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REGULAR ARTICLE

Discrepancy of sap flow in *Salix matsudana* grown under different soil textures in the water-wind erosion crisscross region on the Loess Plateau

Xiaoping Peng · Jun Fan · Quanjiu Wang · David Warrington

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Abstract
Aims An accurate understanding about the variation of sap flow and the interaction mechanisms of sap flow with environmental factors is essential when carrying out vegetation restoration projects in areas where rainfall is limited.
Methods A thermal dissipation probe (TDP) measured sap flow of *Salix matsudana*, growing in typical sandy and loess soils in the same semi-arid watershed on the Loess Plateau, China in 2012 and 2013 from May to October.
Results Similar sap flow diurnal variation patterns occurred for both soils but, based on the sap flow, the calculated total transpiration of *S. matsudana* growing in the loess soil was about five times greater than that growing in the sandy soil due to differences in the sapwood cross-sectional area. Soil texture affected both the vertical distribution of *S. matsudana* fine roots and the soil water cycle, which led to the *S. matsudana* growing in the sandy soil being subjected more frequently to drought stress that stunted its growth. In contrast, *S. matsudana* grew well in the loess soil.
Conclusions Soil texture was the key factor responsible for the discrepancy in the total sap flow of *S. matsudana* in the study region due to its effect on soil water content. Therefore, if afforestation is planned for this or similar regions, soil texture should be taken into account.

Keywords Grain-for-Green · Water deficit · Vegetation restoration · Soil water content · Thermal dissipation probe

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X. Peng · J. Fan (✉) · Q. Wang · D. Warrington
State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University,
No.26, Xinong Road, Yangling City, Shaanxi Province 712100, People's Republic of China
e-mail: fanjun@ms.iswc.ac.cn

X. Peng
e-mail: pengxiaoping354@163.com

Introduction

Plants are able to grow in a wide range of soil textures, ranging from coarse sands to heavy clays. A large number of studies, carried out in a wide variety of seasonally dry regions, have reported that soil texture is an important factor influencing patterns of vegetation structure through soil water availability (e.g., Dodd and Lauenroth 1997; Hultine et al. 2006; Sperry and Hacke 2002). At the same time, water balance components are distinctly affected by vegetation types (Yang et al. 2009).

The Loess Plateau of China is a region that has some of the most fragile ecosystems in the world, and is characterized by a semiarid monsoon climate, severe soil erosion, dense gully occurrence and sparse vegetation. In order to decrease soil erosion and restore the degraded ecosystems of the region, many effective measurements have been implemented by the Chinese government since the 1950s (Fu et al. 2002). For example, the "Grain-for-Green" project has been implemented since 1998 with the main objectives of preventing further deterioration of the natural ecosystems and of restoring vegetation cover.

Re-vegetation can increase the vegetation cover (Xin et al. 2008) and, by 2009, under the "Grain-for-Green" project, 5.33 M ha of marginal agricultural land had been converted to forest (Li 2004) resulting in the recovery of soil physical properties (Vallauri et al. 2002) and improvements in soil nutrient levels (Zhou et al. 2008). Nevertheless, it had become apparent that water supply was a limitation for tree growth in the semiarid regions of northeastern China. Soil water content controlled the establishment of plant communities but, in turn, the plants influenced soil water recharge and usage (Legates et al. 2011). Unsuitable reforestation has often resulted in soil water deficits owing to the high water consumption of the planted trees and, consequently, has led to early degradation of the tree plantations. Hence, the phenomenon of "small aged trees", having stunted growth and a withered appearance, has become more commonly observed on the Loess Plateau, especially on the steeper slopes (Chen et al. 2008; Fan et al. 2010; Hou et al. 1999).

Forest is not actually the dominant land cover among the natural ecosystems on the Plateau (Peng and Coster 2007), but planting trees is still an important measure used for arresting soil erosion and for improving environmental conditions. Considering the requirement for ecosystem sustainability, there currently exists an urgent need to encourage appropriate reforestation practices. The water use strategies of an afforestation species need to be quantitatively investigated under different growth conditions, which include climatic conditions, water supply levels and soil conditions, in order to determine whether the species is suitable for stable forest ecosystem development within a given area. The size of the area under consideration would vary depending on its location and might even be just a small plaque in a watershed that has complex topography and soil distributions.

Plant water use has been measured using several traditional methods, for example, by weighing (Reicosky et al. 1983), whole-tree photometer (Ladefoged 1960), ventilated climate chamber (Greenwood and Beresford 1979), isotope tracing methods and sap flow (Williams et al. 2004). Daily cumulative sap flow in sampled trees is practically equal to the total transpiration for time periods of 1 day or longer (Cermak et al. 1995). Hence, Huber (1932) proposed the thermal method based on sap flow, and Granier subsequently proposed the use of thermal dissipation probe (TDP) methods (Granier 1985, 1987), for estimating total transpiration. Although sap flux density may be underestimated by the TDP method (Steppe et al. 2010), it is nevertheless currently widely used in studies of tree water use (Du et al. 2011; Granier et al. 1996; Licata et al. 2008; O'Brien et al. 2004). Compared with other methods, the TDP method has the advantage of the simplicity of the instrumentation and the relatively low costs.

In this study, the sap flow of Chinese Willow (*Salix matsudana*), which naturally grows in sandy and loessial soils on the Loess Plateau, was measured by the TDP method in the water-wind erosion crisscross region of the Plateau. This is an area where severe soil erosion can occur due, alternately, to rainfall during the wet season and to wind during the dry season. These processes have resulted in complex soil distributions where either loessial soils or sandy soils, resulting from the wind-shifted sands, occur. In the study area, which was representative of the region, *S. matsudana* and poplar (*Populus simonii*) were the dominant tree species, while the understory vegetation was mainly alfalfa (*Medicago satvia*) and korshinsk peashrub (*Caragana korshinskii*). Most of the *S. matsudana* and poplar trees on the slopes exhibited the "small aged tree" phenomenon; however, there is currently a lack of studies about the water use of *S. matsudana* within this region.

The main objectives of the study were (1) to estimate the whole-tree transpiration of *S. matsudana* under different growth conditions; (2) to compare the relationships among sap flow dynamics, solar radiation (Rs), vapor pressure deficit (VPD), and soil moisture conditions; and (3) to clarify the reasons for the differences in sap flow of *S. matsudana* under different growth conditions. The results were expected to contribute not only to the understanding of the differences in water use of this afforestation species under different growth conditions, but also to provide valuable information for forest management in the region.

Materials and methods

Study site

This study was conducted on two typical soils (a sandy soil and a loess soil) in the Liudaogou watershed

(110°21′–110°23′E, 38°46′–38°51′N) located in Shenmu County, Shaanxi Province, China. This area is characterized by a large number of deep gullies and undulating loessial slopes, and by severe soil erosion due to the interaction of water and wind erosion. Liudaogou watershed is in the continental monsoon climate zone, and has an annual mean temperature of 8.4 °C. The annual precipitation is 437.4 mm, of which 70 % mostly falls in intense rainstorms between July and September. Mean annual reference crop evapotranspiration (ET_0) calculated by the Penman-Monteith equation (Allen et al. 1998) was 1200 mm, which would result in water deficits. The complex topography of the watershed, particularly the distribution of the gullies, leads to the creation of different microclimates that may affect solar radiation and VPD.

The dominant soil types of the selected area were a sandy loess soil and a sandy soil. The soils, and especially the sandy soil, had weak cohesion, high infiltrability, low water retention, and were susceptible to wind erosion. In the Liudaogou watershed, these two main soil types both occurred and, therefore, the experiments were carried out in two fields that had either the sandy soil or the loess soil. The sandy soil consisted of 9.3 % clay, 6.5 % silt, and 84.2 % sand, while the loess soil consisted of 11.7 % clay, 35.8 % silt, and 52.5 % sand. In both fields, the only water input was precipitation. There was no runoff from our study plots because the loess soil was on a flat terrace, while the sandy soil had a very high infiltration rate (1.5 mm min^{-1}) and was on a 10° slope with an eastern aspect at the mid-slope (Fig. 1). In the sandy soil field, the water outputs included transpiration, soil evaporation, canopy interception and deep percolation.

Sap flow measurement

All measurements were conducted between May and September in 2012 and 2013. In each field, four *S. matsudana* trees were selected for sap flow measurements using the thermal dissipation method. The mean heights of the selected trees growing in either the sandy soil or the loess soil were 5 and 11 m, respectively, while the mean diameters at breast height were 8 and 18 cm, and all of the trees were about 20 years old.

The thermal dissipation probe (TDP) method (Granier 1987; Granier et al. 1996) was used to measure the sap flow velocity. A pair of probes, one of which contained the heat source, constituted a TDP sensor. The probe tubes for both the temperature sensors and the heat sources were constructed from stainless-steel tubing with outer and inner diameters of 1.3 and 1.0 mm, respectively, and were 13 mm long. The heater probe was made by inserting a loop of enameled wire (diameter 0.13 mm, resistance 87 Ω m^{-1}, Nichrome 80 alloy; Pelican Wire Co., Naples, FL), which acted as the heat source, into the tubing along its entire length. A T-type thermocouple (TT-T-36-SLE, Omega Engineering, Stamford, CT), which acted as the temperature sensor, was positioned at the center of all of the probe tubes. The sensor tubes were then filled with Omega bond 101 epoxy (Omega Engineering, Stamford, CT), which has a relatively high thermal conductivity and is a good electrical insulator, to fix the thermocouple and wiring in place, and to prevent short circuits.

When inserted into the tree, the upper probe of the TDP sensor contained the heat source, which was heated by a constant DC power source. The voltage difference between the upper heated probe and the lower unheated reference probe was measured and converted to sap flux density according to the procedure of Granier (1987), which is given in the next paragraph. One TDP sensor was inserted into the north side of each of the eight studied trees, 1.5 m above the soil surface, and was surrounded by a thick thermally insulated shield to avoid solar radiation heating and to prevent exposure to rain. The vertical separation between probes was approximately 5 cm. All of the TDP sensors were connected to a CR1000 data logger with an AM16/32 multiplexer (Campbell Scientific, Logan UT, USA). A 1-min scan rate was selected, and the mean values of 30 1-min scans were recorded.

Sap flow density on a sapwood area basis was calculated based on the temperature difference between the heated and non-heated probe by an empirical equation (Granier 1987):

$$F_s = A_s \times 0.0119 \left(\frac{\Delta T_{\max} - \Delta T}{\Delta T} \right)^{1.231} \times 3600$$

where Fs is the sap flow (L h^{-1}), and As is the cross-sectional area of sap conducting wood (cm^2), which we term the sapwood area in this paper, ΔT is the temperature difference between the two probes, and ΔT_{max} is the temperature difference at zero flow. Zero flow measurements were automatically conducted every 6 days between the hours of 02:00 and 05:00 because the sap

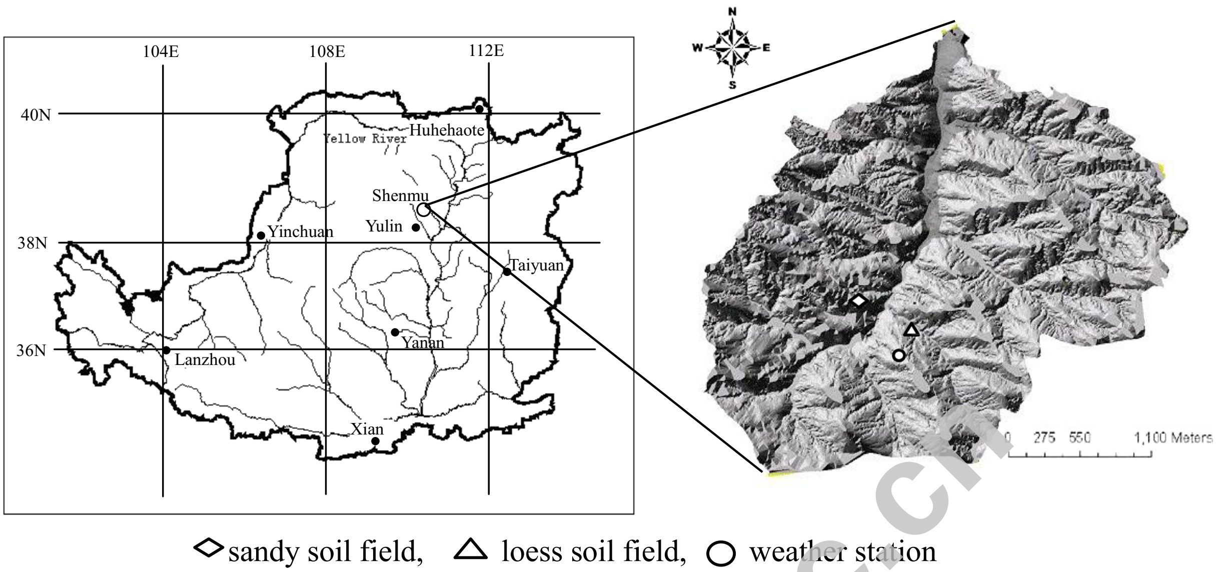

Fig. 1 Locations of the study plots in the Liudaogou watershed on the Loess Plateau

flow velocity can reasonably be considered to be zero or minimal during this period (Dawson et al. 2007).

Sapwood area extrapolation

The sapwood area (*As*) was a critical factor when calculating the daily cumulative sap flow. However, in order to avoid injuring the sampled trees, the sapwood area was determined by cutting other neighboring trees and discriminating between the sapwood and the heartwood based on color differences. The sapwood area was then linearly related to the tree diameter at breast height (Fig. 2), thereby allowing the sapwood area of the sampled trees to be calculated from their diameters at breast height (Chang et al. 2006).

Root measurement

At both study sites, we sampled the roots within soil that was removed either by excavating soil from the sides of 1-m deep soil profile pits or by coring. The sample locations were situated underneath each of the studied tree canopies as well as between their canopies and those of neighboring trees. Roots from only one soil profile were measured in each field due to practical limitations, i.e., the task required a great deal of time and labor, which were limited. From each 1-m soil profile, ten disturbed soil samples were removed as entire blocks (10 cm deep; 40×40 cm in area), which were taken at 10-cm depth intervals. Undisturbed soil cores (10-cm in diameter) were then collected from each 20-cm depth interval between depths of 100 and 300 cm using an auger. The soil and roots were separated by washing over a 1-mm mesh and the roots were then dried at 70 °C to constant mass. Fine roots (<2 mm in diameter) were processed using WinRHIZO (Regents Instruments Inc. Quebec, Canada) to obtain the total fine root surface area, which was then used to calculate the cumulative root fraction with depth, which gives a

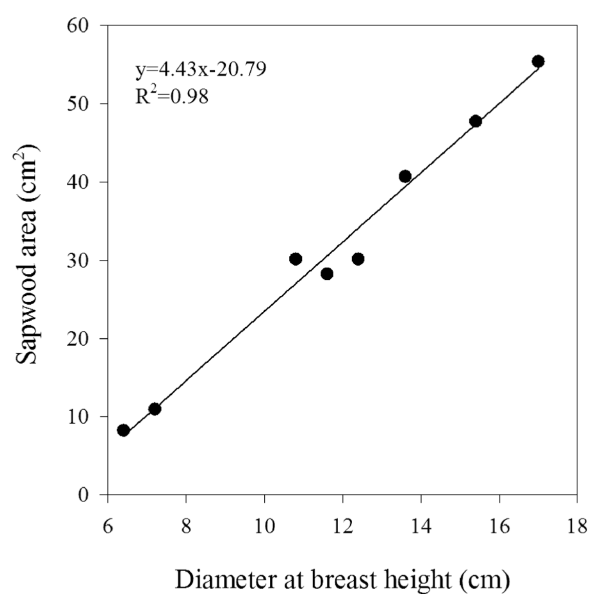

Fig. 2 The relationship between sapwood area and diameter at breast height of *Salix matsudana* trees

description of the vertical root distribution (Gale and Grigal 1987).

Environmental factors

Environmental factors in our study consisted of the meteorological factors and the soil water contents. The meteorological factors considered were the solar radiation (Rs), the vapor pressure deficit (VPD), the air temperature (T), the relative humidity (RH) and the wind velocity (Ws). All the meteorological data was provided by a weather station. The sandy soil field was 500 m away from the weather station and at the same elevation (1260 m). The loess soil field was 250 m away from the weather station at an elevation of 1150 m, and the air temperature and relative humidity were independently monitored at this site in addition to the data provided by the weather station (Fig. 1). Soil volumetric water contents (VWC) were measured by 10 electrical conductivity (EC-5) sensors that were installed around the sampled trees at depths of 10, 20, 50, 100 and 200 cm; all the EC-5 sensors were connected to an EM50 (Decogan, PM, USA) data logger. In addition, the soil water content of the sandy soil was measured to a depth of 6 m by a calibrated neutron probe at monthly intervals.

Data analysis

The mean value of the sap flows of the eight sampled trees was taken as the transpiration rate of *S. matsudana* in this agroforestry system. The relationships between sap flow and environmental factors (solar radiation, vapor pressure deficit, air temperature, relative humidity, and wind speed and soil moisture) were analyzed by regression using the mean daily values. Significant differences between the slopes and intercepts of the relationships for the two soils were tested using the method of Warton et al. (2006). Statistical differences were generally tested at the $p<0.05$ level.

Results

Diurnal and seasonal variation in stand mean sap flow

The sap flow velocity of *S. matsudana*, growing under different soil textural conditions, exhibited pronounced diurnal variations (Fig. 3). Sap flow commenced at about 07:00, after sunrise, and increased to the highest rates at about 10:00 in 2012 and 2013, respectively, before decreasing gradually to almost "zero" at midnight. The diurnal variation exhibited either a double-peaked or a broad-peaked curve. In 2012, the maximum sap flow velocity of *S. matsudana* trees growing in the sandy soil was slightly higher than that of those growing in the loess soil on a sunny day. This phenomenon was more obvious in 2013.

The seasonal dynamics of sap flow may be related to the trends of the solar radiation and precipitation (Fig. 4). In 2012, the monthly total sap flow volume of *S. matsudana* trees followed the same trend for both the sandy soil and the loess soil: August > May > June > July > September (Fig. 4a). However, the trends were different in 2013 where, for the sap flow of trees growing in the sandy soil, it was August > May = June > July > September > October, while for that of trees growing in the loess soil, it was June > May > July > August > September > October (Fig. 4b). Generally, the sap flow in 2013 was higher than in 2012 because there was more rainfall in 2013 (639.7 mm) than in 2012 (475.9) during the rainy season (May to October). Figure 4c and d shows that sap flow decreased when solar radiation decreased and when precipitation increased. There was an exception to this pattern in August 2012, when large rainfall events occurred several times and followed the relatively high rainfall of 176 mm in July. Hence, the availability of soil water that could be utilized for sap flow in August 2012 was greater than in other months. Soil water content data and soil water availability will be discussed in detail later in this paper.

The seasonal trend of sap flow in *S. matsudana* growing in sandy soil was consistent with that for trees growing in the loess soil in 2012, and, even when the trends were different, as in 2013, the sap flow was higher in the trees growing in the loess soil. However, there was a significant difference in the magnitude of the sap flow ($p<0.01$). Monthly sap flow data for trees growing in the sandy soil and the loess soil during the growing season of 2012 and 2013 are given in Table 1. In 2012 and 2013, the total sap flow of *S. matsudana* growing in the sandy soil was 660 and 1042 L, respectively while for those growing in the loess soil it was 3163 and 4701 L. Thus, the total sap flow of the trees growing in the loess soil was 4.8 times greater than for those growing in the sandy soil in 2012, while in 2013 it was 4.5 times greater (Table 1).

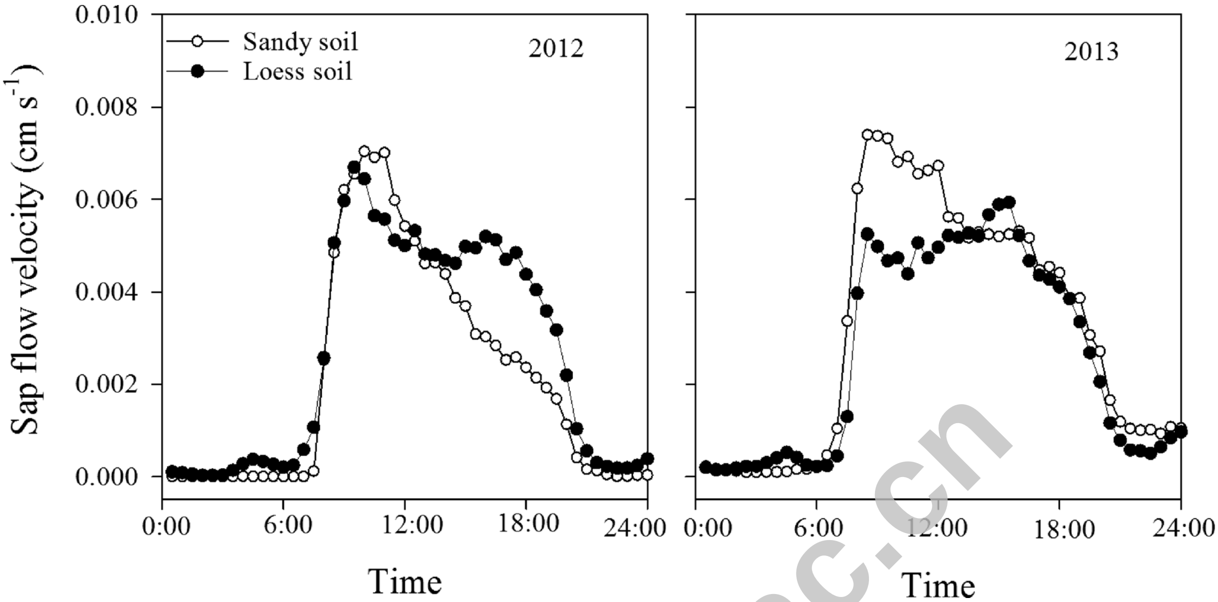

Fig. 3 Diurnal sap flow velocity in *Salix matsudana* trees growing in different soils on a sunny day in May, with similar values of solar radiation, in 2012 and 2013

Sap flow response to meteorological factors

Sap flow was greatly affected by meteorological factors such as solar radiation (Rs), air temperature (T), relative humidity (RH) and wind velocity (Ws). Vapor pressure deficit (VPD) was adopted to comprehensively reflect the synergistic effect of air temperature and relative humidity. In order to examine the effects of the meteorological factors on sap flow, we chose a sunny day during each month of the two growing seasons: 14 May, 11 June, 13 July, 9 August, and 15 September in 2012, and 12 May, 13 June, 21 July, 10 August, and 27 September in 2013. Figure 5 shows the diurnal variation of hourly total sap flow, Rs, VPD, T, RH and Ws on the selected days. The diurnal variation of sap flow was closely related to changes in Rs, VPD, T, RH and Ws. Peak sap flow and solar radiation times corresponded very closely to each other (Fig. 5a, b). However, the peaks of T, RH and Ws did not overlap those of sap flow but rather lagged slightly behind them (Fig. 5c, d, e, f).

The relationships between daily sap flow and Rs or VPD in the two study years are shown in Fig. 6, in which the daily sap flow increased with increases in Rs and VPD. There were statistically significant linear correlations between sap flow and both Rs and VPD. Furthermore, the slopes and intercepts of the linear relationship between sap flow and Rs or VPD were significantly different ($p<0.001$) for the two sites according to the statistical test of Warton et al. (2006). This indicated that, even under the same solar radiation intensity (or the same VPD level), sap flow was higher in the trees growing in the loess soil than in the sandy soil. In addition, for the same increase in solar radiation (or VPD), sap flow responded more intensely when the trees were growing in the loess soil than in the sandy soil.

Sap flow was also linearly correlated with T, RH and Ws; the correlation coefficients of all of the linear relationships and their statistical significance are given in Table 2. Moreover, ET_0, which comprehensively reflects the synergistic effect of the meteorological factors, had the closest relationship with *S. matsudana* sap flow (Table 2).

There were no statistically significant differences between the meteorological factors at the sandy or loess soil sites in the same watershed. In Fig. 5c, d, e, and f, it can be seen that the diurnal variation curves for air temperature and VPD were almost coincident for the two sites. Therefore, we can infer that meteorological factors were not the key reason for the differences observed between the *S. matsudana* sap flows of

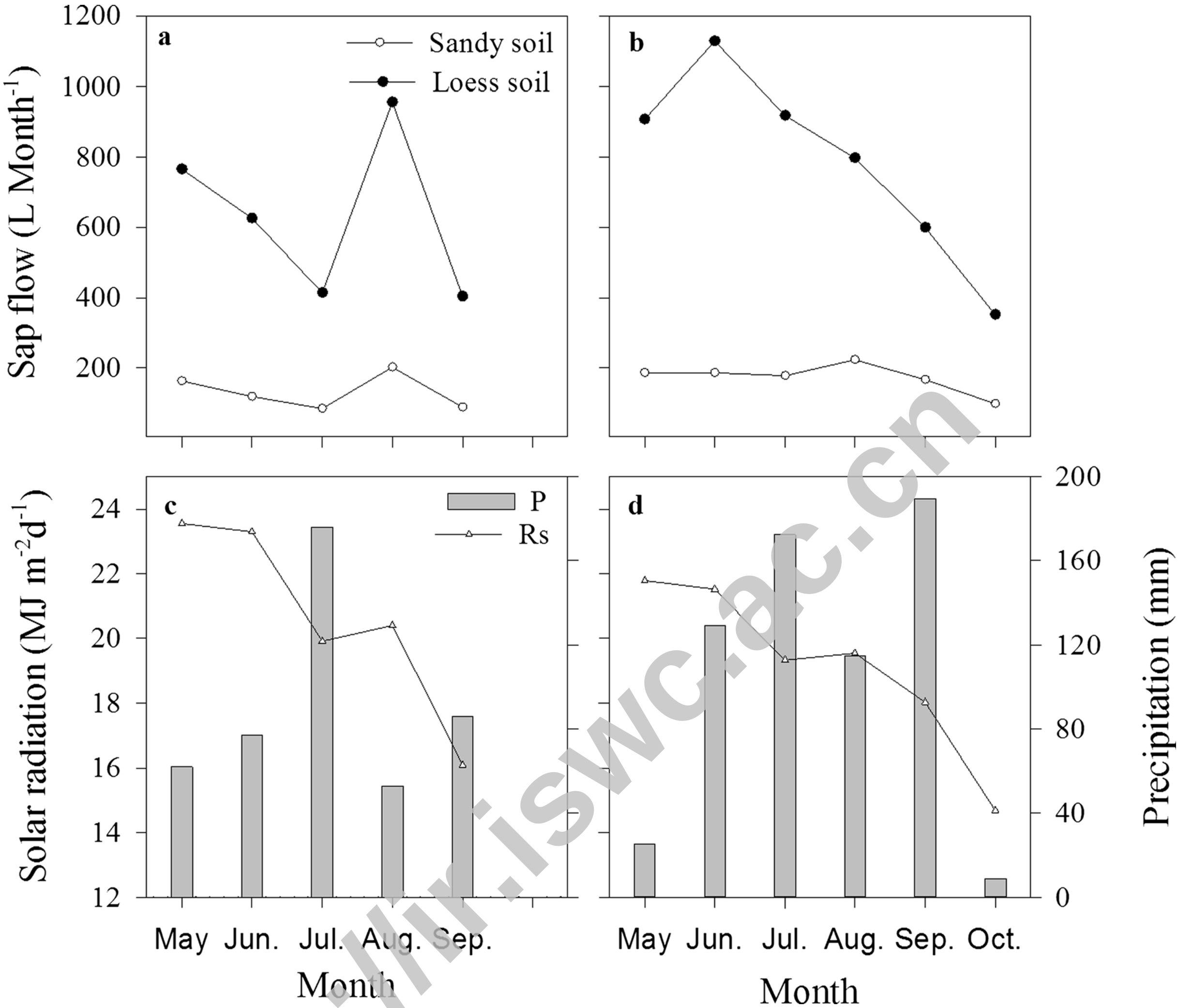

Fig. 4 Seasonal changes in solar radiation, precipitation and the sap flow in *Salix matsudana* trees growing in two different soils in 2012 (**a** and **c**) and in 2013 (**b** and **d**)

trees growing in either the sandy soil or the loess soil. This was because weather conditions were similar in the two fields, which were close to each other, even though they were located at different positions in the watershed and different microclimates could potentially exist.

Table 1 The monthly variation of sap flow in *Salix matsudana* growing in two soils with different soils textures types during the growing seasons of 2012 and 2013

		2012						2013						
		May	Jun.	Jul.	Aug.	Sep.	Total	May	Jun.	Jul.	Aug.	Sep.	Oct.	Total
Sandy soil	Mean daily sap flow (L d^{-1})	5.3	4.0	2.7	6.5	3.0		6.0	6.2	5.7	7.2	5.6	3.2	
	Monthly total sap flow (L)	163	119	85	203	89	660	187	187	178	224	167	99	1042
Loess soil	Mean daily sap flow (L d^{-1})	24.7	20.8	13.3	30.8	14.9		29.2	37.6	29.6	25.7	20.0	11.4	
	Monthly total sap flow (L)	765	625	414	955	404	3163	907	1128	917	797	599	352	4701

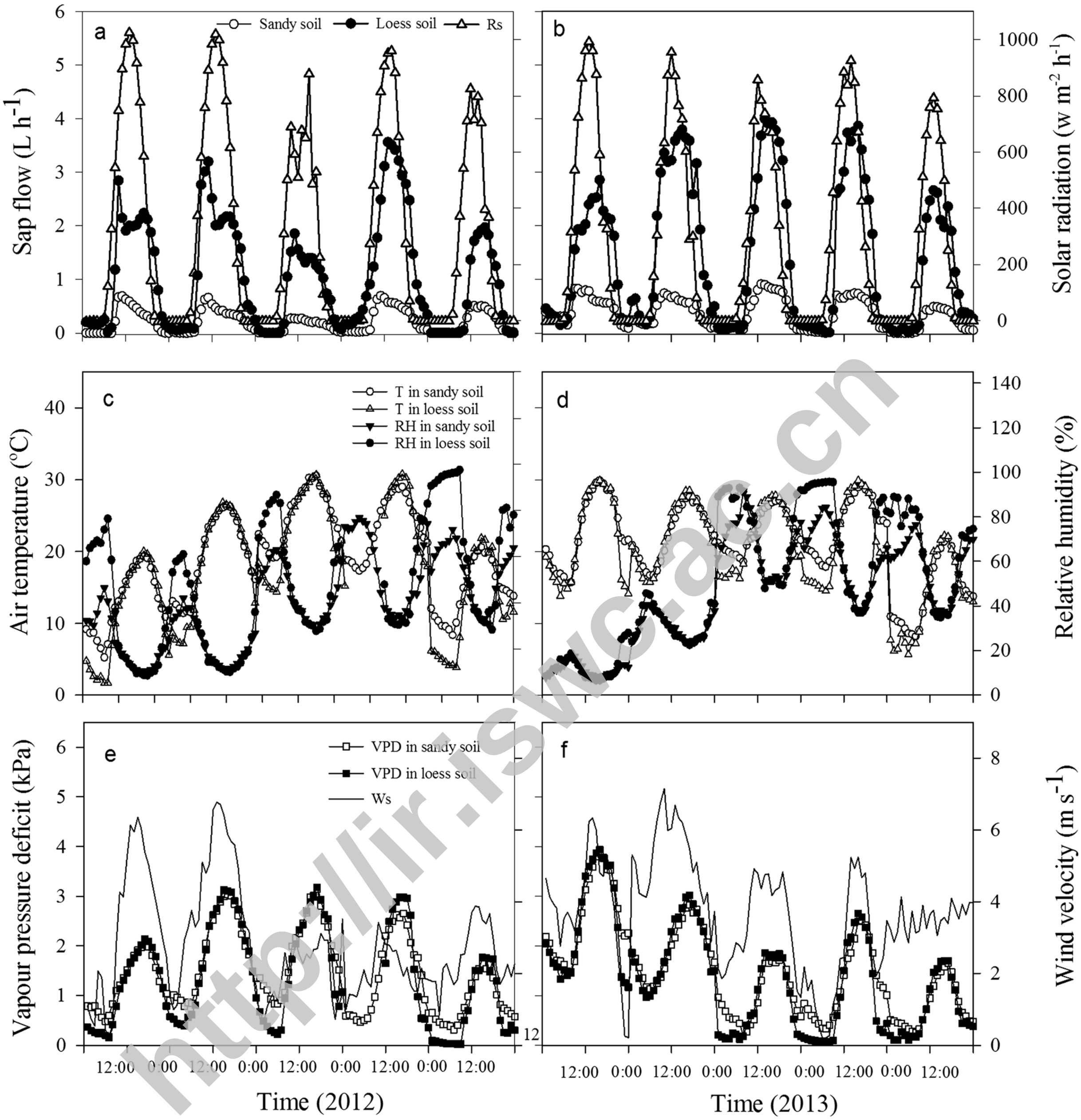

Fig. 5 The diurnal variation of sap flow, solar radiation (*Rs*), air temperature (*T*), relative humidity (*RH*), vapor pressure deficit (*VPD*) and wind speed (*Ws*) on 14 May, 11 June, 13 July, 9 August, and 15 September in 2012, on 12 May, 13 June, 21 July, 10 August, and 27 September in 2013; all days were sunny

Sap flow response to soil water content

In general, *S. matsudana* sap flow for the loess soil was higher than for the sandy soil. Sap flow in 2013 was also higher than in 2012, which we have previously ascribed to the greater number of rainfall events occurring in 2013 (Fig. 7a, b). When a high intensity rainfall event occurred in the daylight hours, the sap flow was greatly reduced due to the lower levels of solar radiation, while at the same time the sap flow could increase rapidly following the rainfall due to the recently increased soil water availability.

The changes in soil water content in each soil profile in the two study years are shown in Fig. 7c, d, e and f.

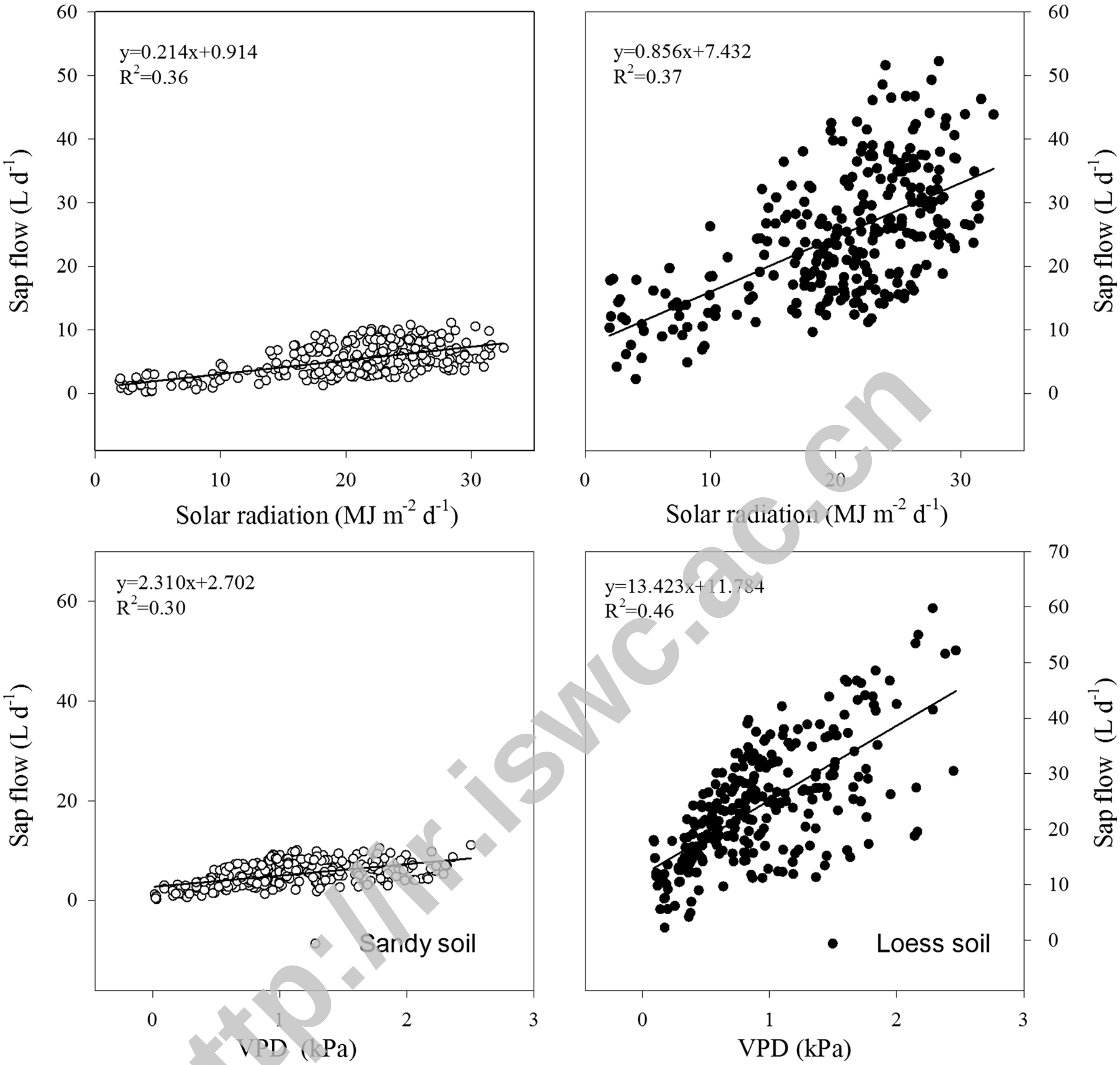

Fig. 6 Measurements of sap flow versus solar radiation, or vapor pressure deficit (*VPD*), and the fitted regression lines for data collected in 2012 and 2013

Lower rainfall events that delivered smaller amounts of precipitation usually only affected the upper soil layers and soil water was easily lost through evaporation. Thus, soil moisture levels were mainly recharged by

Table 2 Coefficient of determination of the relationships between sap flow and meteorological factors

	Solar radiation	VPD	Air temperature	Relative humidity	Wind velocity	ET_0
Sandy soil	0.36**	0.30**	0.17**	0.20**	0.14*	0.42**
Loess soil	0.37**	0.46**	0.31**	0.28**	0.12*	0.45**

VPD vapor pressure deficit

ET_0 = reference crop evapotranspiration

** $p<0.01$, * $p<0.05$

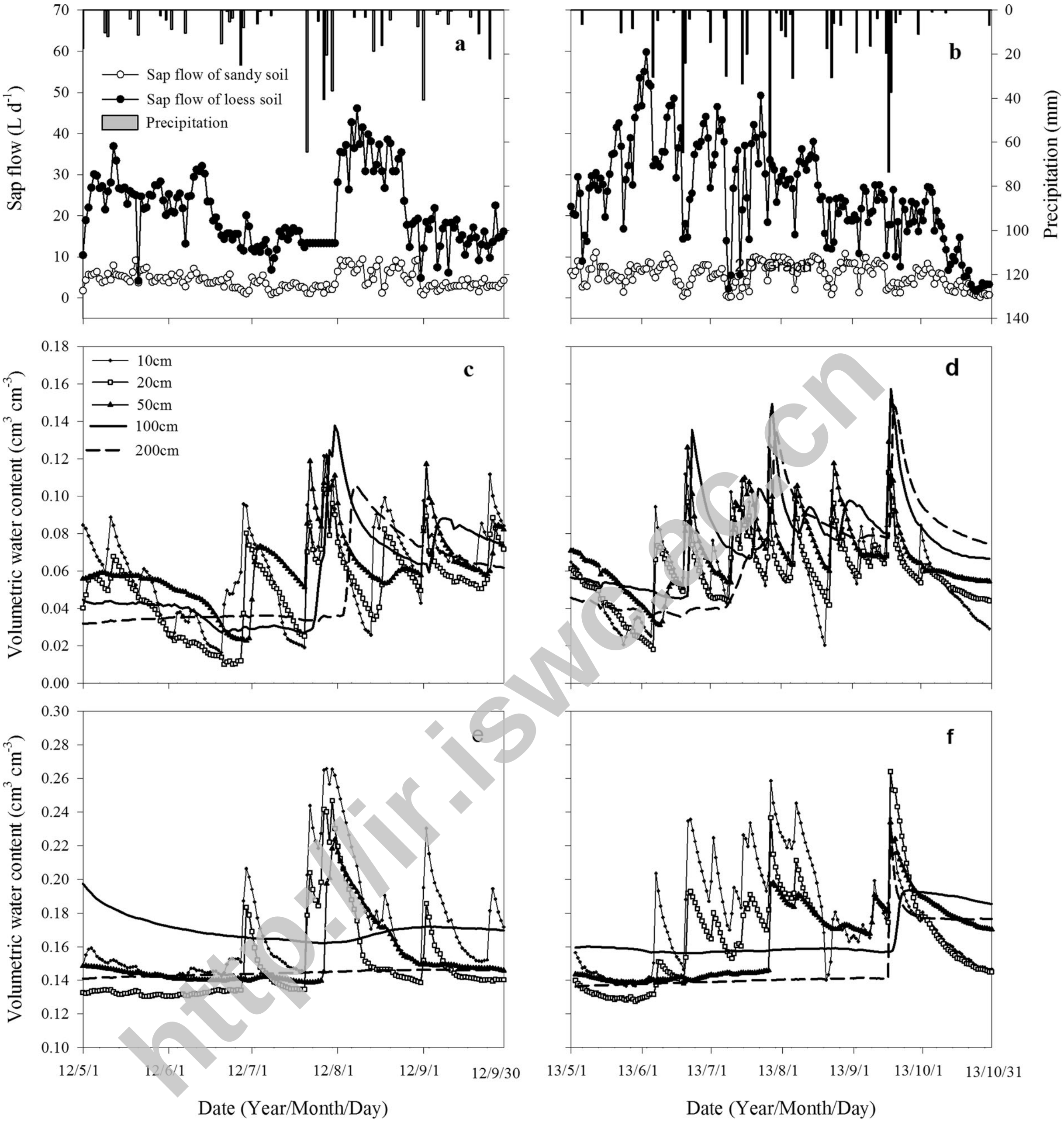

Fig. 7 Dynamics of daily sap flow and precipitation (**a**, **b**), and soil water content profiles (**c**, **d**, **e**, **f**) during 2012 and 2013 in the sandy and loess soils

the higher rainfall events with larger amounts of precipitation (Schwinning and Sala 2004). In our study, consistent results were obtained. In the sandy soil, the soil moisture in the shallow layers, which included the 10, 20 and 50 cm soil depths, fluctuated strongly in response to all rainfall events. However, the soil moisture at the 100 and 200 cm soil depths only changed when large amounts of rainfall occurred (Fig. 7c, d).

Compared with the loess soil, the soil water-holding capacity of the sandy soil was less, while its infiltration capacity was greater than that of the loess soil, so that water rapidly infiltrated into deep soil layers after a large amount of rainfall. Water infiltrated to the 100 cm depth and the water content increased rapidly from 0.028 to 0.138 $cm^3\ cm^{-3}$ after the highest rainfall event (64.3 mm) that occurred on July 20, 2012. Ten days later, water infiltrated to the 200 cm depth, and the soil water content increased to 0.105 from 0.036 $cm^3\ cm^{-3}$. However, the soil moisture at the 100 and 200 cm depths exhibited no obvious changes in the loess soil at that time; the 200 cm depth, especially, maintained an almost constant soil moisture level (Fig. 7e). In 2013, there were three large rainstorms, which occurred on 19 June, 27 July and 17 September, when the total precipitation amounts were 64.7, 69.7 and 73.5 mm, respectively. After the first high rainfall event occurred, the soil water content at the 100 cm depth of the sandy soil exhibited a large fluctuation, and increased from 0.046 to 0.135 $cm^3\ cm^{-3}$. On 24 June, water had infiltrated to the 200 cm soil depth, and the soil water content had begun to rise gradually. However, relatively little water had infiltrated to both the 100 and 200 cm soil depths until the third high rainfall event in the loess soil, following which the soil water content began to increase notably having been stable before the third high rainfall event (Fig. 7f). This means that more water in the sandy soil was lost to the deeper soil layers (deep percolation) after large rainfall events, especially successive large events, and might then be inaccessible or difficult for the trees to use. In contrast, the stable soil water content of the deep soil layers in the loess soil showed that little deep percolation occurred during this 2-year study.

There were slight differences between the fine root distributions in the profiles of the different soil types. The cumulative fraction of roots (Y) from the surface to any depth (d) was calculated for both vertical root distributions (Fig. 8). The lower value of the fitted extinction coefficient (β=0.98) for the loess soil corresponded to the greater proportion of roots nearer to the soil surface. However, differences in the fine root density for the two sites were not statistically significant according to an independent-samples T test (F=1.4, p>0.05). The fine roots in the loess soil were mainly distributed in the upper 80 cm soil layer, which accounted for 86 % of the total, while the maximum rooting depth was 160 cm. In contrast, only 66 % of the fine roots in the sandy soil were distributed in the upper 100 cm soil layer, while 20 % were found in the 220–280 cm soil layer, and the maximum rooting depth was 300 cm.

The changes in available soil water storage can be used to further explain and quantify the variance in sap

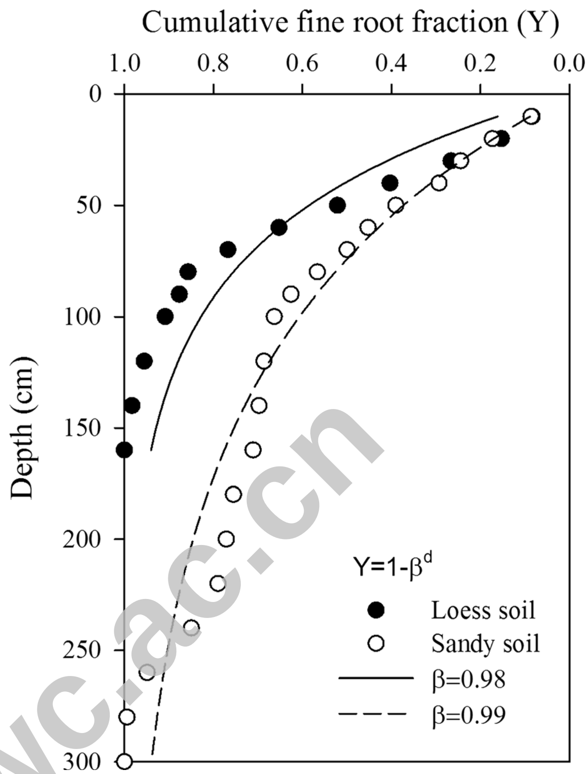

Fig. 8 The distribution of fine roots of *Salix matsudana* in two soils with different textures

flow of the trees growing in the two different soils. The available soil water in the 0–100 cm soil layer was significantly higher in the loess soil than in the sandy soil, being consistently 1.5 times greater in each month (Fig. 9). In both the sandy soil and the loess soil, the fine roots of *S. matsudana* were mainly distributed in the upper 100 cm soil layer, and there was more available soil water in this soil layer in the loess soil than in the sandy soil. This indicated that the loess soil would have more available water for *S. matsudana* growth in the upper 100 cm soil layers.

The maximum rooting depth of *S. matsudana* in the sandy soil was 300 cm, so we analyzed the variation of soil water content to a depth of 600 cm (Fig. 10). The amount of soil water stored in the 280–400 cm soil layer was the greatest, although the soil water below 400 cm was maintained at a high level that was actually higher than that of the surface soil layers because of different soil textures. Therefore, we can infer that the amount of water that *S. matsudana* could absorb was less in the root zone of the sandy soil. As a result, trees growing in the sandy soil were frequently exposed to drought stress and their growth was adversely affected, ultimately to

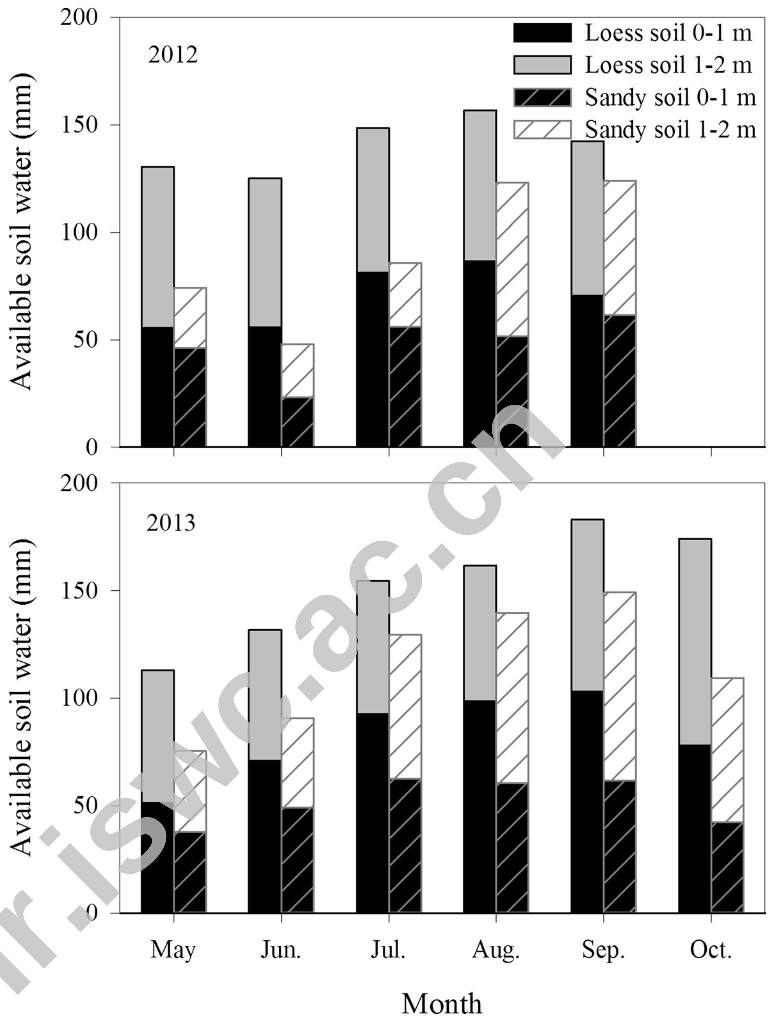

Fig. 9 Available soil water in different layers of sandy and loess soils during the growing season of *Salix matsudana* in 2012 and 2013

the extent that they become "small aged trees". In conclusion, the difference in available soil water caused by the different soil textures was the main reason for the observed differences in the sap flow of *S. matsudana* in the sandy and loess soils.

In order to further confirm the conclusion obtained in the present study, we analyzed the water output from the sandy and loess soils in terms of the water balance. The water input was the same in both the sandy and loess soils, but the water output was very different. In 2013, the soil evaporation and the transpiration were 170 and 262 mm, respectively, for the sandy soil, which were clearly less than those values (284 and 385 mm) for the loess soil (Table 3). This indicated that some water had infiltrated into the deeper soil layers of the sandy soil and, therefore, that the amount of water that *S. matsudana* could potentially absorb from the sandy soil was less than from the loess soil.

In the two study years, 290 mm of rainwater infiltrated below the upper 100 cm soil layer in the sandy soil, but only 64 mm did so in the loess soil. The deep percolation that occurred in 2012 in the sandy soil amounted to 82 mm of water, and mainly occurred in July and August; however, only 5 mm did so in the loess soil, which could be considered negligible. In 2013, the deep percolation accounted for 208 mm of water in the sandy soil, while in the loess soil it was 59 mm, which was 28 % of that in the sandy soil. Based on the above analysis, we arrived at the conclusion that the main reason for the discrepancy between sap flows in *S. matsudana* growing in either sandy soil or loess soil was due to the different amounts of available soil water that was caused by the different soil textures under different soil conditions, which affected the development of the sapwood.

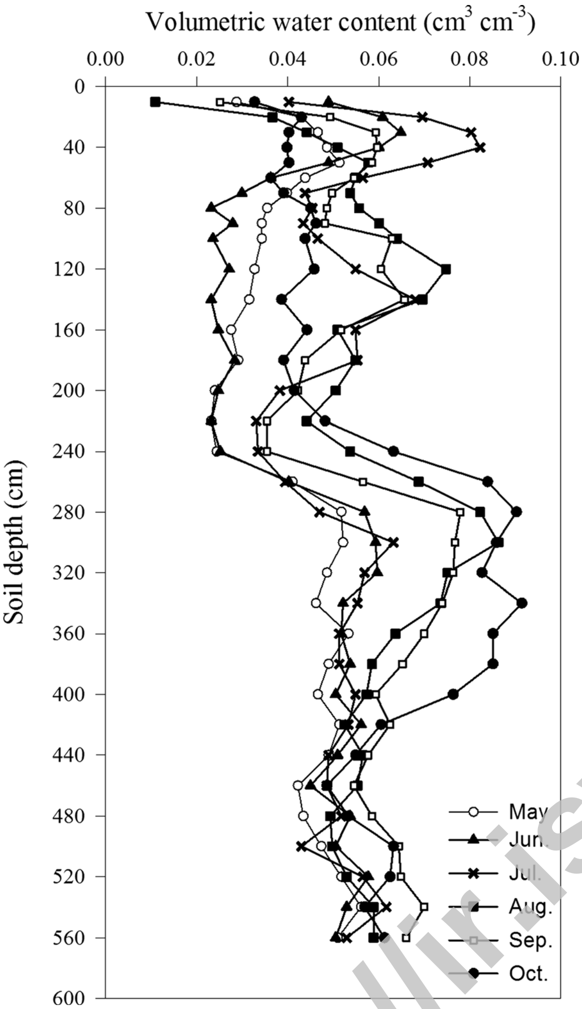

Fig. 10 The variation in soil water contents in a sandy soil profile during 6 months in 2013

Discussion

Estimation of individual tree transpiration

To the best of our knowledge, there are currently no reports in the literature on transpiration of *S. matsudana* in the study region that could be usedfor comparison with our data. In our study, the daily mean transpiration of *S. matsudana* grown in a sandy soil was about 1.20 and 3.08 mm day^{-1}, in 2012 and 2013, respectively, while in the loess soil the values were 1.85 and 5.29 mm day^{-1}. Due to the limitation of the TDP method, these values may be underestimates of the true values (Steppe et al. 2010), but they serve to indicate comparative differences.

Table 3 Water inputs and outputs for *S. matsudana* growing in two different soils

	Precipitation (mm)	Soil evaporation (mm)	Transpiration (mm)
Sandy soil	669	170	262
Loess soil	669	284	385

One main reason for possible underestimations is that the TDP method depends on determining zero sap flow as part of the calibration process (Granier 1987). Zero flow is assumed to occur at nighttime when transpiration and, therefore, sap flow are assumed to be negligible but some instances of transpiration might occur at these times. Two drivers of nighttime transpiration were suggested by Dawson et al. (2007): evaporative demand and soil water availability. In our study, the mean VPD was 0.56 kPa between the hours of 02:00 and 05:00 when the zero flow measurements were made. For only about 20 % of the time, our measured values slightly exceeded 0.7 kPa, which Dawson et al. (2007) suggested as the threshold value needed to induce transpiration in drought prone areas. In our study area, drought or water deficit conditions prevailed and soil water availability was low due to the low annual rainfall (440 mm) and relatively high annual ET_0 (1200 mm). Therefore, sap flow velocity could reasonably be considered to be zero or minimal during the nighttime hours in our study.

Thus, using the sap flow velocities determined by the TDP method comparatively, it can be seen that transpiration was notably affected by the rainfall amount, since 2013 was a wetter year than 2012. The transpiration of *S. matsudana* trees growing in the loess soil was considerably higher than that of those growing in the sandy soil, and the large difference has critical implications for regional water budgets (Schaeffer et al. 2000), which should be considered while the Grain to Green project is being carried out.

Diurnal and seasonal variations in sap flow

The sap flow of *S. matsudana*, which grows in the water-wind erosion crisscross region on the Loess Plateau, exhibited a clear diurnal rhythm in both daytime and nighttime (Fig. 2). This conclusion was similar to those reported by others (Du et al. 2011; Guan et al. 2012; Zhang et al. 2011). The sap flow increased with the increases in solar radiation and in air temperature during the daytime but at nighttime, when photosynthesis almost completely stopped, the sap flow was minimal. Similarly, the diurnal variation of sap flow in *Robinia pseudoacacia* growing elsewhere in the semiarid region of the Loess Plateau has also been reported to exhibit a broad-peaked curve (Wu et al. 2010). For the trees growing in the loess soil in our study, there was also some evidence of a temporary decline in sap flow velocity around midday, a phenomenon that could occur when the water demands of transpiration exceeds the ability of the tree to extract water from the soil.

Differences in leaf phenology, meteorological factors and availability of soil water lead to the seasonal sap flow dynamics. In April, the leaves of *S. matsudana* begin to expand, and grow to full size in May and June, while in September the trees undergo substantial defoliation. Therefore, the overall trend of sap flow of *S. matsudana* in this region was that the sap flow during May and June was higher than at any other time and gradually declined to its lowest levels as the growing season progressed (Fig. 3). Solar radiation is another important determinant factor and there was a strong similarity between monthly patterns of sap flow and solar radiation. However, the trend was influenced by the rainfall. Cermak et al. (1995) found that the relative transpiration increased after a rainfall event. Chang et al. (2006) also demonstrated that soil water content strongly affected the variations in sap flow of Gansu Poplar shelterbelts. In our study, this phenomenon also existed. In 2012, the sap flow sharply increased to 203 L and reached the maximum in August, after heavy rainfall (176 mm) occurred in July. In the study region, large rainfall events markedly affected the change in sap flow with the result that the trees were always suffering some degree of drought stress. Relative to 2012, when the total rainfall was only 475.9 mm, 2013 was a wet year with total rainfall of 639.7 mm. In 2013, the amount of water that could be absorbed by trees was more abundant for those growing in the loess soil than in the sandy soil. The effect of rainfall on sap flow in *S. matsudana* growing in the loess soil was relatively small, so that the sap flow of these trees did not respond to the larger rainstorms in August, unlike the trees growing in the sandy soil where sap flow rapidly increased after that series of rainfall events.

Sap flow responses to environmental factors

Meteorological factors such as solar radiation, vapor pressure deficit, air temperature and relative humidity are important regulators of transpiration that interact with soil water availability and the physiological and phenological status of plants, leading to very close correlations between sap flow and the environmental factors (Huang et al. 2009; Ortuño et al. 2006). Huang et al. (2011) found that sap flow of *Caragana korshinskii* was closely related to solar radiation, relative humidity, air temperature and wind speed, and that the solar radiation and relative humidity were the two main impacting factors. Pataki and Oren (2003) reported that solar radiation was the most important factor controlling stomatal conductance of *Liquidambar styraciflua*, which then affected the variations in sap flow. However, different perspectives were obtained under different conditions. Phillips et al. (1999) detected that VPD had a closer relationship with sap flow on a daily basis, while sap flow was most closely associated with solar radiation during the diurnal course. As mentioned above, the most important factors related to sap flow are solar radiation and vapor pressure deficit. The variation in transpiration observed in our study was also related to the meteorological factors, and the variation of sap flow was most closely associated with the pattern of reference crop evapotranspiration (ET_0), and to a lesser extent the solar radiation, VPD, air temperature, relative humidity and wind speed (Table 2). The increases in sap flow are a mechanism by which to compensate for the water losses due to transpiration (Zhang et al. 2007). Similarly, solar radiation and vapor pressure deficit had the greatest influence on the sap flow of *S. matsudana* in the water-wind erosion crisscross region on the Loess Plateau. Furthermore, the responses of sap flow to solar radiation or vapor pressure deficit were significantly affected by soil texture according to the standard major axis (SMA) analysis (Warton et al. 2006). However, the determination coefficient of linear regression between sap flow and solar radiation was almost equal. It is inherently difficult to distinguish among the impacts on sap flow of each individual meteorological factor because of the complex environment and because it was the combined impact of both the meteorological factor and the soil water content that actually drove the sap flux response at the whole-tree level (O'Brien et al. 2004). Instead, ET_0 is suggested as the best parameter to use in relation to the sap flow in the study region.

Changes in environmental water conditions affect the water physiological characteristics of plants, including water consumption by transpiration, water potential (Roberts 2000) and photosynthesis (Zhou et al. 2008).

Water is one of the main factors that affect plant growth in arid and semi-arid areas. Many treatises reported that soil water content strongly affected the variation of sap flow (Chang et al. 2006; Ewers et al. 2001; Granier et al. 2000). Chang et al. (2014) had established a logistic functional relationship between sap flow and soil water content, which explained 84 % of the variation in sap flow velocity and exhibited great sensitivity. In the present study, the different soil water content under the two kinds of soil conditions was the main reason for the variations observed in the sap flow. The soil texture was different, which in turn meant that other soil physical properties were different. Loess soils exhibit higher water holding capacity but have lower permeability and higher bulk densities than sandy soils. The infiltration process is controlled by ground cover, soil type, hydraulic properties, rainfall intensity, and soil surface features (Laio et al. 2001). Sandy soils lose more moisture and have lower conductivity at higher water potentials than finer soils (Hacke et al. 2000), and the studied sandy soil had low water contents during the growing periods. Therefore, the redistribution of soil moisture was different after rainfall under the two soil conditions. In the case of the sandy soil, after rainfall, more water was lost through drainage to the 100–200 cm soil layer (Fig. 6c, d, e, f) and some was even lost to below 300 cm, the maximum rooting depth of *S. matsudana* measured in this study. In contrast, the loess soil could retain most of the rainwater in the 0–100 cm soil layer.

The roots of *S. matsudana* in the loess and sandy soils were mainly distributed in the 0–100 cm soil layer, although the trees growing in the sandy soil were more deeply rooted than those growing in the loess soil. The same results were reported for *Pinus taeda* by Hacke et al. (2000). Shallow distributions of root systems may also be a reason for sensitive responses to soil water recharge (Kume et al. 2007). Furthermore, the available soil water of the 0–100 cm soil layer in the loess soil was greater than that in the sandy soil. Generally, quantities of water were lost from the root zone due to drainage, and it can be inferred that nutrients would also be leached out of the sandy soil. Trees growing in the sandy soil suffered drought stress, but there was generally sufficient water available for tree growth in the loess soil. Moreover, the larger pore spaces in the sandy soil could only hold water at relatively higher potentials than the loam or finer soils, which should tend to increase resistance to root uptake (Hacke et al. 2000; Sperry and Hacke 2002). Furthermore, woody plants that grow in coarse-textured soils are more vulnerable to cavitation than the same plant species growing in finer soils (Hultine et al. 2006). S*alix matsudana* growing in the sandy soil tend to become “small aged trees” due to the adverse growth conditions, while trees growing in the loess soil grow relatively better. In order to achieve sustainable forest management, the planting density of S*alix matsudana* in the sandy soil should be greatly reduced while ground cover should be maintained by using shrubs or grasses. Furthermore, *Sabina vulgaris* Antoine, an evergreen shrub, has been suggested as a promising alternative with which to replace the “small aged trees” in this region (Dong and Zhang 2000). In conclusion, the soil water content, as affected by the soil texture, was the main reason for producing the discrepancy in sap flow in *S. matsudana* growing in the different soils at the two study sites in the water-wind erosion crisscross region on the Loess Plateau.

Conclusion

The mean daily transpiration rates of *S. matsudana* grown in sandy and loess soils were 1.20 and 1.85 mm d^{-1} in 2012, while the total water consumption was 183 and 280 mm, respectively. In 2013, the corresponding data was 3.08 and 5.29 mm d^{-1}, and 289 and 416 mm. There were considerable differences in the quantities of sap flow in *S. matsudana* growing in either the sandy soil or the loess soil. In the two study fields, there were considerable differences in the soil water content and in the vertical distributions of the fine roots that were related to the different soil textures. The roots were mainly distributed in the 0–100 cm soil layer, while the available soil water in the 0–100 cm layer in the loess soil was greater than that in the sandy soil and, within the entire root zone there was less water that could be used by *S. matsudana* in the sandy soil than in the loess soil. The soil evaporation and transpiration were lower in the sandy soil field than in the loess soil field, and 290 mm of water percolated out of the root zone in the sandy soil, but only 64 mm did so in the loess soil. In summary, the different amounts of available soil water due to soil texture was the main reason for the differences in the sap flow in *S. matsudana* growing either in the sandy soil or in the loess soil. Soil texture should be considered when planting trees such as *S. matsudana* in order to carry out vegetation restoration, even under similar climate conditions.

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