Effects of terracing on soil water and canopy transpiration of *Pinus tabulaeformis* in the Loess Plateau of 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, few studies regarding the quantitative effects of terracing on soil water dynamics and vegetation water use efficiency were reported. To fill these knowledge gaps, in this study, soil water content and canopy transpiration from 2014 to 2015 were monitored in both terrace and slope environments in the semiarid Loess Plateau of China. Results showed that terracing had positive influences on soil water content among 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 the increase of vapor pressure deficit. This study highlighted the critical role of terracing in soil-water improvement and water-stress mitigation 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 (Dumbrovsky et al., 2014; LaFevor, 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; Liu et al., 2013). Terracing in such locations can reduce both flood runoff and the sediment transport modulus (Bai et al., 2015; Li et al., 2014a), and improve soil water conditions noticeably (Courtwright and Findlay, 2011; Huo and Zhu, 2013).

Transpiration constitutes an important part of the water budget in the soil-plant-atmosphere continuum and affect forest water yields across different scales (Wang et al., 2014c). The mechanism-driven studies on transpiration will provide theoretical guidance for forest management (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., 2012). 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 (Chirino et al., 2011; Kumagai et al., 2014; Miyazawa 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, for example, 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). Meanwhile, stomatal closure is an important physiological process 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. When water is sufficient during the rainy days, the parameter of vapor pressure deficit (VPD) can determine the transpiration amount (Chen et al., 2014b). However, transpiration is restricted by the plant’s hydraulic conductance capacity and cannot exceed the total water amount 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 during the dry seasons (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). Due to severe drought, improper plant species selection and high planting density during afforestation, local soil moisture was exhausted and many "dwarf and aged" trees appeared in the Loess Plateau (Li et al., 2013). With the aim of controlling erosion and conserving water resources, many biological and engineering measures were widely implemented (Wang et al., 2015; 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 reducing soil erosion and improving the regional environment (Wang et al., 2010; Yang et al., 2014). 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 introduced plants in the area, were planted in both terrace and slope plots. The specific aims of this study were to (1) examine the effects of terracing on soil moisture dynamics; (2) identify the effect of terracing on canopy transpiration and carbon sequestration.

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 °C 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 (Chen et al., 2010; Wei et al., 2015). In this area, deep percolation can be neglected and groundwater is unavailable for vegetation growth and restoration (Yang et al., 2012). 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 plots (sized in 10 m length × 10 m width for each plot) were chosen for the experiment. Both plots were planted with specimens of *P. tabulaeformis* since 1978. The two plots shared the same climate (solar radiation, air temperature, precipitation, etc.). Slope aspect, slope gradient, soil type, soil texture, and plant species were the same in these two stands (Table 1). The main difference is that one of them has been turned into terraces for over 30 years, while the other one was maintained with natural sloping topography. The site photographs were given in Figure 1.

2.2 Environmental observation

Micrometeorological data such as air temperature (T, °C), 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:

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

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

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

where $\theta_{\max}$ is the field capacity calculated at -33 kPa and $\theta_{\min}$ is the wilting moisture calculated at -1500 kPa. 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]). In 2015, because of the incorrect maintenance and installation, the probe in 10cm of terrace plot was not closely contact with the soil. So when comparing the differences of REW between slope and terrace, the data of the first layer (0–20 cm) were not included in both years (Fig. 3).

2.3 Sap flux and transpiration measurements

Sap flux was monitored continuously over two consecutive growing seasons (2014–2015). At each studied site, six individuals of *P. tabulaeformis* were selected with similar diameter at breast height (DBH, cm), representative of the size classes within the sites. Sap flow was measured with the improved Granier's thermal dissipation probe technique (Granier, 1985). The detailed procedure for measuring sap flow can be found in Zhang et al. (2015).

Sap flux density (SF_d) was calculated based on the temperature difference between probes by an empirical calibration equation:

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

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 of ΔT with zero transpiration assumed.

Sap flux (*SF*, kg·day^{-1}) was obtained by the multiplication of sap flux density and sapwood area (A_s, cm^2, $A_s = 0.657 * \mathrm{DBH}^{1.9413}, R^2 = 0.9965$), neglecting the differences in radial profile (Chang et al., 2014a). For a single individual it was calculated as:

$$SF = 1.44 SF_d A_s \tag{4}$$

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

$$E_c = SF / A_c \tag{5}$$

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

$$g_c = \gamma\lambda E_c / \rho c_p VPD \tag{6}$$

where γ is the psychometric constant (kPa·°C^{-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}·°C^{-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 by 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 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

Over the two consecutive growing seasons, there were no significant differences in solar radiation, air temperature and reference evapotranspiration. The average daily air temperature was 15.7°C in 2014 and 15.9°C in 2015 (Fig. 2 a). Daily mean solar radiation, vapor pressure deficit, and reference evapotranspiration averaged 195.7 W·m^{-2}, 0.63 kPa, and 3.44 mm, and 203.7 W·m^{-2}, 0.69 kPa and 3.43 mm in 2014 and 2015, respectively (Fig. 2 b, c and d).

During the study period, the precipitation level was higher in 2014 (327.6 mm) than in 2015 (227.2 mm) (Fig. 2 e). Weak precipitation events (5 mm or less) were much more frequent than strong precipitation events (more than 10 mm). Weak precipitation events accounted for 77.7% of total events and 11.0% of total precipitation amount in 2014, while 93.4% and 40.4% in 2015. The corresponding proportions of strong precipitation events were 11.7% and 64.6% in 2014, and 3.0% and 39.7% in 2015.

Under the same climatic conditions, differences in soil water content were captured between natural slopes and terraces (Fig. 3). 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. 3 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. Temporal variations of REW between 20–100 cm (Fig. 3 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 Figure 4. 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 $\mathrm{mL\cdot cm^{-2}\cdot min^{-1}}$ at the terrace site and between 0.02 and 0.18 $\mathrm{mL\cdot cm^{-2}\cdot min^{-1}}$ 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. Meanwhile, annual variation analysis showed that the cumulative canopy transpiration at both sites was higher in 2014 than that in 2015 (Fig. 5). 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 of PET at the terrace site were 35.7% and 26.0% in 2014 and 2015, respectively. Furthermore, we examined that the increase of soil water content can make a significant increase in canopy transpiration ($p < 0.0001$, $R^2 = 0.20$; Fig. 6). Plants in terrace site had better growth status than those in slope site (Table 1).

3.3 Canopy conductance

We classified canopy conductance into two levels based on soil water conditions: REW > 0.1 (Fig. 7 a and b) and REW < 0.1 (Fig. 7 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 7. It exhibits that canopy conductance declined logarithmically with the increase of VPD (Fig. 7 b and d), while there was no significant relationship between canopy conductance and solar radiation (Fig. 7 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.

Figure 8 shows the frequency distribution of the time for the sap flux density and VPD reached the maximum. The frequency of the SF_d peak time suggested that *P. tabulaeformis* suppressed SF_d under high VPD conditions regardless of soil moisture conditions (Fig. 8). The maximum SF_d ($SF_{d,\,max}$) was relatively similar 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 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. 3). 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 (0-40 cm), activity layer (40-100 cm), and relatively stable layer (under 100 cm). 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 (18.2%, 27.9%, 23.1%, and 8.0% higher in 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm, respectively). The depth-averaged soil water content in the terrace site was up to 25.4% higher (in 2014) than that at the slope site (Fig. 3). 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., 2012). 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 to 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. 4). 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. 5). 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. 6). In addition to soil moisture, the low regression coefficient (R^2=0.20, Fig. 6) 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 maximum 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 highly negative values of leaf water potential and the subsequent xylem cavitation (Addington et al., 2004; Wang et al., 2014b). When soil conditions are severely stressed or in a 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 chain reaction, such as reducing water transport, and stomatal closure (Pataki et al., 2000). This would explain why canopy conductance decreased logarithmically with the increase of VPD and reduced sharply when soil water condition changed from wet to dry (Fig. 7). 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, respectively. 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. 4) and reduced canopy conductance with an increasing VPD (Fig. 7 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 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. 3), and it increased canopy transpiration significantly (Fig. 5). Meanwhile, the average DBH, height, sapwood area, and crown projected area were 12.0%, 1.5%, 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). Terraces had positive effects on plants growth. Given the scarcity of water resources and the fragile environment, it is crucial to accumulate much more water and increase vegetation grow to approach a balance between water use and carbon sequestration (Kim et al., 2008). Just as Wang et al. (2012) 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 vegetation 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 of canopy transpiration between the terrace and slope sites increased with soil water content variation ($p < 0.0001$, $R^2 = 0.20$). Plants in the terrace site had better growth status, with higher height, bigger DBH and larger crown. 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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References

Addington, R.N., Mitchell, R.J., Oren, R., Donovan, L.A., 2004. Stomatal sensitivity to vapor pressure deficit and its relationship to hydraulic conductance in Pinus palustris. Tree Physiology, 24(5): 561-569.

Bai, X. et al., 2015. Preliminary Study of Effects of Different Terraces on Erosion Control in Loess Plateau. Research of Soil and Water Conservation, 22(3): 10-15.

Bosch, D.D., Marshall, L.K., Teskey, R., 2014. Forest transpiration from sap flux density measurements in a Southeastern Coastal Plain riparian buffer system. Agricultural and Forest Meteorology, 187(0): 72-82. DOI:http://dx.doi.org/10.1016/j.agrformet.2013.12.002

Bréda, N., Huc, R., Granier, A., Dreyer, E., 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Annals of Forest Science, 63(6): 625-644.

Brito, P. et al., 2015. Canopy transpiration of a semi arid Pinus canariensis forest at a treeline ecotone in two hydrologically contrasting years. Agricultural and Forest Meteorology, 201(0): 120-127. DOI:http://dx.doi.org/10.1016/j.agrformet.2014.11.008

Čermák, J., Prax, A., 2001. Water balance of a Southern Moravian floodplain forest under natural and modified soil water regimes and its ecological consequences. Ann. For. Sci., 58(1): 15-29.

Chang, J., Wang, Q., Wu, X., Cui, L., Liu, S., 2013. Water balance of different age *Pinus tabulaeformis* forests in Taihang Mountain, Shanxi. Scientia Silvae Sinicae, 49(07): 1-9.

Chang, X. et al., 2014a. Qinghai spruce (*Picea crassifolia*) forest transpiration and canopy conductance in the upper Heihe River Basin of arid northwestern China. Agricultural and

Forest Meteorology, 198–199(0): 209-220. DOI:http://dx.doi.org/10.1016/j.agrformet.2014.08.015

Chang, X.X. et al., 2014b. Qinghai spruce (Picea crassifolia) forest transpiration and canopy conductance in the upper Heihe River Basin of arid northwestern China. Agricultural and Forest Meteorology, 198: 209-220. DOI:DOI 10.1016/j.agrformet.2014.08.015

Chen, D., Wang, Y., Liu, S., Wei, X., Wang, X., 2014a. Response of relative sap flow to meteorological factors under different soil moisture conditions in rainfed jujube (Ziziphus jujuba Mill.) plantations in semiarid Northwest China. Agricultural Water Management, 136(0): 23-33. DOI:http://dx.doi.org/10.1016/j.agwat.2014.01.001

Chen, H.S., Shao, M.G., Li, Y.Y., 2008. Soil desiccation in the Loess Plateau of China. Geoderma, 143(1-2): 91-100. DOI:DOI 10.1016/j.geoderma.2007.10.013

Chen, L., Wang, J., Wei, W., Fu, B., Wu, D., 2010. Effects of landscape restoration on soil water storage and water use in the Loess Plateau Region, China. Forest Ecology and Management, 259(7): 1291-1298. DOI:http://dx.doi.org/10.1016/j.foreco.2009.10.025

Chen, L. et al., 2014b. Response of transpiration to rain pulses for two tree species in a semiarid plantation. Int J Biometeorol, 58(7): 1569-1581. DOI:10.1007/s00484-013-0761-9

Chen, L.X. et al., 2014c. Soil water affects transpiration response to rainfall and vapor pressure deficit in poplar plantation. New Forest, 45(2): 235-250. DOI:DOI 10.1007/s11056-014-9405-0

Chirino, E., Bellot, J., Sanchez, J.R., 2011. Daily sap flow rate as an indicator of drought avoidance mechanisms in five Mediterranean perennial species in semi-arid southeastern Spain. Trees-Structure and Function, 25(4): 593-606. DOI:10.1007/s00468-010-0536-4

Courtwright, J., Findlay, S.G., 2011. Effects of Microtopography on Hydrology, Physicochemistry, and Vegetation in a Tidal Swamp of the Hudson River. Wetlands, 31(2): 239-249. DOI:10.1007/s13157-011-0156-9

Cui, J., 2012. The studies on the relationship of trees water physiology characteristics and soil water in Semi-arid Region on Loess Plateaus. Doctor Thesis Thesis, Beijing Forestry University.

Du, S. et al., 2011. Sapflow characteristics and climatic responses in three forest species in the semiarid Loess Plateau region of China. Agricultural and Forest Meteorology, 151(1): 1-10.

Dumbrovsky, M., Sobotkova, V., Sarapatka, B., Chlubna, L., Vachalova, R., 2014. Cost-effectiveness evaluation of model design variants of broad-base terrace in soil erosion control. Ecol Eng, 68: 260-269. DOI:DOI 10.1016/j.ecoleng.2014.03.082

Engdawork, A., Bork, H.R., 2014. Long-Term Indigenous Soil Conservation Technology in the Chencha Area, Southern Ethiopia: Origin, Characteristics, and Sustainability. Ambio, 43(7): 932-942. DOI:DOI 10.1007/s13280-014-0527-6

FAO, 1990. FAO-UNESCO Soil map of the world: Revised legend, world soil resources report 60. Food and Agriculture Organization of the United Nations, Rome.

Granier, A., 1985. Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Ann. For. Sci., 42(2): 193-200.

Heilmeier, H. et al., 2002. Soil drought increases leaf and whole-plant water use of Prunus dulcis grown in the Negev Desert. Oecologia, 130(3): 329-336. DOI:10.1007/s004420100808

Huo, Y., Zhu, B., 2013. Analysis on the Benefits of Level Terrace on Soil and Water Conservation in Loess Hilly Areas. Research of Soil and Water Conservation, 20(5): 24-28.

Igarashi, Y. et al., 2015. Environmental control of canopy stomatal conductance in a tropical deciduous forest in northern Thailand. Agricultural and Forest Meteorology, 202(0): 1-10. DOI:http://dx.doi.org/10.1016/j.agrformet.2014.11.013

Jian, S., Zhao, C., Fang, S., Yu, K., 2015. Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau. Agricultural and Forest Meteorology, 206(0): 85-96. DOI:http://dx.doi.org/10.1016/j.agrformet.2015.03.009

Kim, H.S., Oren, R., Hinckley, T.M., 2008. Actual and potential transpiration and carbon assimilation in an irrigated poplar plantation. Tree Physiology, 28(4): 559-77.

Kumagai, T.o. et al., 2014. Estimation of annual forest evapotranspiration from a coniferous plantation watershed in Japan (1): Water use components in Japanese cedar stands. J Hydrol, 508(0): 66-76. DOI:http://dx.doi.org/10.1016/j.jhydrol.2013.10.047

LaFevor, M.C., 2014. Restoration of degraded agricultural terraces: Rebuilding landscape structure and process. J Environ Manage, 138: 32-42. DOI:DOI 10.1016/j.jenvman.2013.11.019

Li, H., Wei, W., Chen, L., Guo, E., Huang, Y., 2013. Progress in the study of soil water balance under forest and grassland covers on the Loess Plateau. Research of Soil & Water Conservation, 20(01): 287-293.

Li, J., Zhang, W.J., Zhang, J.P., 2012. Comparative Analysis of water reduction benefits between terrace and slope land in southern area of Ningxia: Taking Haoshuichuan Watershed as an example. Advances in Hydrology and Hydraulic Engineering, Pts 1 and 2, 212-213: 83-87. DOI:DOI 10.4028/www.scientific.net/AMM.212-213.83

Li, M., Wang, K., Chen, Z., Kang, L., 2011. Storage of Water and Sediment Reduction Benefits of Reverse-slope Terrace under the Different Slopes. Research of Soil and Water Conservation, 18(6): 100-104.

Li, X.H., Yang, J., Zhao, C.Y., Wang, B., 2014a. Runoff and Sediment from Orchard Terraces in Southeastern China. Land Degrad Dev, 25(2): 184-192. DOI:Doi 10.1002/Ldr.1160

Li, Y.Z. et al., 2014b. Physiological mechanism for the reduction in soil water in poplar (Populus deltoides) plantations in Dongting Lake wetlands. Wetl Ecol Manag, 22(1): 25-33. DOI:DOI 10.1007/s11273-013-9319-1

Limousin, J.M. et al., 2009. Long-term transpiration change with rainfall decline in a Mediterranean Quercus ilex forest. Global Change Biol, 15(9): 2163-2175. DOI:DOI 10.1111/j.1365-2486.2009.01852.x

Liu, S.L. et al., 2013. Effects of different terrace protection measures in a sloping land consolidation project targeting soil erosion at the slope scale. Ecol Eng, 53(0): 46-53. DOI:http://dx.doi.org/10.1016/j.ecoleng.2012.12.001

Luis, V.C., Jiménez, M.S., Morales, D., Kucera, J., Wieser, G., 2005. Canopy transpiration of a Canary Islands pine forest. Agricultural and Forest Meteorology, 135(1–4): 117-123. DOI:http://dx.doi.org/10.1016/j.agrformet.2005.11.009

Miyazawa, Y. et al., 2014. Tropical tree water use under seasonal waterlogging and drought in central Cambodia. J Hydrol, 515: 81-89. DOI:DOI 10.1016/j.jhydrol.2014.04.049

Molina, A.J., Latron, J., Rubio, C.M., Gallart, F., Llorens, P., 2014. Spatio-temporal variability of soil water content on the local scale in a Mediterranean mountain area (Vallcebre, North Eastern Spain). How different spatio-temporal scales reflect mean soil water content. J Hydrol, 516: 182-192. DOI:DOI 10.1016/j.jhydrol.2014.01.040

Nie, L., Li, J., Zhai, H., 2005. Study of the rate of stem sap flow in *Pinus tabulaeformis* and *Quercus variabilis* by using the TDP method. Acta Ecologica Sinica, 25(08): 1934-1940.

Pataki, D.E., Oren, R., Smith, W.K., 2000. Sap flux of co-occurring species in a western subalpine forest during seasonal soil drought. Ecology, 81(9): 2557-2566. DOI:10.1890/0012-9658(2000)081[2557:SFOCOS]2.0.CO;2

Shen, Q., Gao, G., Fu, B., Lü, Y., 2015. Responses of shelterbelt stand transpiration to drought and groundwater variations in an arid inland river basin of Northwest China. J Hydrol, 531: 738-748. DOI:http://dx.doi.org/10.1016/j.jhydrol.2015.10.053

Stavi, I., Fizik, E., Argaman, E., 2015. Contour bench terrace (shich/shikim) forestry systems in the semi-arid Israeli Negev: Effects on soil quality, geodiversity, and herbaceous vegetation. Geomorphology, 231: 376-382. DOI:10.1016/j.geomorph.2014.12.028

Vergeynst, L.L., Dierick, M., Bogaerts, J.A.N., Cnudde, V., Steppe, K., 2015. Cavitation: a blessing in disguise? New method to establish vulnerability curves and assess hydraulic capacitance of woody tissues. Tree Physiology, 35(4): 400-409. DOI:10.1093/treephys/tpu056

Wang, B., Wen, F., Wu, J., Wang, X., Hu, Y., 2014a. Vertical Profiles of Soil Water Content as Influenced by Environmental Factors in a Small Catchment on the Hilly-Gully Loess Plateau. Plos One, 9(10): e109546-e109546. DOI:10.1371/journal.pone.0109546

Wang, H.L., Guan, H.D., Deng, Z.J., Simmons, C.T., 2014b. Optimization of canopy conductance models from concurrent measurements of sap flow and stem water potential on Drooping Sheoak in South Australia. Water Resources Research, 50(7): 6154-6167. DOI:Doi 10.1002/2013wr014818

Wang, L. et al., 2012. Dryland ecohydrology and climate change: Critical issues and technical advances. Hydrology & Earth System Sciences, 16(8): 2585-2603.

Wang, L., Good, S.P., Caylor, K.K., 2014c. Global synthesis of vegetation control on evapotranspiration partitioning. Geophysical Research Letters, 41(19): 6753–6757.

Wang, Y., Shao, M.a., Shao, H., 2010. A preliminary investigation of the dynamic characteristics of dried soil layers on the Loess Plateau of China. J Hydrol, 381(1–2): 9-17. DOI:http://dx.doi.org/10.1016/j.jhydrol.2009.09.042

Wang, Y.Q. et al., 2015. Choosing an optimal land-use pattern for restoring eco-environments in a semiarid region of the Chinese Loess Plateau. Ecol Eng, 74: 213-222. DOI:DOI 10.1016/j.ecoleng.2014.10.001

Wei, W., Chen, L., Zhang, H., Chen, J., 2015. Effect of rainfall variation and landscape change on runoff and sediment yield from a loess hilly catchment in China. Environmental Earth Sciences, 73(3): 1005-1016. DOI:10.1007/s12665-014-3451-y

Yang, D. et al., 2009. Impact of vegetation coverage on regional water balance in the nonhumid regions of China. Water Resources Research, 45(7): 450-455. DOI:10.1029/2008wr006948

Yang, F., Chen, L., Zhu, Q., Bi, H., 2008. Analysis of water consumption of main afforestation species in western Shanxi of Loess Plateau. Research of Soil and Water Conservation, 15(01): 41-45.

Yang, L., Wei, W., Chen, L.D., Chen, W.L., Wang, J.L., 2014. Response of temporal variation of soil moisture to vegetation restoration in semi-arid Loess Plateau, China. Catena, 115(0): 123-133. DOI:DOI 10.1016/j.catena.2013.12.005

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. J Hydrol, 475(0): 111-122. DOI:DOI 10.1016/j.jhydrol.2012.09.041

Yuan, Z.-Q. et al., 2016. Effects of legume species introduction on vegetation and soil nutrient development on abandoned croplands in a semi-arid environment on the Loess Plateau, China. Sci Total Environ, 541: 692-700. DOI:10.1016/j.scitotenv.2015.09.108

Zhang, H. et al., 2015. Analysis of Sap Flow Characteristics of the Chinese Pine in Typical Loess Plateau Region of China. Environmental Science, 36(1): 349-356.

Zhang, X., Zhang, L., Zhao, J., Rustomji, P., Hairsine, P., 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. Water Resources Research, 44(7): 2183-2188. DOI:10.1029/2007wr006711

Zhang, Y., Cao, N., Wu, M., Wu, F., 2005. Analysis on soil moisture character of level terrace on the south Loess Plateau. Chinese Agricultural Science Bulletin, 21(08): 215-220.

Tables

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

	Parameter	Type	
		Slope	Terrace
Geographical parameters	Plot area (m^2)	100	100
	Slope gradient	20°	20°
	Slope aspect	N	N
	Slope position	Middle	Middle
Soil parameters	Clay (<0.002 mm; %)	6.47 ± 0.28	6.76 ± 0.56
	Silt (0.05-0.002 mm; %)	75.29 ± 0.83	76.26 ± 0.80
	Sand (0.05-2 mm; %)	18.24 ± 0.99	16.97 ± 0.70
	Soil bulk density ($g \cdot cm^{-3}$)	1.33 ± 0.11	1.36 ± 0.15
Biological parameters	Dominant plant	Chinese pine	Chinese pine
	Sample number	6	6
	Total number	14	21
	Canopy coverage	82.9%	82.1%
	DBH (cm)	12.90^a ± 3.66	14.45^a ± 2.40
	Height (m)	6.84^a ± 1.01	6.94^a ± 0.50
	Sapwood area (A_s,cm^2)	99.09^a ± 44.87	117.74^a ± 33.16
	Crown projected area (A_c, m^2)	9.55^a ± 3.56	15.61^b ± 5.11

Note: slope aspect and slope position were determined 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.

Figure Legends


Slope site

Terrace site

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

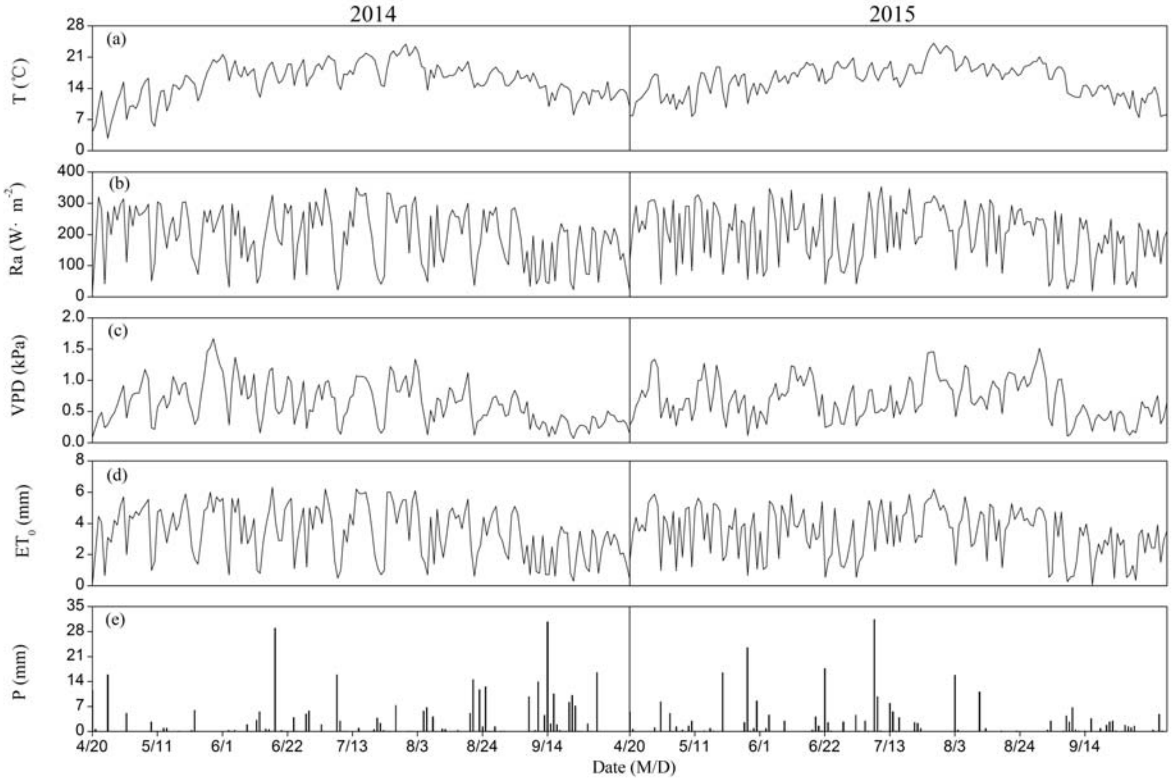

Fig. 2. Temporal variations of air temperature (T), solar radiation (R_a), vapor pressure deficit (VPD), reference evapotranspiration (ET_0) and precipitation (P) over two consecutive growing seasons (2014-2015).

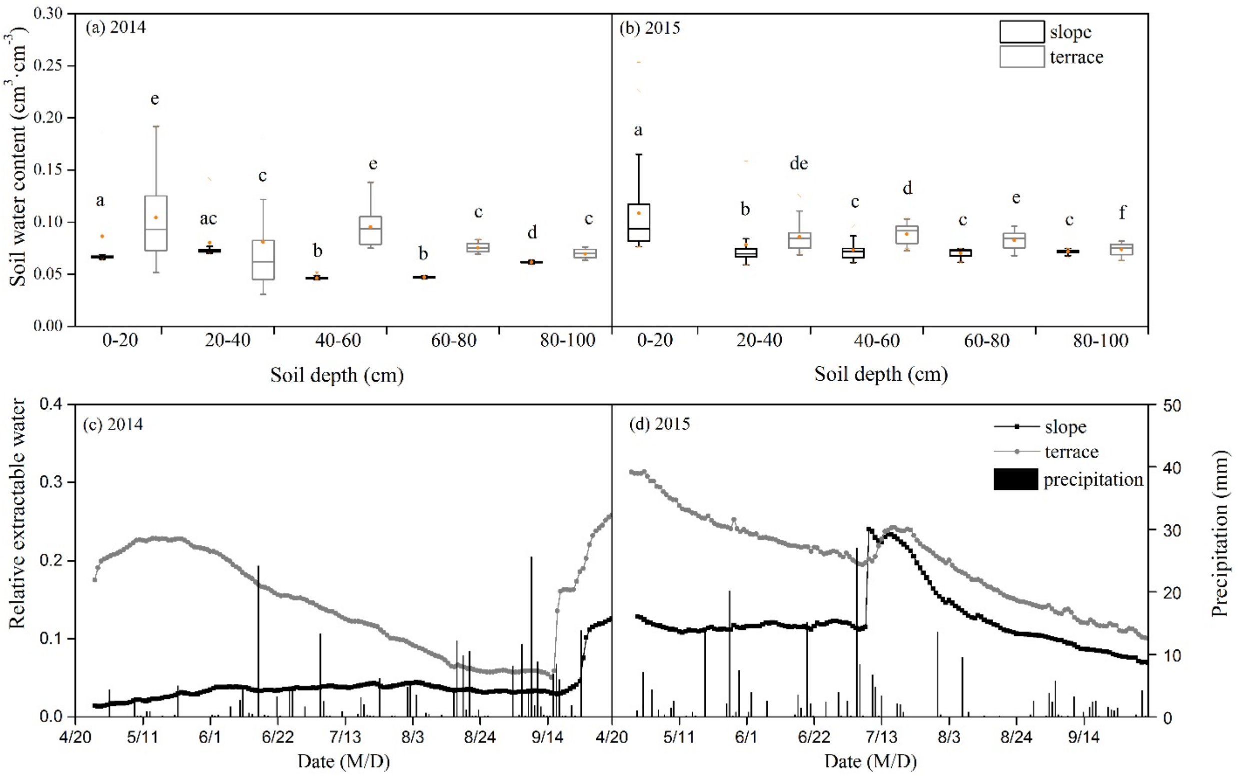

Fig. 3. Soil water content of different layers (a and b) and relative extractable water in the 20–100 cm layer (c and d) between the slope and terrace sites during two consecutive growing seasons (2014–2015). Means without common letters are significantly different at $p < 0.05$ according to *t*-test.

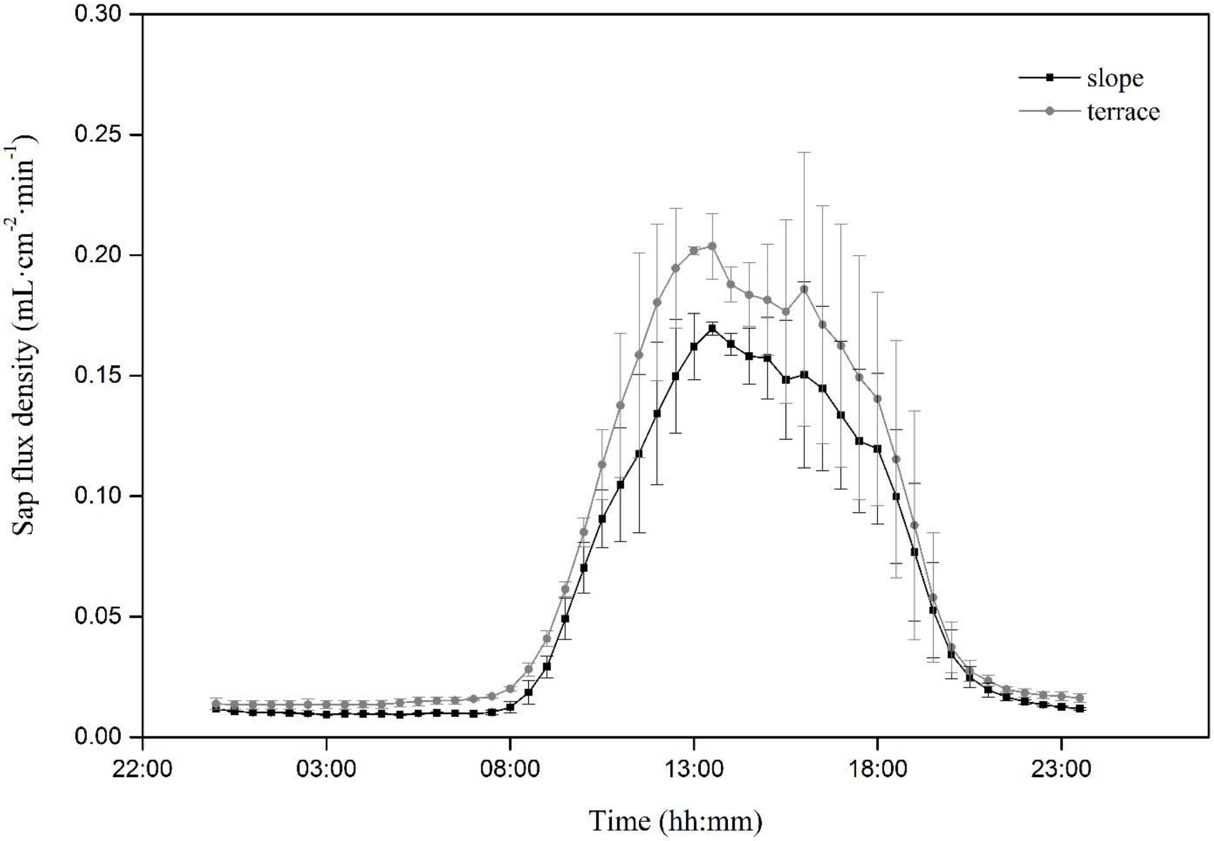

Fig. 4. Diurnal time courses of sap flux density at the slope and terrace sites. Data represent means ± standard deviation (n = 3).

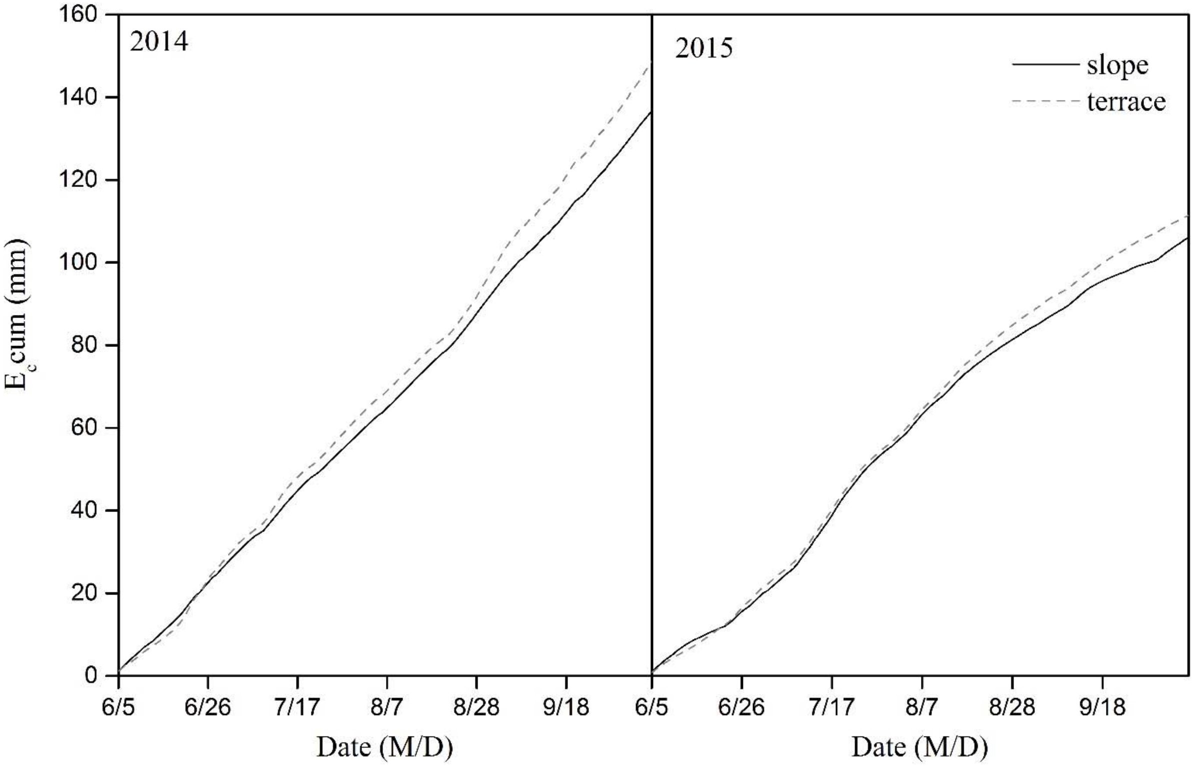

Fig. 5. Variation of accumulated canopy transpiration (E_c cum) during two consecutive growing seasons (2014–2015).

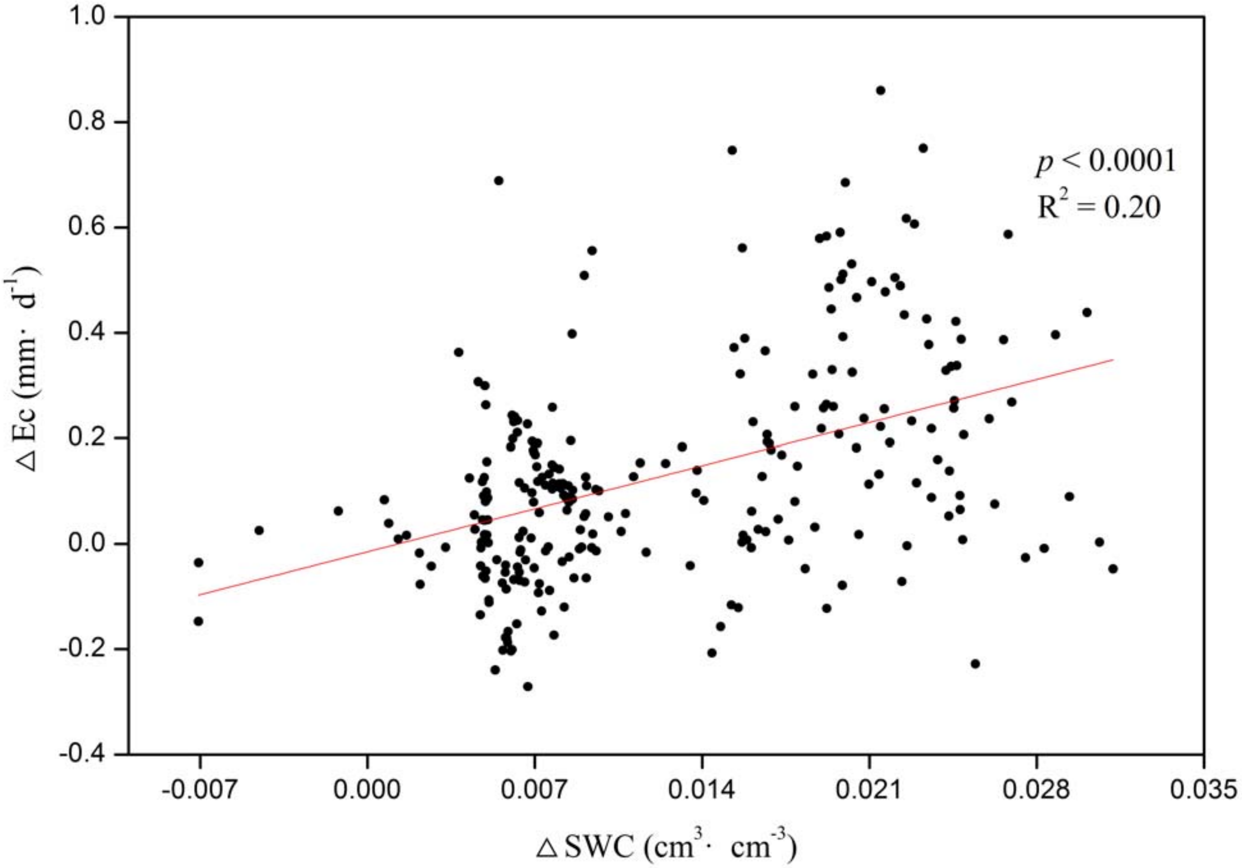

Fig. 6. Correlation of ΔE_c ($E_{c\ terrace} - E_{c\ slope}$) in response to ΔSWC ($SWC_{terrace} - SWC_{slope}$) within 100 cm during two consecutive growing seasons (2014–2015). Data of the slope site are the baselines subtracted by those of the terrace site to assess the relationship between E_c variation and SWC variation.

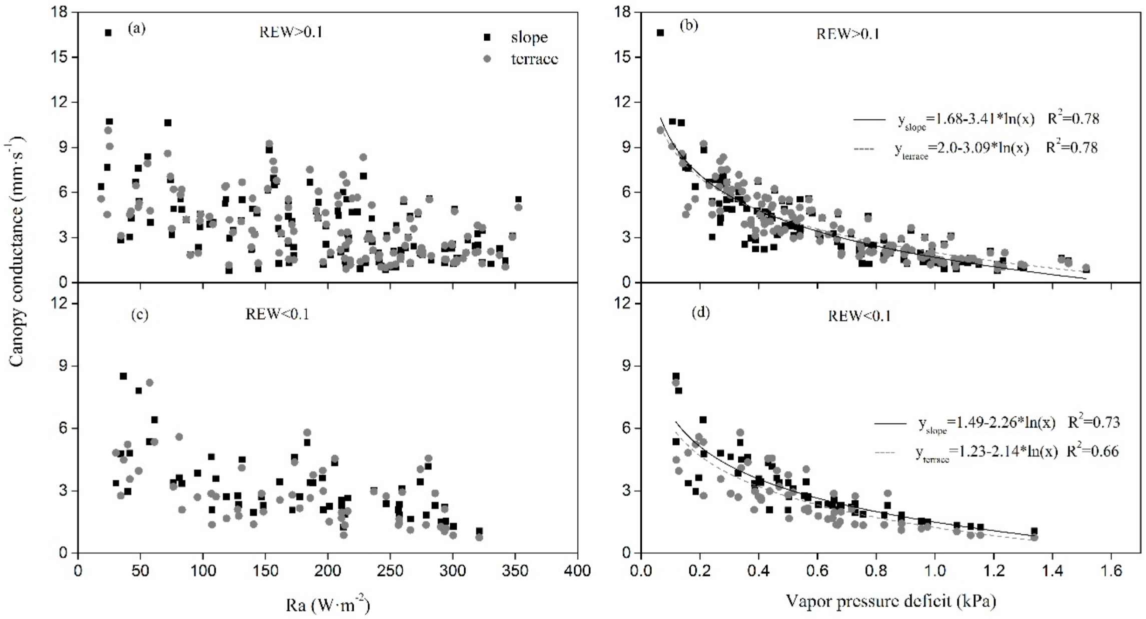

Fig. 7. Relationships between canopy conductance and solar radiation (a and c) versus relationships between canopy conductance and vapor pressure deficit (b and d) under relatively wet (REW > 0.1) and dry (REW < 0.1) soil conditions.

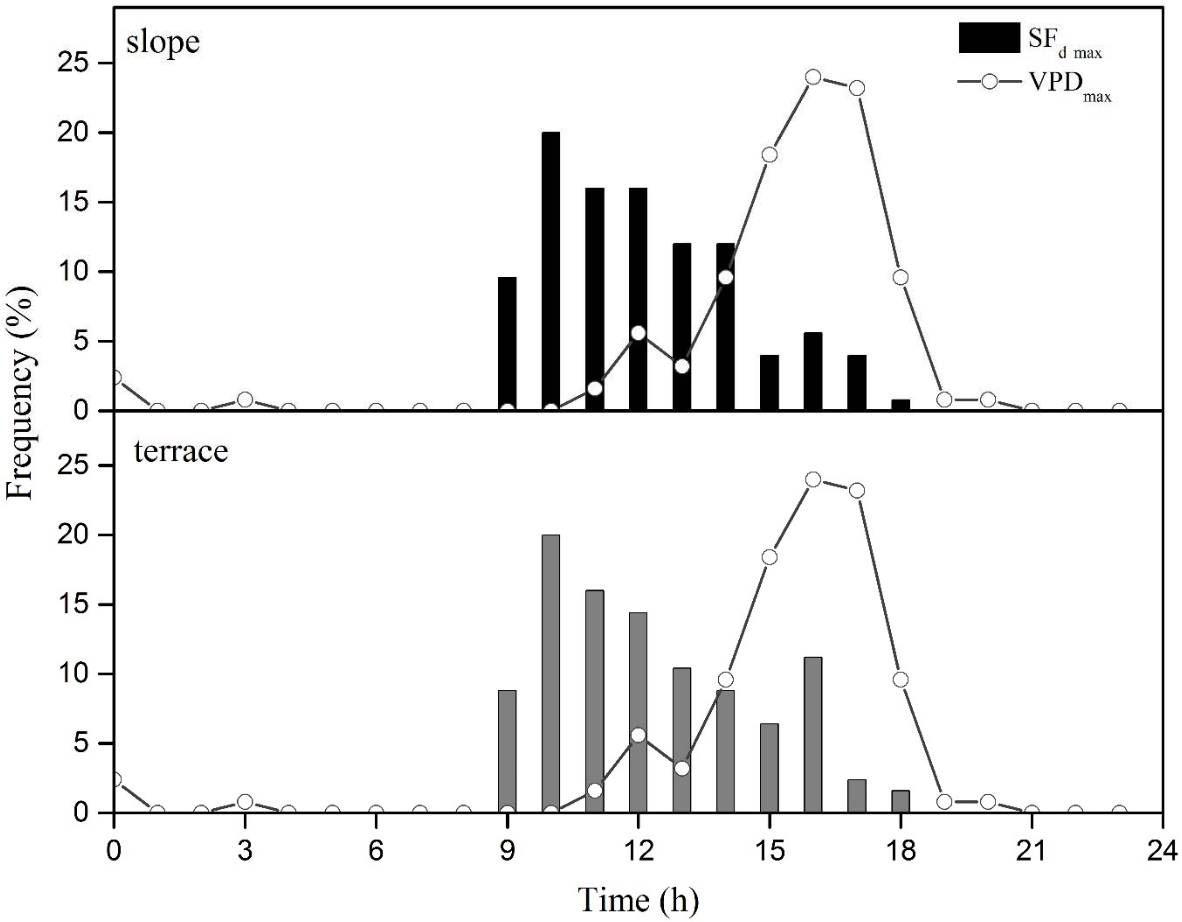

Fig. 8. Frequency distribution of the maximum sap flux density ($SF_{d,\ max}$) and maximum VPD (VPD_{max}) in the form of diurnal patterns. Data sets cover the growing seasons in 2014 and 2015.