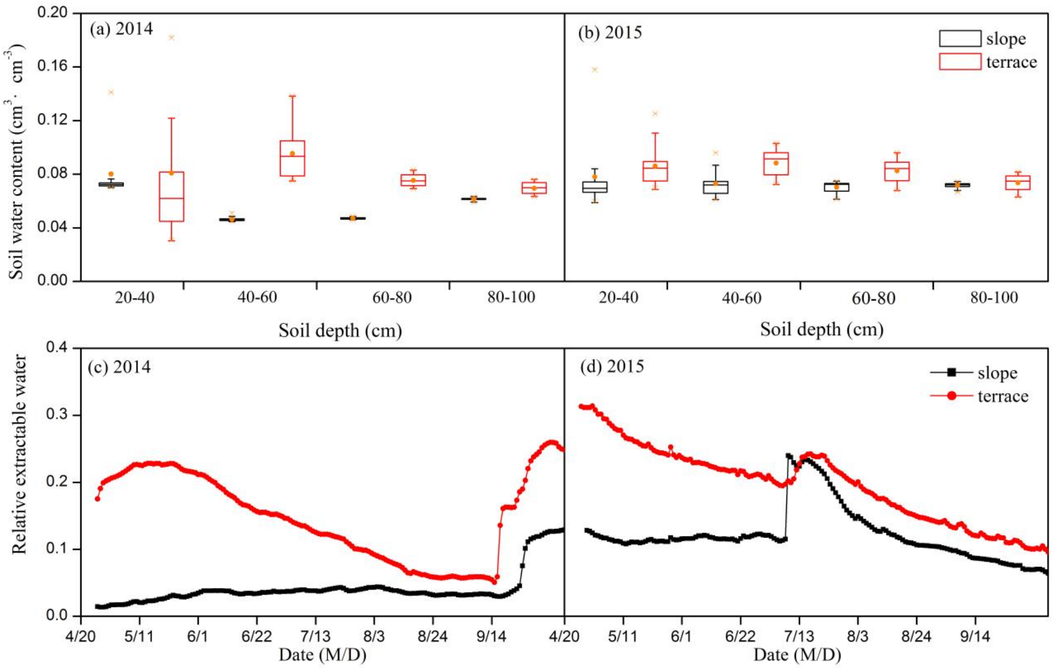

Fig. 2 Soil water content of different layers (a and b) and relative extractable water in the 20–100 cm layer (c and d) between the slope and terrace sites during two consecutive growing seasons (2014–2015).

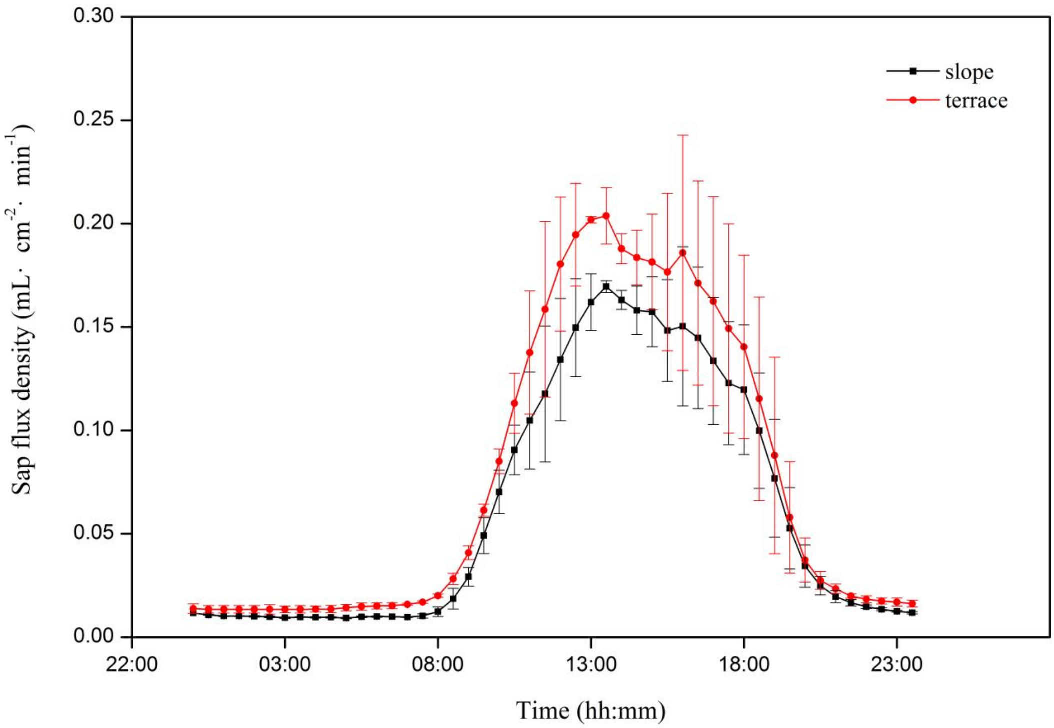

Fig. 3 Diurnal time courses of sap flux density at the slope and terrace sites. Data represent means ± standard deviation (n = 3).

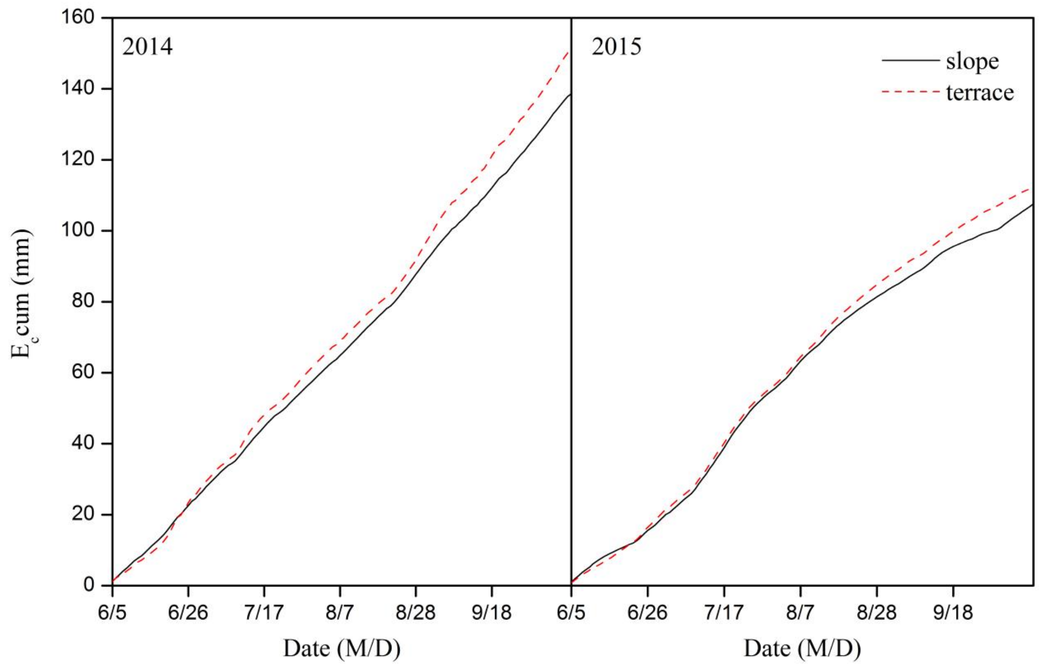

Fig. 4 Variation of accumulated canopy transpiration (E_c cum) during two consecutive growing seasons (2014–2015).

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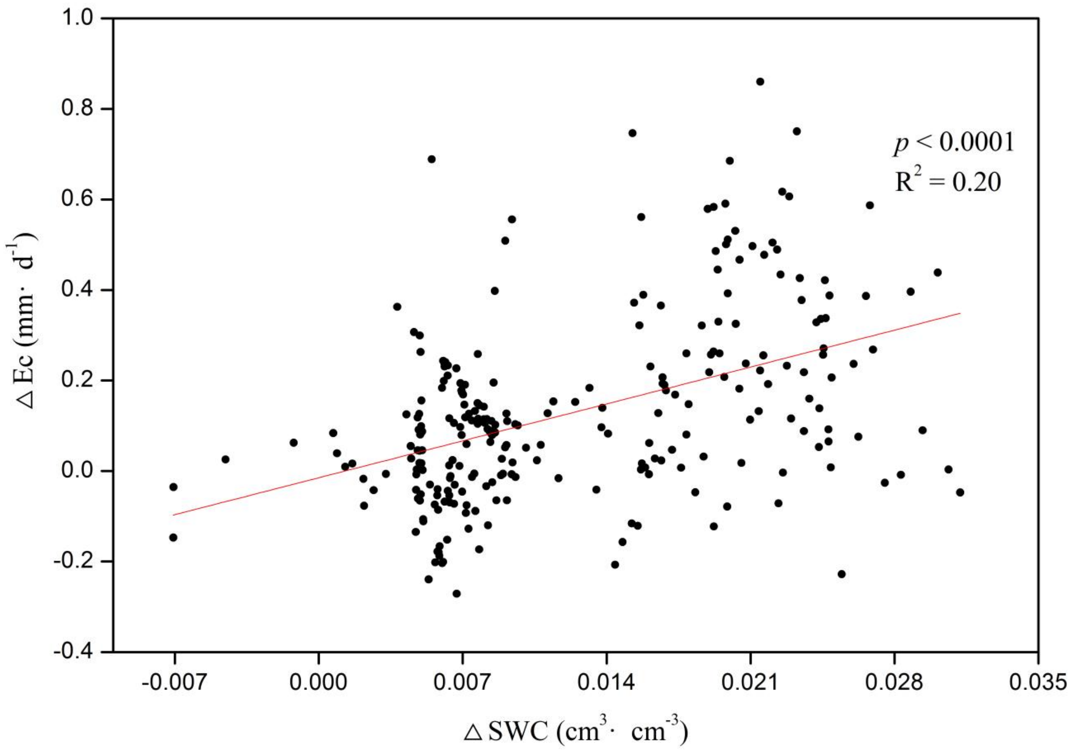


Fig. 5 Correlation of E_c variation in response to SWC variation within 100 cm during two consecutive growing seasons (2014–2015). Data of the slope site are the baselines subtracted by those of the terrace site to assess the relationship between E_c variation and SWC variation.

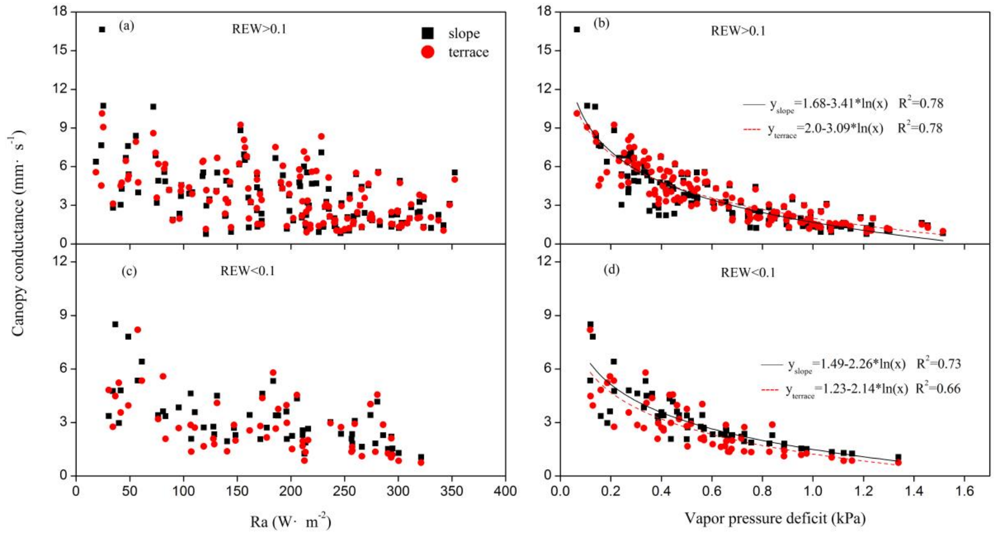
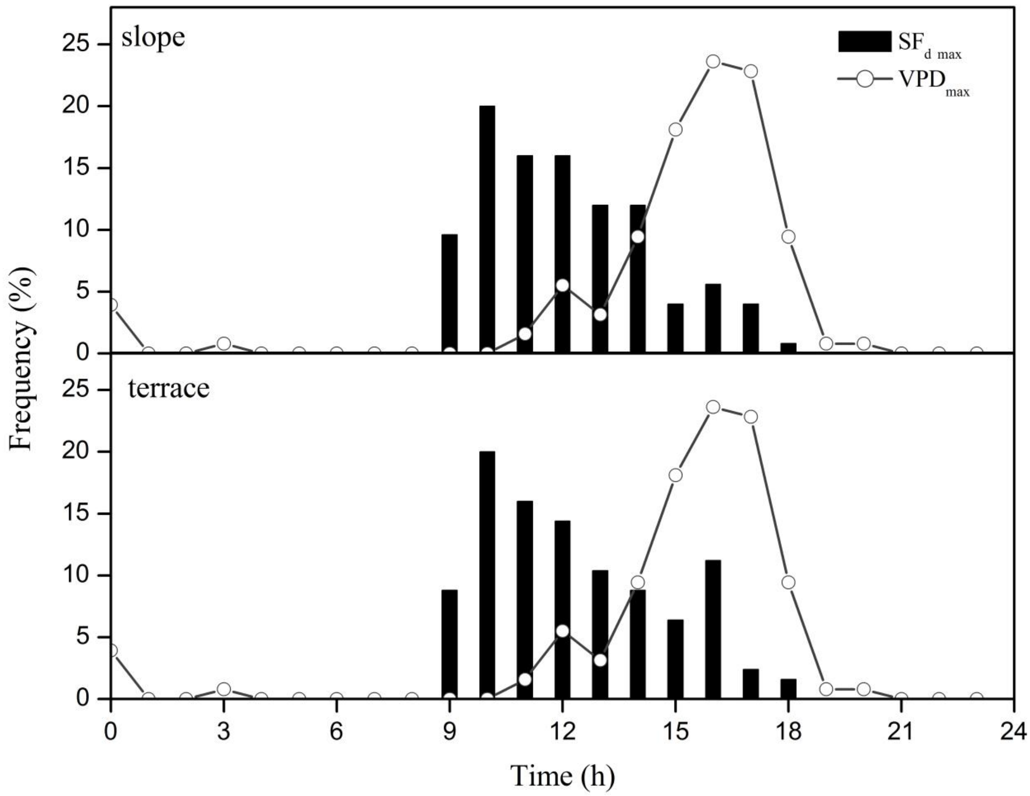


Fig. 6 Relationships between canopy conductance and solar radiation (a and c) versus relationships between canopy conductance and vapor pressure deficit (b and d) under relatively wet (REW > 0.1) and dry (REW < 0.1) soil conditions.



1

2 Fig. 7 Frequency distribution of maximum sap flux density ($SF_{d, max}$) and VPD peak times in the

3 form of diurnal patterns at contrasting sites for the comparison of SF_d - VPD evolvement patterns.

4 Data sets cover the growing seasons in 2014 and 2015.