Severe drought greatly reduces sap flow of Mongolian Scots pine (*Pinus sylvestris* var. *mongolica*) and its recovery ability in a sandy and semi-arid environment

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Abstract. Trees growing in water limited ecosystems are often exposed to the significant challenges of soil water stress due to low precipitation and high variation. In this study, we aimed to quantify the water use of Mongolian Scots pine (*Pinus sylvestris* var. *mongolica*) growing on a sandy soil, in a region characterised by an erratic rainfall pattern. Measurements were made over three successive years of contrasting annual rainfall - a wet year (2013), a dry year (2014), and a second dry year (2015). Over the three years, sap flux density (J_s) was measured at individual tree level for 25 tree samples, and were up-scaled to estimate tree transpiration at plot level (T_s). Due to the high variation of rainfall in three years, the measurements reflected the tree response to wide range of water stress from wet (2013), mild-drought (2014) to severe-drought (2015). The daily transpiration T_s of trees during growing seasons was 3.7 mm day^{-1} in 2013, 2.6 mm day^{-1} in 2014, but sharply decreased to 1.4 mm day^{-1} in 2015 after a long-period drought stress, resulting a large difference in total annual stand transpiration as 357 mm in 2013, 268 mm in 2014 and 149 mm in 2015. Under a long-period of drought stress in late season in 2014 and early season in 2015, the recovery of T_s was incomplete (63–69%). The erratic rainfall and sandy soil coupling with a declining groundwater table, tree water use fluctuated widely over quite short time scales (months or weeks). Our results help elucidate the interplay between the effects of the atmosphere and soil moisture on tree water use, and highlight the negative effects of drought on water use of mature forest tree. Our findings provide the evidence for the observed premature degradation of these Mongolian

Scots pine plantations in terms of an eco-hydrological perspective.

Keywords: sap flux; Mongolian Scots pine (*Pinus sylvestris* var. *mongolica* Litv*)*; soil water availability; water stress; sandy soils; semi-arid climate.

1 Introduction

Reforestation has been used widely in semi-arid areas to control soil erosion, to capture carbon and to serve as wind breaks (D'Odorico and Porporato, 2006). However, trees growing in severely water-limited ecosystems are often exposed to significant challenge due to insufficient soil water (Wesche et al., 2011; Su et al., 2014). Many factors influence the amount of soil water and its availability to vegetation, for instance, the amounts and timings of rainfall interval, soil water capacity, root water-uptake capacity and the availability of alternative water sources such as groundwater (Meinzer et al., 2006). Under climate change, the increasing in the frequency and severity of drought decreases soil water availability in the future (Leo et al., 2013). This would increase tree mortality rate through excessive competition for water and thus influences the structure and function of forest ecosystems (Barbeta et al., 2015). Quantification of water use by trees at individual and forest levels could help us to understand how environmental factors affect their water usage. It is necessary to properly assess the impacts of climate change on ecological and hydrological processes in these fragile ecosystems (Bovard et al., 2005). These knowledge would allow us to make better forest establishment decisions and management actions.

Mongolian Scots pine (*Pinus sylvestris* var. *mongolica*, MP), a geographical variety of Scots pine (*P. sylvestris*), is naturally widely distributed in northern China and in parts of Russia and Mongolia. It is found in the Daxinganling Mountains (50 °10 ′–53°33′ N, 121°11′–127°10′ E) and in Honghuaerji on the Hulun Buir sandy plains of the northeast (Zhu et al., 2008; Zheng et al., 2012). The MP is a popular species for reforestation in northern China due to its traits of good drought and cold resistance. Consequently, more than 6.7×10^5 ha of MP plantations have been established to control desertification, in the great project of the Three-North Shelter Forest Program (TNSFP) launched in China from 1978 (Zheng et al., 2012). Unfortunately, serious degradation and considerable concern has occurred in these plantations since the mid-1990s, such as poor tree health and numerous tree death, particularly on the sandy soils in southern Horqin (42°43′ N, 122°22′ E, our study area) (Jiao, 2001; Zhu et al., 2008) (**Fig. 1**).

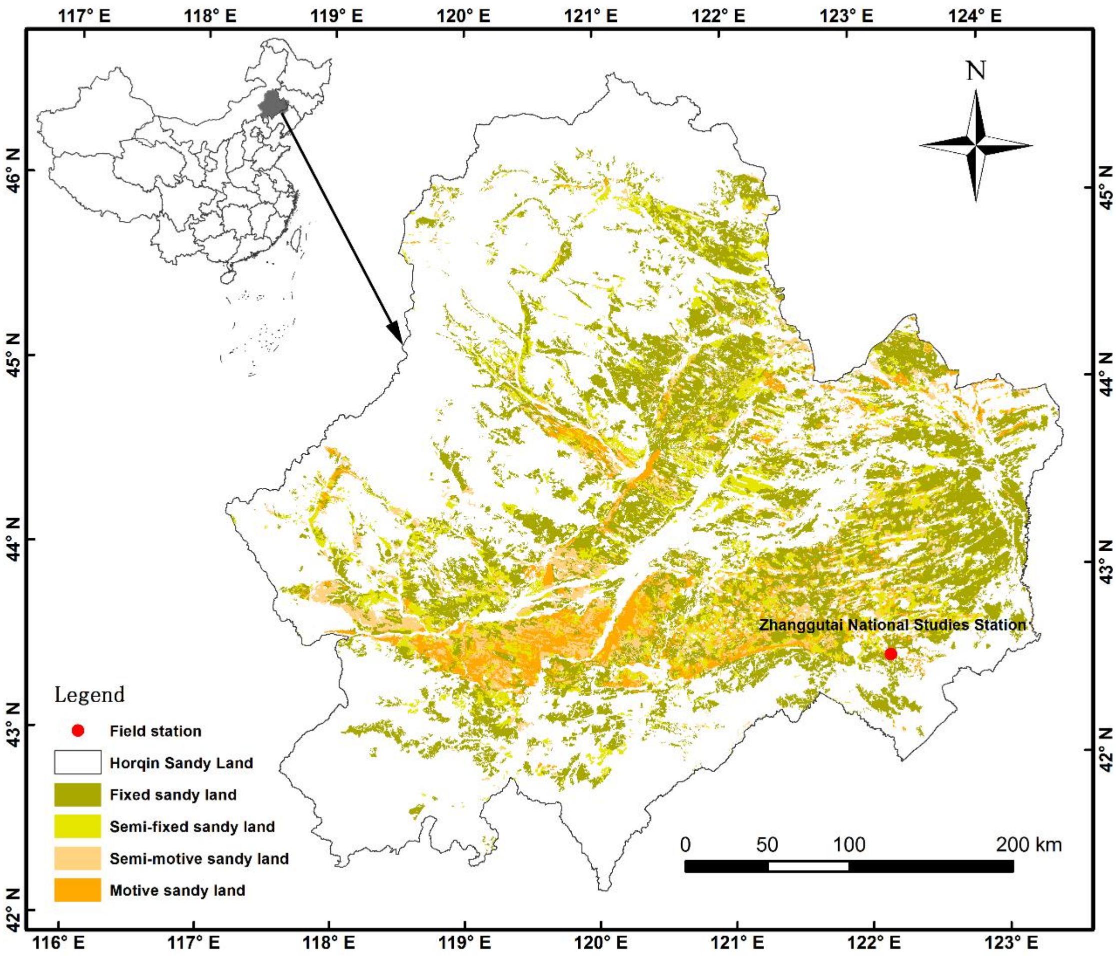

Figure 1 Location and eviornment of Horqin region in Liaoning province, China (study area)

A key driver for the degradation in water-limited ecosystems is regional low and erratic precipitation, which reduces soil water availability (Mereu et al., 2009). In semi-arid southern Horqin, three main soil-water related factors causes the degradation, i.e. the high inter-annual variation in precipitation, the high intra-seasonal variability in precipitation and the declining groundwater table. The forest's sensitivity to drought is highly species-specific, climate-specific and site-specific. However, it remains unclear how, and to what extent, these three factors are responsible for the degradation recorded in this region.

In general, plants native to arid and semi-arid environments have developed a wide range of water-use strategies to cope with drought, e.g. by 'water saver' plants to avoid drought by minimizing transpiration with limiting leaf area growth, or by defoliation and stomatal closure (Levitt, 1980; Gartner et al., 2009; Chirino et al., 2011). The MP is a shallow-rooted species and more than 85 % of roots system grows in the upper 0.4 m soil layer. The root density is sharply decreased below 1.0 m soil depth (Su et al., 2006).

We hypothesize that on the long-period drought in semi-arid sandy environment raising from the high variation of precipitation and low water holding capacity is the major reason causing the degradation of forest. The aims of this study were: (1) to quantify daily water use of MP based on sap-flux measurements in relation to the three contrasting precipitation years; (2) to determine the relationships between J_s and the main meteorological variables and soil water availability over the extended (three-year) period; (3) to explore the effect of the severity of the drought stress over number of cycles of soil wetting and drying on daily water use and recovery ability.

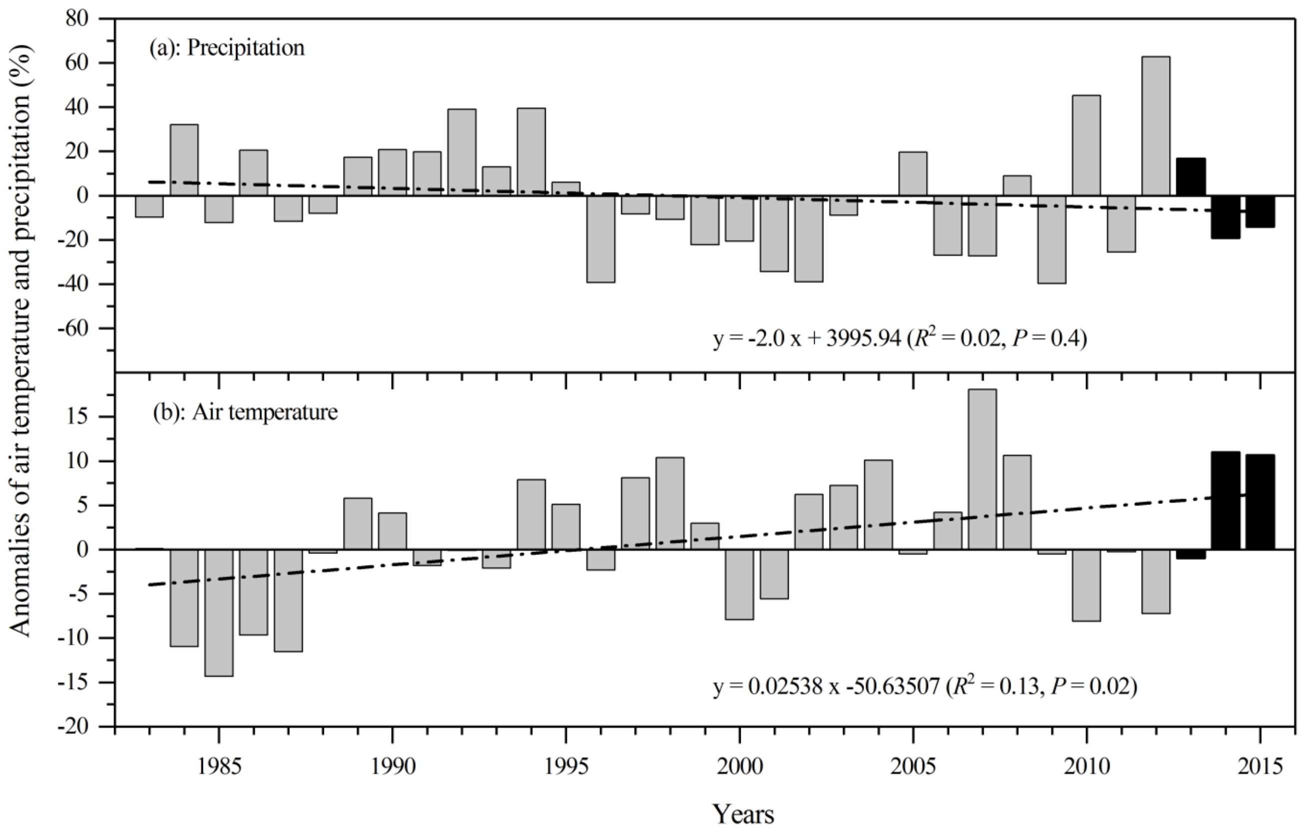

Figure 2 Annual variations of precipitation (a), mean air temperature (b) at Zhanggutai. Grey color indicates the data before the experiment (1983-2012) and black for the years of experiments (2013-2015). The dashed lines indicate the linear regressions over the whole period.

2 Materials and methods

2.1 Site description

The trial was carried out at the Zhanggutai National Desertification Control Trial Station located at the southern edge of the Horqin region in Liaoning province, China (122° 22′ E, 42° 43′ N, at 226.5 m a.s.l.) (**Fig. 1**). The experiment was conduced in a 40 ha plantation with 35-year old MP. Tree density was 625 trees per ha. Management interventions and other human disturbances were limited by the installation of a secure fence around the experiment field. The site has a semi-arid, continental climate with a mean annual temperature of 7.9 ^{o}C, a frost-free period of 150–160 days per year, a mean annual evaporation of 1553 mm and a long-term annual mean precipitation of 475 mm (P_{ave}) over the last 30 years (1983–2012) with coefficient of variance of 0.27 (Zhu et al., 2005). Over the long period, there have been a number of consecutive dry years. For instance, annual precipitation between 1996 and 2004 were below P_{ave} (**Fig. 2a**). Usually, about 60 to 70 % of annual rainfall occurs in the three months from June to August. The value of annual temperature over the last 30 years was increased slightly at a rate of 0.03 ^{o}C yr^{-1} (**Fig. 2b**), while annual precipitation was slightly decreased with a rate of 2.0 mm yr^{-1} (**Fig. 2a**). The soil is sandy with a sedimentary aeolian sand layer more than 3 m and an ancient alluvial sand layer with the total depth more than 126 m (Jiao, 1989). The mean bulk density of the upper 2 m soil layer is 1.61 g cm^{-3}. The mean soil texture is 83 % of sand (> 0.05 mm), 9 % of silt (0.05–0.002 mm) and 8 % of clay (< 0.002 mm). The organic matter content is 0.3–1.0 g kg^{-1}. The understory plant species in the forestry are *Acer pictum* subsp. *mono* Maxim, *Crataegus pinnatifida var. major N. E. Brown.*, *Lespedeza bicolor* Turcz., *Artemisia halodendron* Turcz et Bess., *Cleistogenes chinensis* Maxim.

2.2 Experimental design and samplings

To break the prevailing northerly winds, the MP were planted in a square-grid pattern with 4 m for both row spacing and plant distance. Total area of experiment was 400 m^{2} (20×20 m) containing 25 trees. All trees in the area were planted at same year in sole system surrounded by a wire fence (**Fig. 3**). The growth of trees in the experiment was normal in 2013, however, the leaves of trees in 2015 turned to grey slightly. The obvious defoliation or death did not occurred in 2015. Sap flow sensors were installed in each tree (totally 25 trees) in experimental area in 2013. Due to the damage of sensors, 22 left in 2014 and 13 left in 2015. The characteristics of the sampled trees are shown in **Table 1**. Diameters at breast height (DBH) were measured with a diameter tape and tree height with an altimeter. The thickness of bark, sapwood and heartwood were measured by sampling core with a Pressler increment borer at breast height. Thickness measurements were made with a Vernier caliper with tissue boundaries identified based on color. In our Mongolian Scots pine, the sapwood colour was yellow-white and that of the heartwood was tan. A few drops of methyl orange solution helped define the interface where the boundary was indistinct. The DBH, tree height and sapwood areas of the sampled trees in 2013, 2014 and 2015 were not significantly different ($P > 0.05$), indicating a good uniformity of testing trees.

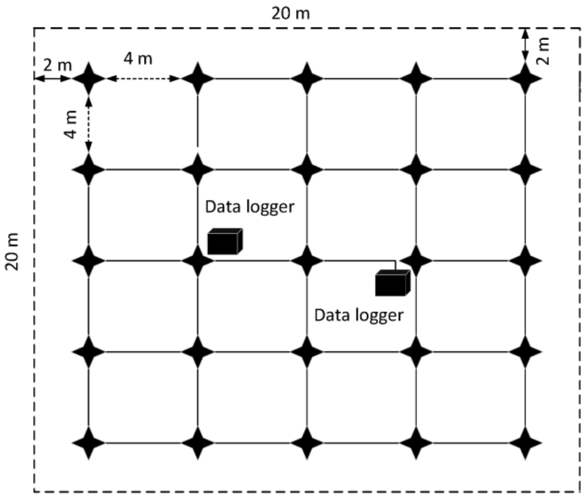

Figure 3 Sketch map of 25 sample trees (stars) planted in a 4×4 m spaced square grid of about 400 m^2 (dashed line is border fence). Tree ages were identical and tree sizes were similar. The number of instrumented trees decreased in 2014, and again 2015. Details of samples see **Table 1.**

Table 1 Diameter at breast height (DBH, cm), tree height (H, m), height of first live branch (H_b, m), 1st quartile of DBH (Q_1), 3rd quartile of DBH (Q_3), sapwood width (SW, cm), sapwood area (A_s, cm^2) in 2013 to 2015. The mean values and standard deviations (S.D.) were given, the n is the number of sampling trees.

Year	DBH (cm)			H (cm)	H_b (cm)	SW (cm)	A_s (cm^2)
	mean ± S.D.	Q_1	Q_3				
2013 (n = 25)	18.0 ± 2.7	16.1	18.9	10.3 ± 0.7	4.5 ± 1.1	5.5 ± 0.6	203 ± 58.6
2014 (n = 22)	17.1 ± 2.1	15.6	18.7	9.3 ± 0.8	3.7 ± 0.5	5.3 ± 0.5	182 ± 42.0
2015 (n = 13)	17.7 ± 2.2	17.2	18.8	9.1 ± 0.8	3.7 ± 0.3	5.4 ± 0.5	189 ± 52.3

2.3 Measurements

2.3.1 Micrometeorological variables

Micrometeorological variables including solar radiation (R_s), net radiation (R_n), air temperature (T_a), relative humidity (RH), wind speed (W_s) and rainfall (R) were measured using an automatic weather station (AR5, Avalon Scientific, Inc. USA) located about 50 m away from the experimental field. All sensors were installed 2.0 m above the ground except the rain gauge, which was 0.5 m above the ground. Variables were measured at 1 min intervals, averaged and recorded per hour. Reference evapotranspiration (ET_0) was calculated using the FAO Penman-Monteith equation based on the variables R_n, T_a, RH and W_s (Allen et al., 1998) at hourly base (Eq. (1)). Daily ET_0 was summed from hourly ET_0 for a day.

$$\mathrm{ET}_0 = \frac{0.408(R_\mathrm{n}-G)+\gamma\frac{900}{T_\mathrm{a}+273}u_2(e_\mathrm{s}-e_\mathrm{a})}{\Delta+\gamma(1+0.34u_2)} \qquad (1)$$

where ET_0 = reference evapotranspiration (mm h^{-1}),

Δ = slope of saturated water vapour pressure against air temperature T_a (kPa °C^{-1}),

R_n = net radiation (MJ m^{-2}),

G = soil heat flux (MJ m^{-2}),

γ = the psychrometric constant (kPa °C^{-1}),

e_s = saturated vapour pressure (kPa),

e_a = actual vapour pressure (kPa), and

u_2 = mean wind speed at 2 m height (m s^{-1}).

The value of vapor pressure deficit (D, kPa) was calculated using the following formula (Campbell and Norman, 1998):

$$D = 0.611exp^{\left(\frac{17.502T_a}{T_a+240.97}\right)}(1-\mathrm{RH}) \qquad (2)$$

2.3.2 Soil moisture content and groundwater table

Volumetric soil moisture contents (θ, %) were measured at depths of 0.1, 0.2, 0.4, 0.6, 0.9, 1.2, 1.6 and 2.0 m using ECH_2O EC-5 sensors (Decagon Devices Inc., USA). Three placements in experiment area were measured. Each placement was set between four neighborhood sample trees. Measurements were done at 10 min intervals with hourly means recorded by a SQ2020 data logger (Grant Instruments Ltd, UK). The sensors was calibrated using a site-specific equation based on the oven-drying method (Eq. (3)):

$$\theta = 0.9677\theta_{\mathrm{s}} + 0.2635 \ \ (R^2 = 0.96, n = 194, \mathrm{RMSE} = 0.41) \qquad (3)$$

where θ_{s} are the output of the sensors; θ is the calibrated soil moisture content at each depth and placement. The mean θ within a certain soil layer was weight-averaged based on the depth of sensor installation. The mean field capacity (θ_{f}) in 0-1 m soil layer of testing soil is 18.0 % by field observation. The minimum soil moisture content (θ_{min}) measured during three years was 2.3 %. Relative extractable water (REW) in the upper 1.0 m soil layer was calculated using Eq. (4) (Granier, 1987).

$$\mathrm{REW} = \frac{\overline{\theta}_{0-1.0\ m} - \theta_{min}}{\theta_f - \theta_{min}} \qquad （4）$$

The more specific classification to quantify the degree of drought at our site is defined in **Table 2**.

Groundwater table (g_{w}) was monitored *in situ* manually once per month using a measuring tape with a cone.

Table 2 Classification of soil drought based on relative extractable water (REW) from the measurements and preliminary reports in Mongolian Scots pine. The T_{r} indicates transpiration rate, C_{s} for stomatal conductance and C_{i} for intercellular carbon oxide concentration.

Parameter	Volumetric soil moisture content (%)	REW	Degree of drought	Description for bio-physiological variance
D_0	$\overline{\theta}_{0\text{–}1.0\ \mathrm{m}} > 0.4\ \theta_{\mathrm{f}}$	REW > 0.31	No drought	Normal growth
D_{mil}	$0.3\ \theta_{\mathrm{f}} \leq \overline{\theta}_{0\text{–}1.0\ \mathrm{m}} \leq 0.4\ \theta_{\mathrm{f}}$	0.20≤ REW ≤ 0.31	Mild drought	Weak growth (Jiao, 2001); T_{r} , C_{s} and C_{i} decreased by 46.2 %, 33.2 % and 0.9 %, respectively (Zhu et al., 2005; Tang et al., 2015);
D_{mod}	$0.2\ \theta_{\mathrm{f}} < \overline{\theta}_{0\text{–}1.0\ \mathrm{m}} < 0.3$	0.08 ≤ REW < 0.20	Moderate drought	30% leaves withered (Zhu et al., 2005); T_{r} , C_{s} and

	θ_f			C_i decreased by 62.1 %, 48.6 % and 51.1 %, respectively (Zhu et al., 2005; Tang et al., 2015);
D_s	$\overline{\theta}_{0\text{–}1.0\ \mathrm{m}} \leq 0.2\ \theta_\mathrm{f}$	REW < 0.08	Severely drought	Leaves withered and some of the branch die (Jiao, 2001); T_r , C_s and C_i decreased by 70.9 %, 77.3 % and 67.6 %, respectively (Zhu et al., 2005; Tang et al., 2015)

2.3.3 Sap flux measurements

Sap flux in the outermost sapwood (0–3 cm depth) ($J_{\text{s-outter}}$, cm min^{-1}) was measured continuously using the Granier-type thermal dissipation method (Dynamax Inc., Houston. TX. USA). Each probe was installed under the cambium on the north side of the stem at breast height (1.3 m) with pairs of probes 0.04 m apart vertically. The upper probe included a heater and the lower probe was unheated and so remained at trunk temperature for reference. Each sensor was carefully removed at the end of each growing season and reinstalled next year. The temperature difference between the upper (heated) probe and the lower (reference) probe was measured at 1-min intervals, with mean values recorded at 10-min intervals using SQ2020 data loggers. The sensors were shielded with thick aluminum-faced foam to minimize warming by radiation and exposure to rain and physical damage. The Granier empirical equation for J_s was adopted as Eq. (5):

$$J_{\mathrm{s-outter}} = 119 \times 10^{-4} \left(\frac{\Delta T_0 - \Delta T}{\Delta T}\right)^{1.231} \qquad (5)$$

where ΔT is the actual temperature difference observed between heated and reference probes, and ΔT_0 is the maximum ΔT value when sap flow is close to zero (generally just predawn) determined over about 10 consecutive days (Lu et al., 2004; Dang et al., 2014).

Since the sap flux at inner part of sapwood (beyond 3 cm depth) ($J_{\mathrm{s-inner}}$) is low due to the relative inactivity of conductive xylem, we adopted a coefficient 0.56 (Lu et al., 2004; Nadezhdina et al., 2002) for the calibration.

2.3.4 Calculation of sap flow

Volumetric sap flow ($\mathrm{cm}^3\ \mathrm{h}^{-1}$) were the product of sap flux and corresponding sapwood area. At first, the sap flux measurements J_s was converted to a daily base (Eq. (6)). The daily mean J_t for all measured trees in experiment area was then used to calculate daily transpiration (T_s, mm day^{-1}) of the forestry (Eq. (7)). Because all trees were at the same age and regularly-spaced, each tree was assumed to occupy equal ground per sapwood area. Hence, the ground area fraction of each tree ($A_{\mathrm{g,i}}$, cm^2) was approximated as the product of individual sapwood area and the ratio of total stand sapwood area ($A_{\text{s-stand}}$, m^2) divided by total stand ground area ($A_{\text{g-stand}}$, m^2).

$$J_{\mathrm{t,i}} = \sum_{j=1}^{24} \frac{(J_{\mathrm{s-outter,i}} \times A_{\mathrm{s-outter,i}} + J_{\mathrm{s-inner,i}} \times A_{\mathrm{s-inner,i}}) A_{\mathrm{s,i}}}{A_{\mathrm{g,i}}} \times 60 \tag{6}$$

$$T_\mathrm{s} = \frac{1}{n} \sum_{i=1}^{n} J_{\mathrm{t,i}} \tag{7}$$

where,

$J_{\text{s-outter, i}}$ is the mean sap flux density in the probe-touched sapwood of a tree i and $J_{\text{s-inner, i}}$ is probe-untouched part, $A_{\mathrm{s,\ i}}$ is sapwood area of tree i ($A_{\text{s-outter}} + A_{\text{s-inner}}$), $A_{\mathrm{g,\ i}}$ is ground area of a tree i weighted by sapwood area, $J_{\mathrm{t,\ i}}$ is the daily sap flow of a tree i (mm day^{-1}), n is the numbers of trees measured each year.

2.4 Statistical analyses

The effect of soil moisture content on normalized transpiration (T_s / ET_0) was tested by one-way analysis of variance (ANOVA) and a Tukey HSD *post hoc* multiple comparisons test using SPSS 20 (SPSS Inc., Chicago, IL, USA). Significant correlations between T_s or T_s / ET_0 and environmental factors over different periods were determined by Pearson's correction coefficient tests at $P < 0.05$ or 0.01. The other statistical analyses and plots employed OriginPro 2016 version 9.3 (OriginLan Inc., Northampton, MA, USA).

3 Results

3.1 Seasonal dynamics of stand transpiration and environmental factors

The amounts of precipitation during the investigation periods were 554 mm in 2013, 384 mm in 2014 and 408 mm in 2015.

Rainfall was concentrated over quite short periods (**Fig. 4a**). The rainfall variation in experimental years in study region was high.

Daily soil moisture content exhibited large variances. The heterogeneity of soil moisture content with soil depth was significant ($P < 0.01$). In a wet year 2013, soil moisture content was higher than a dry year 2014 (**Fig. 4b**). In the second dry year 2015, there was a long drought period in July and August. After a heavy rainfall in late August (232 days), the soil of both upper and deep layers were refilled with a high soil moisture content. Based on our classifications (**Table 2**), the days of moderate and severe drought ($D_{\mathrm{mod}} + D_{\mathrm{s}}$) accounted for 19 %, 34 %, 66 % and 85 % of the whole three-year period for the four soil layers at 0–0.6, 0.6–1, 1–1.5 and 1.5–2 m, respectively. Thus, for MP it is the upper 1.0 m soil layer that provides the main water source, having the highest levels of soil moisture $\overline{\theta}_{0\text{–}0.6\ \mathrm{m}}$ and $\overline{\theta}_{0.6\text{–}1\ \mathrm{m}}$. Intense rainfall that infiltrated to, and thus helped recharge, the deeper layers of soil ($\overline{\theta}_{1.5\text{–}2\ \mathrm{m}}$) were very rare from the later July in 2013 to later August in 2015.

There were no significant differences between years for daily R_{s} ($P = 0.4$) or daily mean D ($P = 0.25$) (**Figs. 4c, 4d**). The D over the whole period never exceeded 2.4 kPa (**Fig. 4d**). The groundwater table (g_{w}) at the start of the experiment was 5.2 m but significantly lowered to 5.6 m at the end of the experiment in 2015 (**Fig. 4e**).

The daily T_{s} showed similar seasonal patterns with R_{s} (**Fig. 4f**), indicating the radiation was a major factor to affect plant transpiration. Overall, T_{s} was at a relative high level in May each year until August, and then gradually decreased to a low level in late October. The seasonal dynamics of T_{s} reflected the variations in physiological traits of MP and meteorological factors. The T_{s} between the years was significantly different ($P < 0.01$). The maximum daily T_{s} in 2013 was 3.73 mm day^{-1} with a mean value of 1.94 mm day^{-1} during growing season. In 2014, the maximum daily and seasonal average T_{s} were decreased to 2.55 mm day^{-1} and 1.46 mm day^{-1}. In 2015, the great decrease of maximum T_{s} occurred down to a value of 1.40 mm day^{-1}, as well as for the seasonal mean down to 0.81 mm day^{-1} (**Fig. 4f**). The decreasing T_{s} between seasons was partially due to less rainfall and water availability, and probably also due to the plant recovery capability in relation to the permanent changes in plant physiological traits.

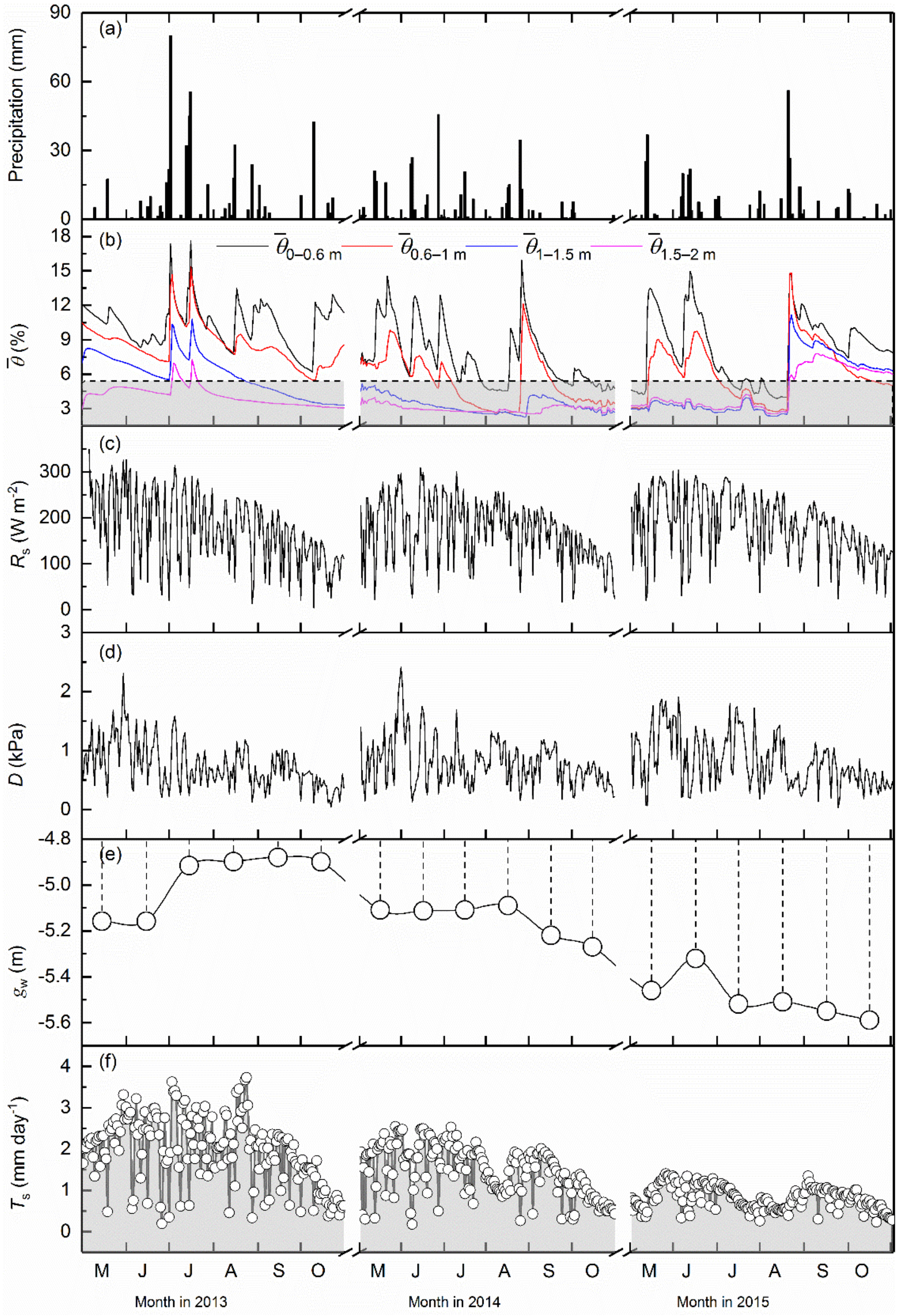

Figure 4 Seasonal time courses of precipitation, mean volumetric soil moisture content ($\overline{\theta}$), solar radiation (R_s), vapour pressure deficit (D), groundwater table (g_w), and daily mean sap flux of stands (T_s) in 2012 to 2015. The grey area in (b) indicates moderate and severe drought.

3.2 Normalized transpiration affected by soil relative extractable water

The normalized transpiration T_s / ET_0 under sufficient water supply D_0 was about 0.29 ± 0.09 (**Fig. 5a**), 15% higher than under mild drought, 62% higher than under moderate drought and 149 % higher than under severe drought. The maximum ratio of daily sap flux to reference evapotranspiration (T_s / ET_0) increased with REW sharply at low REW but keep constant when the REW was above 0.31 (**Fig. 5b**). This indicated that there are the other factors besides the atmospheric and soil moisture affected the water use of MP, in which the stomatal regulation or the seasonal variation of biological rhythms is important one.

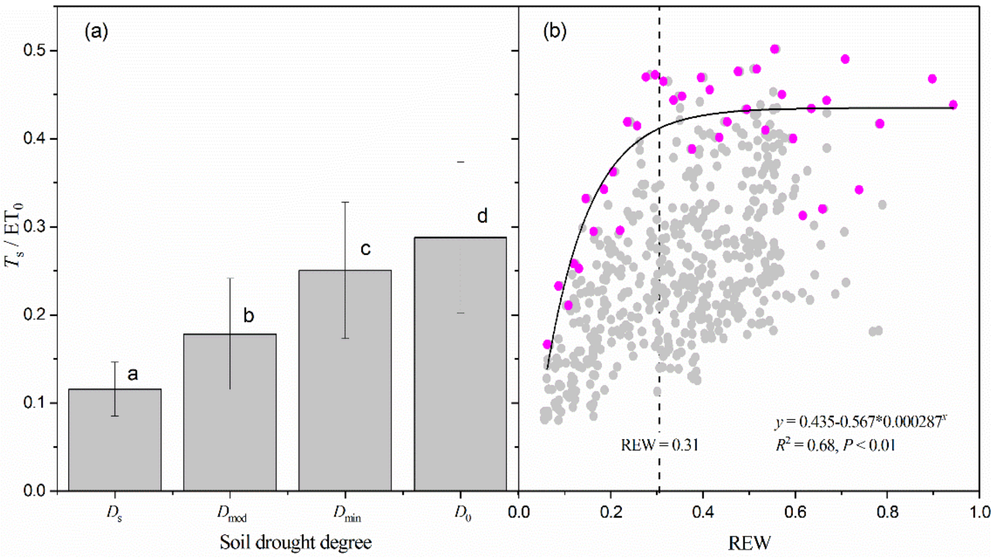

Figure 5 Normalized transpiration T_s / ET_0 affected by soil droughts. Normalized sap flux by using reference evapotranspiration indicates a potential transpiration ability under maximum evaporative demand caused by metrological factors, the relationship between T_s /ET_0 and relative extractable water (REW) is mainly affected by plant traits. The maximum of T_s / ET_0 at the REW step of 0.02(dimensionless) are selected out (red circles in (b)) and modelled by an exponential function. The dashed line is at REW=0.31. Values of T_s / ET_0 followed by different letters are significantly different at $P < 0.05$ by univariate ANOVA (post hoc Tukey HSD).

3.3 Progressive decline of sap flux with developing of drought and recovery following rain

The 49-day periods from DOY 203 to 251 each year was chosen to illustrate the changes in T_s with REW, a dry-wet shift. In the period of wet year (2013), the soil moisture is always in D_0 (without water stress) and mean T_s was about 2.15 mm day^{-1} (**Fig. 6a**). In the first dry year (2014), T_s decreased by as much as 18 % under a mild water stress (D_{mil}) and further by 40 % under moderate stress (D_{mod}). The T_s was greatly recovered after a heavy rain (**Fig. 6b**). In the second dry year (2015), the T_s decreased by 73 % under D_{mod} and further by 74 % under D_s stage (**Fig. 6c**). The daily T_s under D_s was only 0.55 mm day^{-1}. This very little transpiration likely only sufficient to maintain the survival of MP. After a heavy rainfall, even the soil water status was improved a lot, the T_s of trees was still very low (less than 1.4 mm day^{-1}), indicating the T_s of MP was difficult to be recovered.

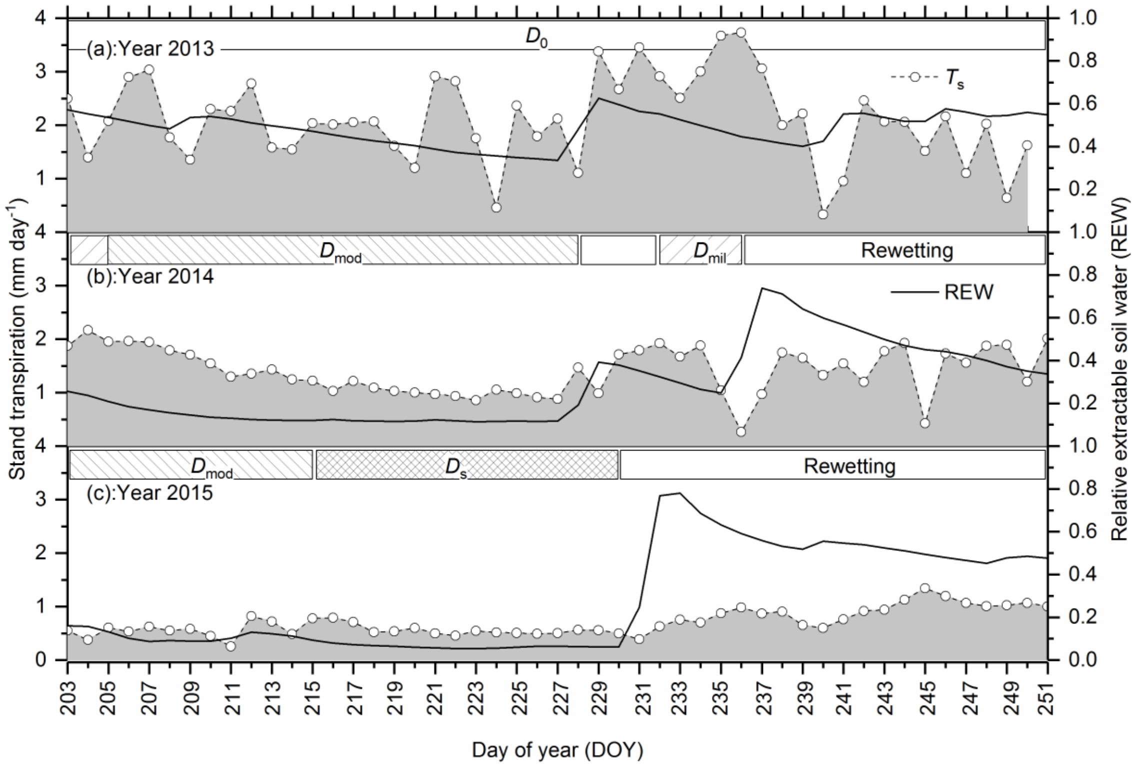

Figure 6 The comparison of measured transpiration (T_s) and relative extractable water (REW) in the upper soil layer (above 1 m) during maximum growth period from DOY 203 to 251 in 2013 to 2015. D_0, D_{mil}, D_{mod}, and D_s are no, mild, moderate and severe droughts, respectively (see Table 2). The increase of REW was due to the rainfall.

4 Discussion

4.1 Reduction of soil moisture content under droughts

In our site, the long term trends for increasing air temperature and decreasing annual precipitation (**Fig. 2**) is unfavorable to the growth of trees. The declining groundwater and the coarse sandy soil (>83 % sand particles in our site) prevented capillary ascension efficiently (less than 0.5 m) (Vincke and Thiry, 2008). Sandy soils have low water holding capacity and high hydraulic conductivity, thus water percolates through this soil quickly after a rain. During the three-year periods in our site, there are an effective rain event every 14 days averagely (rainfall intensity is more than 10 mm per times). Under well-wetted soil conditions (D_0), $\overline{\theta}_{0\text{–}1.0\ \text{m}}$ was depleted at the high rate of 1.9 vol % per day during the first two days and at the rate of 0.35 vol % per day during the subsequent nine days (**Fig. 7**) because of either soil water holding capacity or great water uptake by trees.

The depleting rate of $\overline{\theta}_{0\text{–}1.0\ \mathrm{m}}$ under the drought conditions was only 0.09 vol % per day under severe drought. That indicates the only little of water was absorbed by trees under severe water stress. Our results suggested the plant might adjust their physiological traits, e.g. closing stomatal and reduing root system to at first priority for the survival. The sap flux declines very quickly in desiccated root system (Mereu et al., 2009).

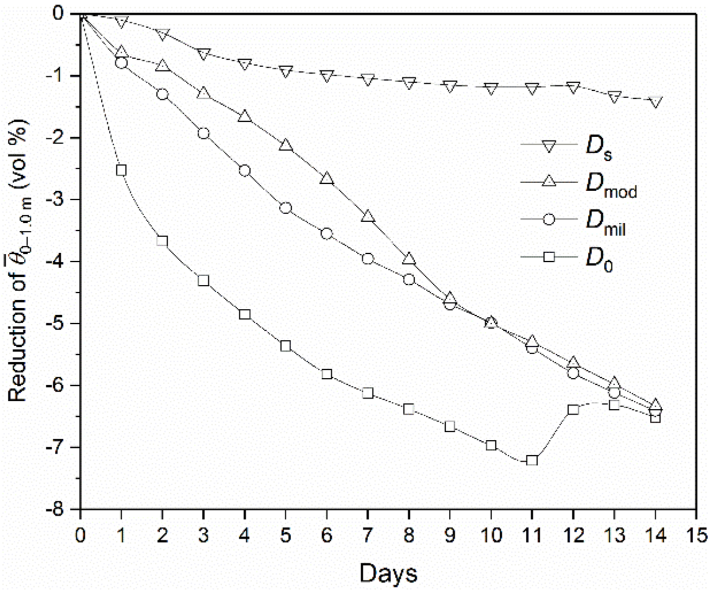

Figure 7 There will be an effective rain event every 14 days averagely in our site (Rainfall intensity is more than 10 mm per times), which acted as a window to analyze the decrease rate of soil water during this period. Scatter-line plot described the relationships between decrease rate of upper soil moisture ($\overline{\theta}_{0\text{–}1.0\ \mathrm{m}}$) and time under different initial degree of drought levels which were defined in **Table 2**.

4.2 Contribution of water in the upper and deep soil layers

The MP is a shallow-rooted species with root density decreasing sharply below 1.0 m (Jiang et al., 2002; Zhu et al., 2005; Zhu et al., 2008), implying the soil moisture in the upper 1.0 m layer provides major water source for transpiration (Su et al., 2006; Wei et al., 2013; Song et al., 2014). In our study, the rapid recovery of T_s when $\boldsymbol{\overline{\theta}}_{0\text{–}1.0\ \mathrm{m}}$ was increased after a rain (**Figs. 4 and 6**) suggested that MP was very sensitive to the changes in the available water in the upper soil layer. Uptake by the shallow roots decreased very significant as this soil layer dried out (**Fig. 6**). However, under severe drought, for example in August of 2015, the MP trees used quite amount of deep soil water. It might be carried out by developing more letaral root system in deep soil. The fine roots of Scots pine die quickly under drought conditions (Vanguelova and Kennedy, 2007). Therefore, it would cause a death of new developed fine root system, resulting a permanent declining in the capability of transpiring water even when the soil water status was improved (**Fig. 4**). The death of fine root in deep soil layer may explain why after a rainfall, post-stress sap flux recovery is very small after a long and severe drought in 2015.

4.3 Groundwater is an important source for plant adaptation under long and severe drought

Mongolian Scots pine is a dimorphic-rooted species where, the maximum taproot depth in a sandy soil can up to 2.7 m (Canadell et al., 1996), and even to 5.2 m for a 42-year-old tree in a sandy soil near our site (Jiang et al., 2002). Our results on the depletion of soil water in 1.5-2 m soil layers, existed but not large, also suggested a deep taproot depth in MP. This enables MP trees to use deeper water source (i.e. groundwater), especially under drought (Barbeta et al., 2015; Hentschel et al., 2016). This is likely to occur when soil moisture content in the upper soil layers (0–60 cm) declines to 3.6 % (Wei et al., 2013; Song et al., 2016a). In our site, g_w lowered from 5.03 ± 0.14 m in 2013 to 5.47 ± 0.09 m in 2015 (**Fig. 4e**). From late 2014, the value of g_w was always far deeper than 5.2 m and thus unlikely accessible directly by our instrumented trees if their tap roots were shallower than 5.2 m. However, in the severe drought (D_s, with minimum $\overline{\theta}_{0\text{–}1.0\ \text{m}}$ as low as 2.3 %), we recorded a clear diurnal pattern of sap flux with the much reduced daily T_s (mean 0.56 mm day^{-1}, or 28.2 % of that for D_0). Hence, we inferred that significant groundwater contributions to T_s occurred only under severe drought conditions though determining just what proportion of that water came from the groundwater or from tree storage is beyond the scope of this study. It has been reported that as rainfall decreases, tree dependence on groundwater increases (Kume et al., 2007).

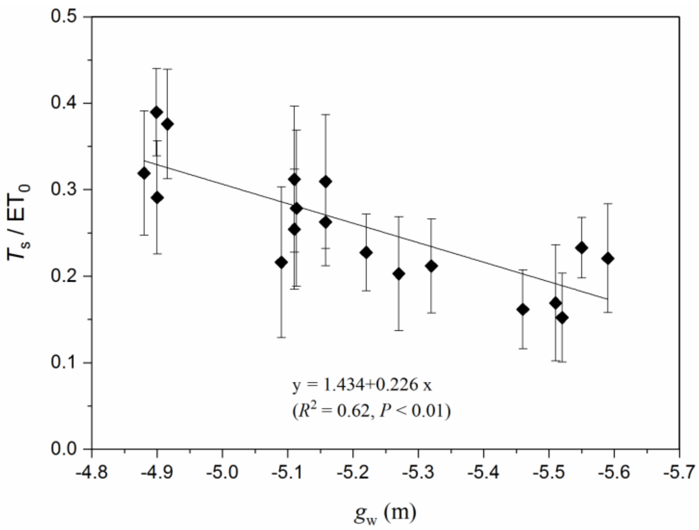

Figure 8 Normalized transpiration (T_s / ET_0) in Mongolian Scots pine affected by the groundwater table (g_w) .

4.4 Transpiration of the plantation and implications

There is a complex interplay between the various meteorological factors, e.g. solar radiation, vapour pressure deficit, air temperature, wind speed and relative humidity, and directly or indirectly influences transpiration in a tree. These variables were aggregated into a variable ET_0, which serves as an index of atmospheric water demand power (Zha et al., 2010). Therefore, as expected, changes in ET_0 trigger a prompt plant response in terms of transpiration. Changes in precipitation (and hence soil mositure) affect transpiration but likely over a long temporal scale (Yan et al., 2016). Our results also showed a strong reduction in normalized transpiration T_s / ET_0 mostly after a long period drought. Using normalized transpiration allows to focus on the effects of soil water availability and plant physiological responses. This behavior has also been found in Scots pine in Europe (Poyatos et al., 2005), presenting the strong effects of stomatal regulation for controlling the rate of water loss. The significant fall in g_w seems to explain the difficulty in plant recovery of T_s after a heavy rain.

The reduction in transpiration of MP due to soil water shortage was 25% in first dry year and 58% in the second dry year (**Table 3**). This is comparable with reported values of 40 to 80 % for different species in different habitats (Leuzinger et al., 2005; Gartner et al., 2009; Betsch et al., 2011). Average cumulative T_s values in testing MP during a whole growing season ranged from 145 to 357 mm. This was higher than in a sparse forest of 150-year-old Scots pine growing in an inner Alpine dry valley (Wieser et al., 2014) and in northeastern Germany (Lüttschwager et al., 1998) due to the larger canopy size and environmental conditions. In this study, the annual water transpiration by MP in wet year (357 mm) is nearly equal to 75 % of the total annual precipitation in a historical normal year. However, considering the soil evaporation, transpiration by understory plants (e.g. weeds), and leaf interception and vaporization, the current stand density of 625 trees per ha is likely too high for a sustainable ecosystem of Mongolian Scots pine forestry.

Transpiration in a coniferous forest is often conservative with relatively low values of canopy conductance (Levitt, 1980). For instance, Scots pine has a rather conservative water use strategy with a very plastic response to intermittent dry periods with high use of stored water (Arneth et al., 2006; Verbeeck et al., 2007). In our study, we found MP was more moderate in its water consumption than many broad-leaved forest tree species growing nearby (e.g. *Populus* spp) (Zhu et al., 2005). Although the groundwater table decreases in our experiment, the MP still contributes less to the groundwater table decline than the more extensive and/or intensive agricultural land uses (0.1 m per year) (Song et al., 2016b). The lateral roots of an MP tree can extend laterally to about 0.65-times tree height (Jiang et al., 2002; Su et al., 2006). This helps MP to obtain water from the upper soil layers efficiently (Song et al., 2014). The ability of MP to maintain a low sap flux even during severe drought suggests a strong adaptation under climate change (Waromg et al., 1979), especially when the extreme weather events increase in the future. However, the advanced mature period was found when Mongolian Scots pine introduced from the north (origin distribution region) to south (planted region, this study area) (Jiao et al. 1989; 2001). The difficulty in recovery for water uptake by 30 years MP trees under severe drought might also caused by the low growth vigor of old trees. It implies that the re-forestry might be necessary when MP trees are over 30 years old.

5 Conclusions

Mongolian Scots pine was relatively conservative in water use with a maximum of 3.73 mm day^{-1}. Stand transpiration during the growing season ranged from 149 mm in an extreme dry year to 357 mm in a wet year. The sap flux in MP responded strongly to soil water availability. The daily sap flux reduced with drought by 74% as the duration and intensity of drought was high in dry years. The ability of recovery in plant transpiration was limited by the duration and severity of drought. Our results suggest that the degradation in MP plantation is attributable to the combined effects of large temporal variation in rainfall and the ability of specific recovery after the occurrence of drought. The results could help farmer improve the management and sustainability of MP forestry by optimizing plant density and reforestation in semi-arid region.

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