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Soil-water deficit in deep soil layers results from the planted forest in a semi-arid sandy land: Implications for sustainable agroforestry water management

Ze Huang [a,b], Yu Liu [a], Kaiyang Qiu [b], Manuel López-Vicente [c], Weibo Shen [a,*], Gao-Lin Wu [a,b,d,**]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, College of Natural Resources and Environment, Northwest A & F University, Yangling, Shaanxi 712100, China
[b] School of Agriculture, Ningxia University, Yinchuan, Ningxia 750021, China
[c] Group Aquaterra, Advanced Scientific Research Center, University of A Coruña, As Carballeiras, s/n, Campus de Elviña, 15071 La Coruña, Spain
[d] CAS Center for Excellence in Quaternary Science and Global Change, Xi'an 710061, China

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ABSTRACT

Forest planting is a common practice in semi-arid sandy land restoration, but problems may appear associated with forest age like higher soil water consumption that threatens restoration program's success. This study quantified the distribution and variation of soil water storage in a *Pinus sylvestris* (*P. sylvestris*) plantation under various stand ages (20, 30, 40, 50 and 60 years) along 0–1000 cm soil profile in the Mu Us sandy lands (North China). Results indicated that the 20-yr forests mainly consumed the soil water of the 0–200 cm depth soil profile, the 30-yr and 40-yr forests mainly consumed the soil water of the depth of 0–400 cm, whereas the oldest (50–60-yr) pines mainly consumed the soil water located at the deepest soil profile (500–700 cm). Variation of soil water storage (△*SWS*) was decreased with stand ages, reaching the minimum value in the 30–40-yr stands, and then gradually increased in the 50–60-yr stands. The △*SWS* was relatively uniform on the 50-yr and 60-yr stands. this pattern was associated with soil desiccation and soil-water depletion. The lower △SWS indicated lower soil water storage which was associated with soil desiccation and soil-water depletion. These findings proved that planted forest gradually aggravated soil water consumption along the increasing forest age, caused a serious soil water deficit in the 200–700 cm depth soil layer, which may be exceeding the water environmental carrying capacity. Therefore, we suggest that forest should be thinned on the periods with the highest △SWS, which would maintain long-term forest sustainability by minimizing soil desiccation for planted forest management in semi-arid sandy lands.

1. Introduction

Drylands account for 41% of the global land surface, and land degradation affects 10%–20% of these landscapes (UNCCD, United Nations Convention to Combat Desertification, 1994; Reynolds et al., 2007; Wang et al., 2015). Land degradation has become one of the serious environmental problems in the world (Ravi et al., 2010; Culas, 2012; Tomasella et al., 2018) because it threatens topsoil fertility –associated with crop yield–, human well-being and ecosystem services. Desertification is a phenomenon of land degradation, which occurs in arid, semi-arid and dry- or sub-humid areas (Reynolds et al., 2007; Zheng et al., 2012) as an outcome of complex interactions between climatic variations and human activities. Desertification were accelerated and exacerbated by anthropogenic activities (D'Odorico et al., 2013; Seddon et al., 2016; Sterk et al., 2016). In semi-arid areas, the sandy land ecosystem was generally fragile and it gradually tends to desertification owing to social and economic development and the continuous increase of population and livestock (D'Odorico et al., 2013; Mganga et al., 2018). In this ecosystem, landscape degradation was occurring at an alarming rate (MEA, 2005), agricultural productivity

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* Corresponding author.

** Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, College of Natural Resources and Environment, Northwest A & F University, Yangling, Shaanxi 712100, China.

E-mail addresses: shenweibo@nwafu.edu.cn (W. Shen), wugaolin@nwsuaf.edu.cn (G.-L. Wu).

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was declining (Ohte et al., 2003), and human pressure on land degradation was increasing. The social and environmental problems caused by desertification have become one of the key elements hindering sustainable development in these landscapes since the 1990 s (Fleskens and Stringer, 2014; Jiang et al., 2019).

In order to prevent desertification and improve soil properties in semi-arid sandy land areas, the shelterbelt systems have been advocated and established in desertification-prone areas (Souza et al., 2013; Zheng et al., 2012). After decades of implementation, some benefits were observed, namely: i) the vegetation coverage has increased in the sandy land, ii) the harm of wind-sand has been reduced, and iii) the production and life conditions of people have been improved (Teng et al., 2019; Geeson et al., 2016; D'Odorico et al., 2013). For example, in China, the *Pinus sylvestris* (*P. sylvestris*) forests were introduced to prevent wind erosion and hold sand due to its cold tolerance and adaptability to the harsh environmental conditions of the semi-arid regions (Zhu et al., 2008). At this time, *P. sylvestris* is one of the main sand fixation species planted to combat wind erosion (Song et al., 2018; Wang et al., 2015). However, the planted forest has brought a series of negative effects with the increase in planting years. After several decades of planting, some studies have found that some of the *P. sylvestris* forests began to die and the groundwater level dropped in particular after 30–35 years of plantation (Song et al., 2016b; Zheng et al., 2012). The decline of SWC was the most important reason to explain the death of *P. sylvestris* forests (Liu et al., 2017). Therefore, there is an urgent need for the evaluation of SWC dynamics and its interaction with natural and planted vegetation.

Soil water is the main water source that plants can utilize, which is generally supplemented by rainfall and groundwater (Duan et al., 2008). Water limitation is a serious restrictive indicator for plant growth in semi-arid sandy land ecosystems (D'Odorico et al., 2013; Lamoureux et al., 2018; Song et al., 2016a; Wei et al., 2019). The severe soil water deficit could cause the degradation of plants and desertification in the frail sandy land (Zucca et al., 2011). Thus, water scarcity is a huge challenge for plants growth in semi-arid sandy land areas (Lamoureux et al., 2018). For this reason, plants with different survival strategies to cope with water scarcity. For instance, many plant species presented different root systems that allow them to switch between shallow and deep water for normal growth in arid and semi-arid regions (Nie et al., 2012; Prieto et al., 2012). In addition, deep water reserves are essential for vegetation to withstand dry periods in water-limited drylands (Barbeta et al., 2014). Generally, older forests are more dependent on deep soil water than younger forests (Drake et al., 2011; Kerhoulas et al., 2013), while young forests were more susceptible to drought than older forests (Giordano et al., 2011). Song et al. (2016b) studied the water use patterns of planted forest under different ages in a semi-arid sandy land of Northeast China, and reported that the 10- and 22-year-old forests used water from the 20–100 cm soil layers, but the 32- and 42-year-old forests could absorb water from groundwater, and the contribution of groundwater to forest transpiration increased with the decrease of soil water. Thus, the planting of deep-rooted forests in sandy land led to an increase of soil water evaporation and groundwater consumption that aggravated soil water scarcity (Li et al., 2016; Smits et al., 2012).

Moreover, the management practice showed significant effects on the water consumption intensity of plants, and played an essential role in maintaining the survival rates and the continuous growth of planted forests (Zucca et al., 2011). Several decades ago, due to ignoring the effects of planting patterns together with the influence of climate change to future vegetation survival, the issues gradually emerged, such as vegetation degradation, soil water deficit and groundwater recession, which was the legacy problem of vegetation restoration. Nowadays, the best way to solve or remit the excessive consumption of soil water and maintain the vegetation sustainability may be thinning forests during the suitable growth period.

Therefore, it is necessary to understand the soil water changes for developing practical measures which could help protect and restore degraded sandy ecosystems in arid and semi-arid land environments (Matzner et al., 2003). However, the spatio-temporal relationships between soil water and the stand ages remain poorly understood in some ecosystems. In this study, soil water variation of *P. sylvestris* forest at different stand ages along 0–1000 cm soil layer were analyzed. The aims of this study were: (1) to quantify the variation of sandy soil water storage in the soil depth of 0–1000 cm along the stand ages; and (2) to determine the mainly soil water consumption layers of planted *P. sylvestris* forest with different stand ages in sandy land. These results will be contributed to better understand the existing relationships between the soil water content and the stand ages of forest plantations in semi-arid sandy land, and provide basis for the proper management of artificial forest in semi-arid sandy land areas for landowners and policy makers.

2. Materials and methods

2.1. Study site

The experiment was conducted in the Hongshixia forest park (38°19′ N, 109°42′ E), located 5 kilometers north of Yulin city, in Shaanxi Province, northwest China. The study region is the junction of Shaanxi, Shanxi and Inner Mongolia, which is also located at the southern rim of the Mu Us desert. The study area is a wind-sand grass shoal located at an elevation of ca. 1100 m a.s.l. The climate is monsoon-influenced semi-arid continental with a warm temperate zone. This part of inland China has obvious continental climate and the underlying surface contributes to the sandy climate characteristics. This region is characterized by a dry spring with sufficient sunshine, a hot summer with concentrated precipitation, a rainy autumn with marked temperature differences and a cold winter with windy sand storms. The mean annual temperature is 7.9 ℃ with minimum and maximum air temperatures of −32.7 ℃ and 37.2 ℃, respectively. The average temperature is ca. −10 ℃ and 24 ℃ in the coldest (January) and hottest (July) months, respectively. The annual frost-free period lasts 130–150 d and the mean annual sunshine duration is 2900 h. The mean annual precipitation is 415 mm, and most rainfall occurs as rainstorms, primarily occurs from July to September, accounting for 60%–70% of the total annual rainfall. Annual evaporation is 4–10 times of annual precipitation. The soil in the study area is the common aeolian sandy soil of the semi-arid areas of northwest China, which is characterized by loose structure and poor quality. The mean sediment concentration is 92.6%, and pH is between 8.01 and 8.71.

The dominant natural vegetation species include *Artemisia ordosica* and *Salix Psammophila.* Nowadays, the *Pinus sylvestris* (*P. sylvestris*) forests are distributed in the Greater Xing'an Mountains of China. This species of pine is so adaptable that it can grow in eolian sand, slope sand, windward slope sand and loess stone field. The *P. sylvestris* has become the main introduced species in the semi-arid deserted areas of China at present (Wang et al., 2015; Song et al., 2018). Near the study area, the *P. sylvestris* was introduced from the forestry bureau of Honghua Erji (119°43′–119°51′ E , 48°06′–48°07′ N) in Hulun Buir, Inner Mongolia and planted in 1964. Then, it began to be planted in large areas after the 1980 s, interspersed with shrubs such as *Amorpha fruticosa* and *Hippophae rhamnoides.*

2.2. Experimental design, soil sampling and soil water storage estimate

This experiment used the method of spatial sequence instead of temporal sequence to study the effects of stand ages of forestland to soil water conditions. Five different ages: 20-, 30-, 40-, 50- and 60-year-old *P. sylvestris* were selected. A bare control land was also chosen at the Hongshixia forest park. *P. sylvestris* with different forest ages has a certain distance (approximately 100 m), and the sampling points were selected in the inner of each plot to avoid the edge effects. The slope of the study area is approximately 2–3^{o} at an altitude of about 1100 m. In the five artificial forests, almost an equal number of seedlings of

P. sylvestris were planted. Plant death occurred because of the survival rate and natural selection, and after they died the trees were not left in the artificial forest.

In each of the five age groups, five plots (50 × 20 m) were established, and three quadrats (10 × 10 m) were chosen in each plot. The density (trees per hectare) and diameter at breast height (DHB; cm) were measured in all quadrats (Fig. 1). DHB were measured at a height of 1.3 m of trees. In the experimental design, nine sampling points were established in the bare land and in each forest of the five age groups. The measurement of soil water content along 0–1000 cm soil profile was finished within two weeks in July, 2018. Five days before and during measurement, there was no effective precipitation (> 5 mm). The variation of soil water content between forest and bare land generally represents the water consumption of forest at different stages. Due to some constraints associated with the natural environment of the study area and human and material resources, it was difficult to collect soil samples of the 0–1000 cm depth layer in some extent during the sampling process. In total, three complete sampling points were chosen in each treatment and the bare land, respectively. In each plot, the distance from tress to sampling point was the same to avoid the spatial heterogeneity caused by root distribution. Soil samples to a depth of 1000 cm were obtained by a soil auger (40 mm of diameter) at 10 cm intervals for one point. The soil samples were weighed in aluminum boxes, and then, oven-dried to constant weight in a given context (105 ℃, 24 h). The soil bulk density (*B*; g cm^{-3}) was measured at 10 cm intervals, by using a cutting ring with 100 cm^3 cubage, at each age group. There were three replicate samples to estimate the average values for each soil layer.

The soil water storage (*SWS*; mm) and the variation of *SWS* (ΔS; mm) were calculated by the following formula:

$$SWS_i = D_i \times B \times SWC \times 10^{-1} \quad (1)$$

$$\Delta S = S_{is} - S_{ib} \quad (2)$$

where the subscript *i* is the 0-*i* cm soil profile, D_i (cm) is soil depth of *i*, *SWC* (% weight) is the mass soil water content, S_{is} (mm) is the *SWS* of *i* cm under the different stand ages, and S_{ib} is the *SWS* of *i* cm in the bare control land.

2.3. *Statistical analyses*

The statistical analyses were performed using the IBM SPSS 22.0 software (IBM, Montauk, New York, USA). One-way ANOVA (analysis of variance) followed by the Tukey's HSD test was used to analyze the differences of *SWS* and soil water relative deficiency among the different stand ages. Significant differences were evaluated at the 0.05 probability level. All data are presented as means ± standard errors of the means. All figures were created by using the program Origin 9.0 (Origin Lab, Northampton, Massachusetts, USA). Fig. 3 was the contour map of soil water content in 0–1000 cm soil depth along different stand ages of *P. sylvestris*.

3. Results

3.1. *Changes in the planted forest density*

The forest density of afforestation increased firstly and then decreased with increasing stand ages (Fig. 2), and it maintained a similar average rate (ca. 1400 trees per hectare) in the 20-yr, 30-yr and 50-yr stand ages. The density was highest in the 40-yr stand with 1883 trees per hectare and the lowest density was observed in the 60-yr stand (683 trees per hectare).

3.2. *Soil water storage changes in the different planted forest stand ages*

Regarding the soil layers, the *SWS* firstly decreased and then increased with increasing soil depths (Fig. 3). The lowest *SWS* in the 40-yr stand age (ca. 42.66 mm) was found in the 0–200 cm soil profiles. The △*SWS* in the 200–400 cm soil profiles of 30-yr stand age was 36.33 mm. The lowest values of *SWS* of the 50-yr stand age appeared in the soil layers of 400–600 cm (37.78 mm) and 600–800 cm (142.89 mm). In the 800–1000 cm soil profiles, the *SWS* of the bare land (568.96 mm), and of the 20-yr (550.38 mm) and 30-yr (663.94 mm) stand ages were higher than the *SWS* observed in the other stand ages and soil depths: 517.98, 290.45 and 220.04 mm in the 40-yr, 50-yr and 60-yr stand ages, respectively. Then, the *SWS* rapidly decreased after 30 years of forest plantation (Fig. 4).

With respect to the plantation age, the *SWS* firstly decreased and then increased with the increasing stand ages, meanwhile, the *SWS* in the deeper layers (400–1000 cm) was significantly higher than that in the shallow soil layers (0–400 cm) (Fig. 3). The *SWS* suddenly increased in the 800–1000 cm soil layer of the bare land plots (from 166.07 to 568.96 mm) and in a similar way in the 20-yr stand age (from 267.72 to 550.38 mm). In the 400–600 cm soil layer, the *SWS* increased in the 30-yr (from 149.63 to 663.94 mm), 40-yr (from 101.59 to 517.98 mm), and 50-yr stand ages (from 37.78 to 290.45 mm) (Fig. 4). However, none obvious turning point was observed in the *SWS* in the 60-yr stand age. The observed *SWS* at the 200–400 cm depth was similar to the *SWS* at the 400–600 cm (171.10 mm), 600–800 cm (185.42 mm), and

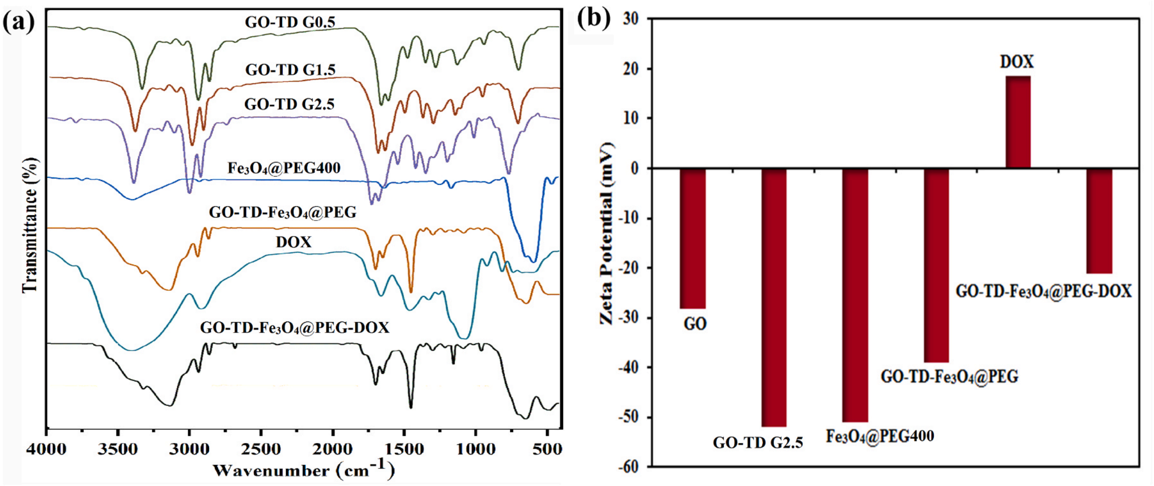

Fig. 1. Location of the artificial forest in the Mu Us Desert (North China) and pictures of the sampling points and stands. DBH is the diameter at breast height. Different lowercase indicated the difference of DBH in different forest ages were significant at 0.05 level.

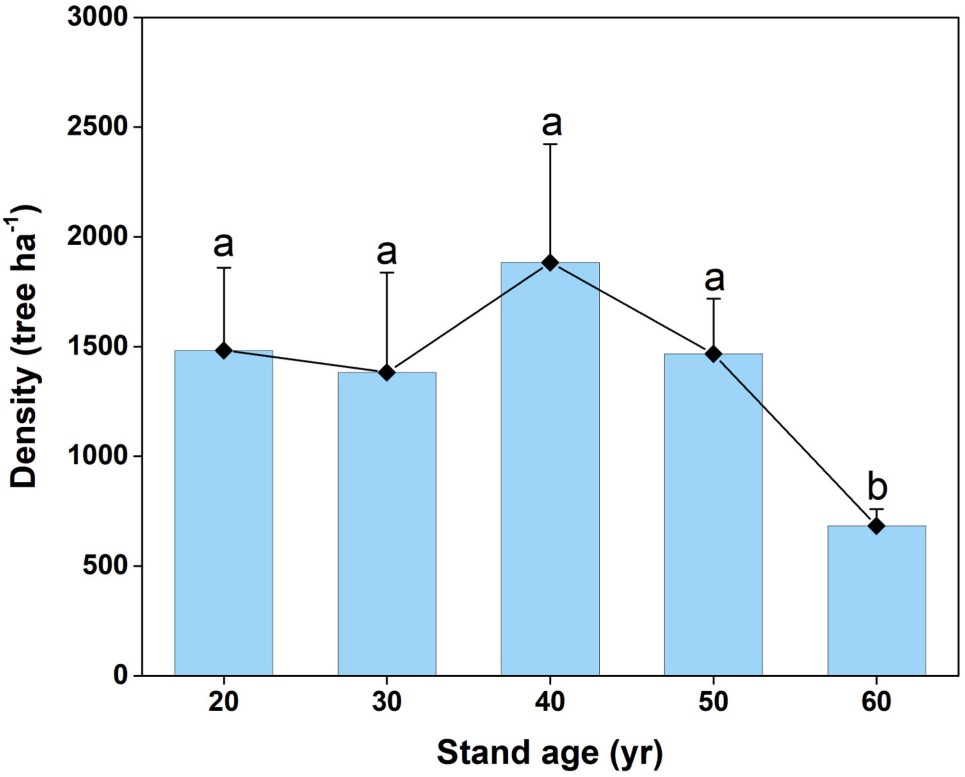

Fig. 2. The density (trees per hectare) of *P. sylvestris* forests under different stand ages in this study. The error bars indicate standard errors. Different lowercase indicated the difference of stand density in different forest ages were significant at 0.05 level.

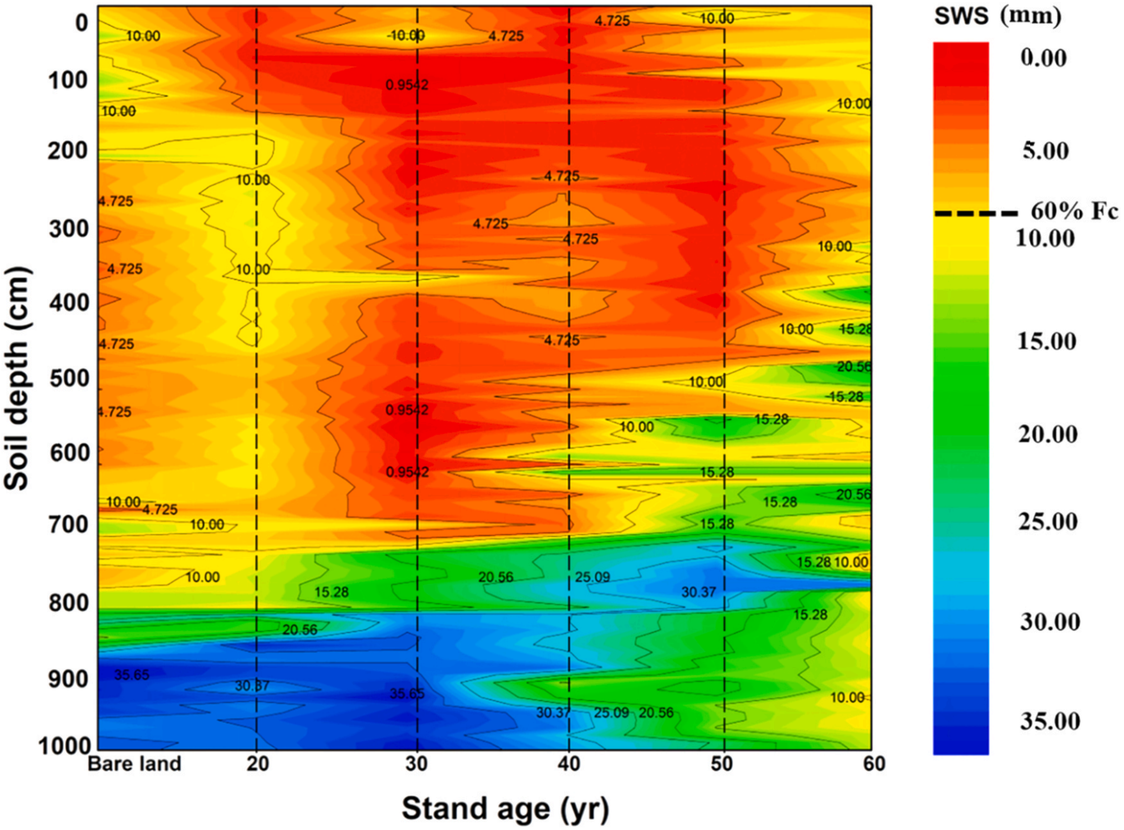

Fig. 3. Vertical distribution of soil water storage (*SWS*) in the bare land and different stand ages. The soil water storage is labelled with Arabic numbers on the soothing contours. Fc indicates the soil water content at field capacity (−33 KPa).

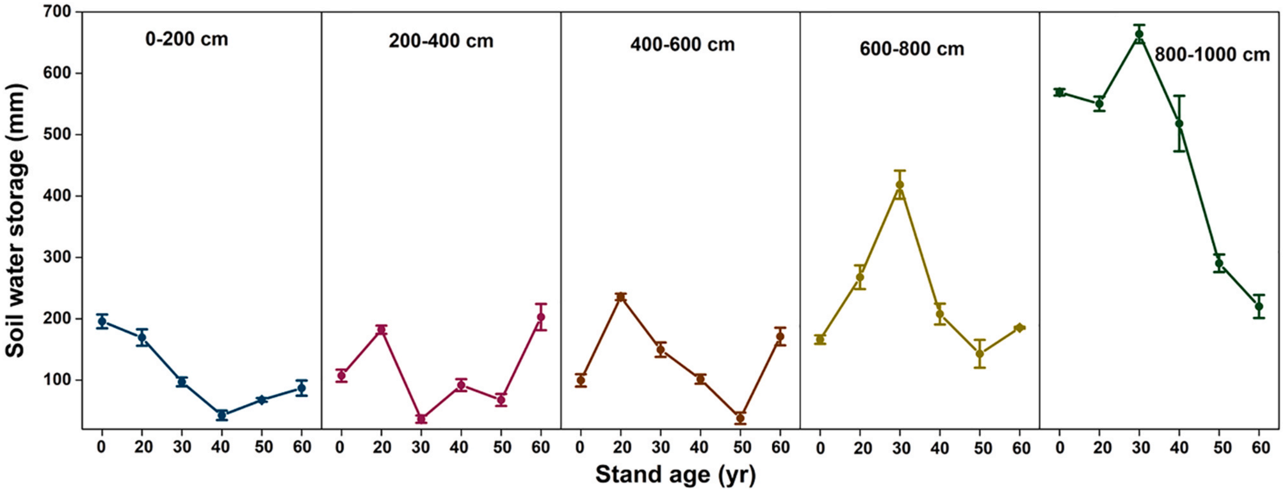

Fig. 4. Soil water storage (*SWS*) of the different stand ages in different soil layers (0–200 cm, 200–400 cm, 400–600 cm, 600–800 cm, 800–1000 cm soil depth). The stand age of 0-yr means bare land. The error bars indicate standard errors.

800–1000 cm (220.04 mm) depths (Fig. 5F).

3.3. *Variations of soil water storage in the soil profile under different planted forest stand ages*

Across each soil layer, the *SWS* was more variable in the bare land (Fig. 6). Compared to bare land, *SWS* in each soil layer and different stand ages were decreased, as well as the variations of *SWS* were lower than zero. In the 20-yr stand age, the variation was − 26.05 mm in the 0–200 cm soil layers. The variations were also negative in the 0–200 and 200–400 cm soil layers in the 30-yr (−97.79 and −153.30 mm, respectively) and 40-yr (−70.86 and −13.59 mm, respectively) stand ages. During the whole period of 50 years, all the variations were negative from the 0–1000 cm soil layers. After 60 years of forest

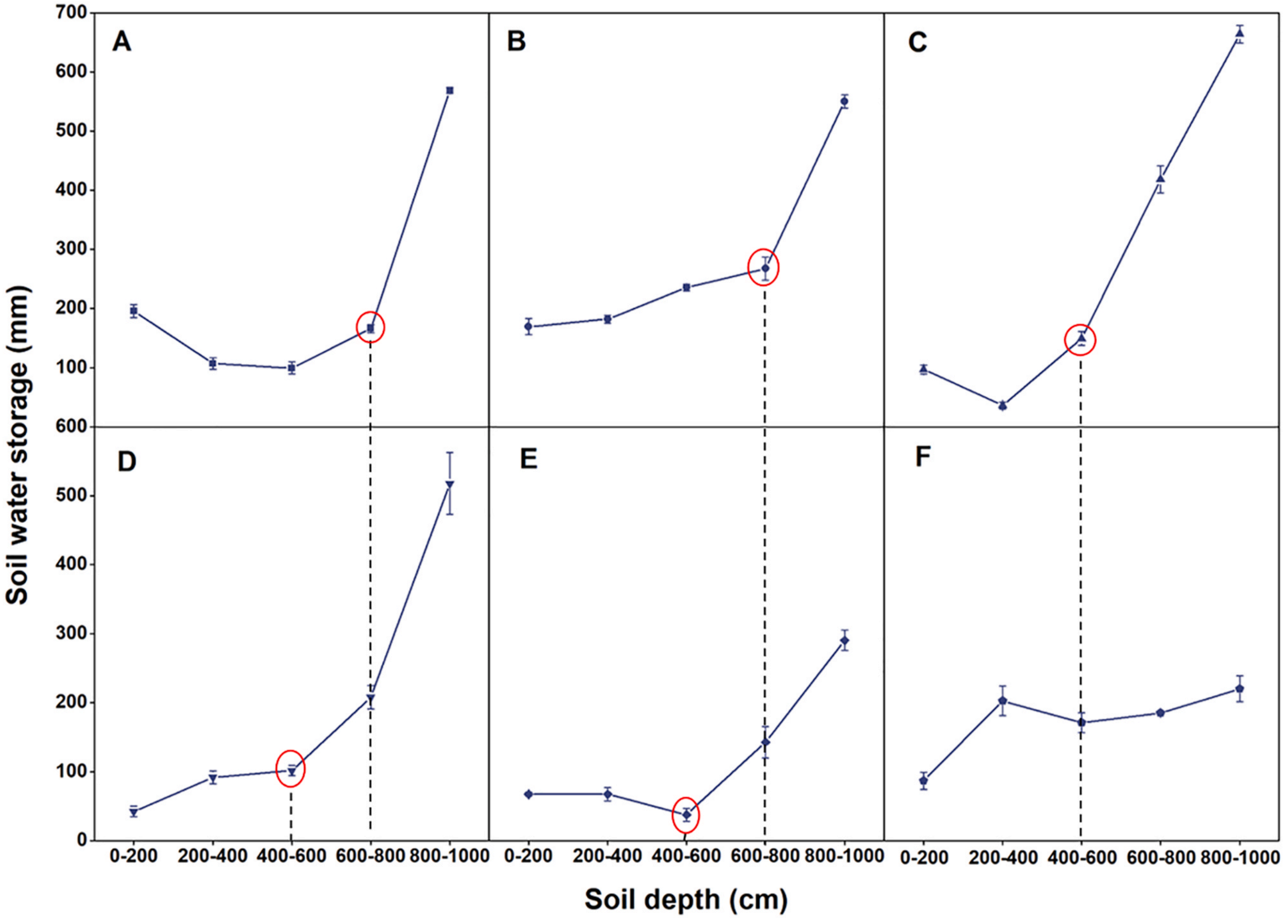

Fig. 5. Soil water storage (*SWS*) under different soil depth and stand ages (A for bare land, B for 20 years, C for 30 years, D for 40 years, E for 50 years, F for 60 years). The red circles mean the turning point. All data are presented as means ± standard errors.

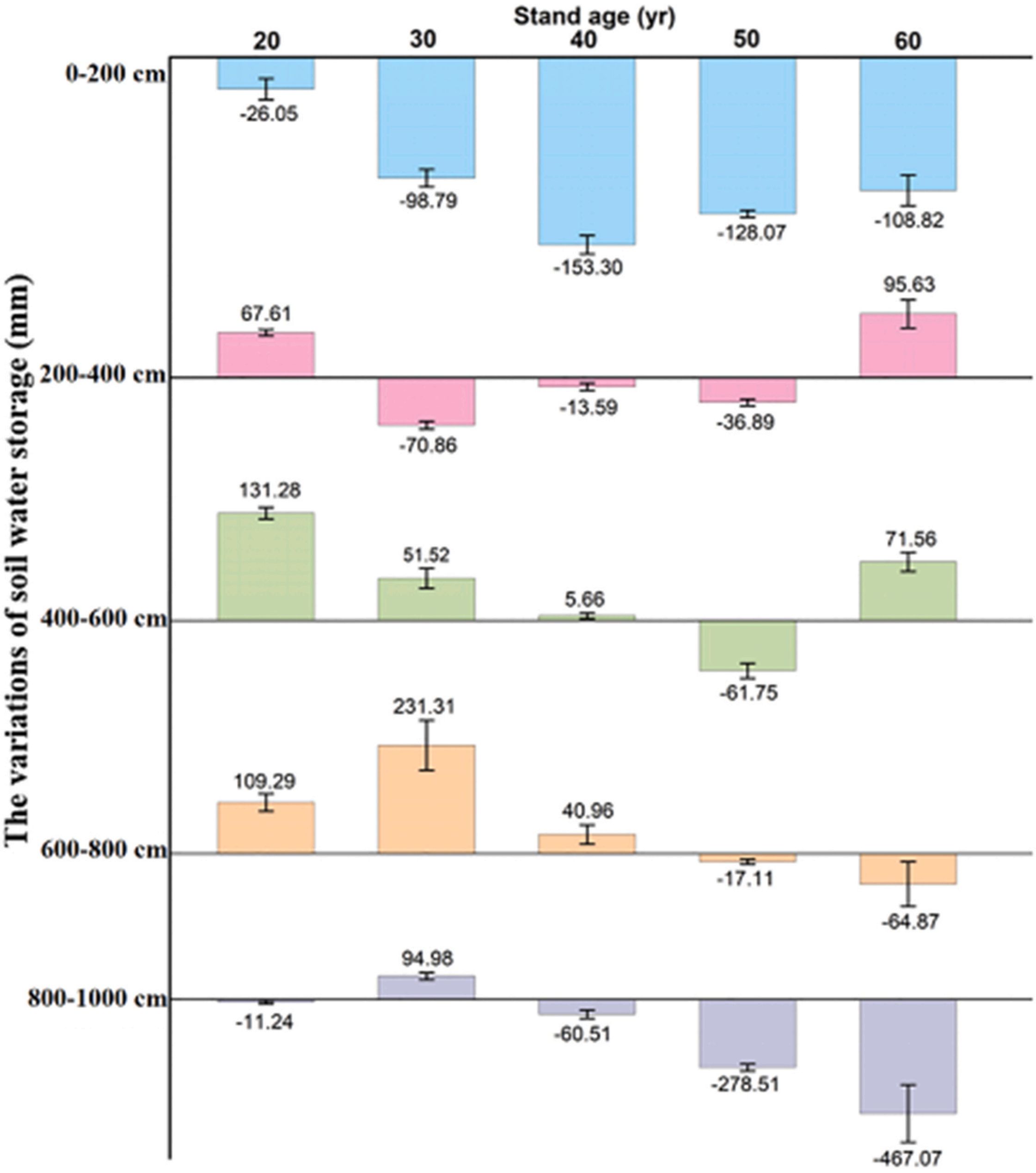

Fig. 6. The variations of soil water storage (*SWS*) in the soil layers under different stand ages (20 years, 30 years, 40 years, 50 years, and 60 years) and for the bare land. All data are presented as means ± standard errors.

plantation, there was a special point and the variations were negative in the 0–200 cm (−108.82 mm), 600–800 cm (−64.87 mm) and 800–1000 cm (−467.07 mm) soil layers. Taking into account the whole 0–200 cm soil profile, △*SWS* was the highest in the 40-yr stand age (−153.30 mm), it was significantly higher than that of 20-yr (−26.05 mm), 30-yr (−98.79 mm), 50-yr (−128.07 mm) and 60-yr (108.82 mm) stand ages (Fig. 6).

4. Discussion

It is essential to maintain a sustainable soil water for vegetation, especially in arid regions where water scarcity is the greatest restrictive factor for vegetation growth and sustainable development (Matzner et al., 2003; Song et al., 2016a; Wei et al., 2019). Previous reports showed that *P. sylvestris* was adapted to the environment of the semi-arid sandy land areas, and this species was suitable for establishment to reduce wind speed and thus to solidify sand (Song et al., 2018; Zheng et al., 2012). However, the improper varieties of artificial forest, the high plantation density or water shortage all lead to more serious desertification again (Kerhoulas et al., 2013; Cao, 2008). This study highlights the existence of a soil water "bottleneck" during the process of forest growth with the forest’s stand ages.

4.1. Soil water variation with the increasing stand ages

Soil moisture plays a very important role in the driving growth patterns in semi-arid environments (Wang et al., 2017). Specifically, the emphasis of the data analysis in this study focused on the relationships between the stand ages and the soil water use of the planted forest in a semi-arid sandy land. In this study, the main period of soil water decreasing was in 30–40 years, after that soil water storage gradually increasing (Fig. 3). The above phenomenon was attributed to plantation dieback, which often occurred approximately 30–35 years after planting (Song et al., 2016b). Song et al. (2018) suggested that the most important reason for forest degradation and dieback was an unbalanced pattern of water due to the lack of direct use of precipitation. Liu et al. (2017) also emphasized that the demand for water and other resources in forest is higher after approximately 30–40 years of plantation, due to the individual gradually growth accompanied by an increased photosynthetic rate of the young pines. In the study area, an important reason of part of forest dying maybe due to water scarcity after 40 years, resulted in a lower forest density (Fig. 2). Studies have indicated that *P. Sylvestris* entered the mature period when the stand ages were over 35 years (Song et al., 2016b). Hence, after 40 years, not only the forest density were diminished, but the growth rate also decreased. And then the *SWS* continued to be slowly consumed over time in the 50-yr and 60-yr stand ages. Moreover, Vertessy et al. (2001) advanced that the leaf area index decreased with the increasing stand ages that reduced transpiration and canopy interception as the forest ages. These effects increased rainfall infiltration and decreased the consumption of soil water.

4.2. Soil water distribution and consumption characteristics in the soil profile along stand ages

Soil water utilization depth of forest was increased with the increasing stand ages. Specifically, the forest in 20-yr stand age obtained soil water mainly from shallow soil layer (0–200 cm), and it was deeper in the 30-yr and the 40-yr forests which reached 400 cm soil layer. With the increasing stand ages, the utilize depth of soil water up to 1000 cm soil layer in 50-yr and 60-yr stand ages. On the one hand, the soil water utilization depth was highly correlated with the root distribution (Song et al., 2016b). Previous study has reported that the roots of the *P. sylvestris* were primarily distributed in the 0–100 cm soil layers, the taproots were located between 0 and 400 cm, and the lateral roots covered 200–300 cm of radius from the trunk and had a mass of root hairs (Zheng et al., 2012). The range of root distribution were gradually broader with the increasing stand ages and aggravated deep soil water consumption (Drake et al., 2011; Kerhoulas et al., 2013). Song et al. (2016a) have reported that the planted forests with different stand ages use various water sources due to the differences in their vertical root distribution, which lead to the difference of soil water distribution. On the other hand, evapotranspiration was different during different growing periods that influenced the soil water consumption intensity of forests. Water suction by roots was the important way to provide water for the growth and transpiration of plants (Verma et al., 2014). In the dry lands, evapotranspiration was generally several times higher than that of rainfall. Soil water consumption of vegetation transpiration induced the increasing degree and depth of soil water deficit. Once the soil water supply in the shallow layers (0–200 cm) was insufficient, planted pines needed more water to maintain a rapid growth rate after maturity. The young forests consumed predominantly shallow soil water at the start of their growth, while mature forests used both the shallow and deep soil water because of their deeper taproots (Kerhoulas et al., 2013; Liu et al., 2015a, 2015b).

Deeper water sources play an important role in the response to droughts (Anderegg et al., 2013; Barbeta et al., 2014), and it is effectively supplemented by groundwater (Musa et al., 2019). The SWS of the deep soil layer (800–1000 cm) was higher compared to 0–800 cm soil layer, and gradually decreased with the increasing stand ages. This result demonstrated that the soil water consumption intensity and depth were increased with increasing stand ages. This may be due to the prolonged root system aggravated deeper soil water usage, causing the reduction of deep soil water. Liu et al. (2018) observed that the finer roots of *P. sylvestris* sought for deep layer water in order to deal with drought stress. On the other hand, although the groundwater can provide replenishment of soil water, the deep soil water still declined with the stand age. This may lead to the decline of groundwater level (Zheng et al., 2012). This was explained by the planting of vegetation decreased the replenish of rainfall to soil water and increased the utilization of soil water that reduced the recharge to groundwater. Another aspect to consider was the instability of the groundwater recharge process that could also cause the deep soil water changes. Therefore, we assumed that the soil water content in the deeper layers in this study was affected by both the forest ages and fluctuations of groundwater table over time.

Moreover, the stand ages of 20–30-yr showed the higher SWS compared to bare land below the 200 cm soil depth. In the bare sandy land, the main soil water consumption was evaporation. Except for evaporation, there is transpiration in the forests. Generally, the water consumption intensity of evaporation is higher than that of transpiration (Liu et al., 2015a, 2015b). The existence of plants restricted evaporation, especially after rainfall. While the sandy soil with higher infiltration rate and lower water holding capacity, which resulted in the higher soil water content of forest in deeper soil layer than that of the bare land. Furthermore, the planted forests gradually utilized the water resources of the deep soil layers by extending the root system, but it also favored a release of the absorbed water into the shallow soil (Dawson, 1996). Meanwhile, the distribution of soil water showed uneven, discontinuous and irregular during the 60-year period. Our results proved that soil water was insufficient to replace serious soil water loss through the long-term transpiration of plants, and thus, the utilization of soil water under the artificial forest was unbalanced. Forese thinning was proposed as a management tool to reduce net stand water use and improve water-availability for remaining forests and reduced their dependence on deeper water, which may decrease their subsequent drought vulnerability (McDowell and Allen, 2015; Giuggiola et al., 2013; Zausen et al., 2005). Based on our findings and the available literatures, we proposed that the artificial forest should be gradually thinned over the period of 30–40 years old when presented the highest degree of soil water storage decreasing, to maintain the normal survival and sustainable development of forest vegetation.

5. Conclusions

The benefits of the planted forest practices to control land degradation and wind erosion in semi-arid sandy areas are in danger due to soil desiccation and dieback of artificial forests. The important death rate of forest in the forest plantation was explained by the insufficient water supply with increasing the stand age. Our research showed that there were significant differences in the soil water storage of the planted forest with different stand ages. The 20-yr forests mainly consumed shallow soil water (0–200 cm of soil depth), the 30-yr and 40-yr forests mainly consumed the soil water stored at 0–400 cm depths, and the 50–60-yr forest consumed the soil water of the 0–1000 cm soil layer. Importantly, our findings showed that the main period of soil water storage decreasing was in 30–40 years, after which the variation of soil water storage was gradually decreased. In the studied semi-arid sandy land, the worst of the soil water decreasing for *P. sylvestris* forests occurred during 30–40 years, and later, the soil water storage gradually increased due to and the decreasing forest density. Consequently, Therefore, this study suggests that the intermediate felling may be considered for reducing soil water consumption for artificial forests to maintain the sustainability of artificial forests in semi-arid sandy land.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Anderegg, L.D.L., Anderegg, W.R.L., Abatzoglou, J., Hausladen, A.M., Berry, J.A., 2013. Drought characteristics' role in widespread aspen forest mortality across Colorado, USA. Glob. Change Biol. 19, 1526–1537. https://doi.org/10.1111/gcb.12146.

Barbeta, A., Mejia-Chang, M., Ogaya, R., Voltas, J., Dawson, T.E., Penuelas, J., 2014. The combined effects of a long-term experimental drought and an extreme drought on the use of plant-water sources in a Mediterranean forest. Glob. Change Biol. 21, 1213–1225. https://doi.org/10.1111/gcb.12785.

Cao, S.X., 2008. Why large-scale afforestation efforts in China have failed to solve the desertification problem. Environ. Sci. Technol. 42, 1826–1831. https://doi.org/10.1021/es0870597.

Culas, R.J., 2012. REDD and forest transition: tunneling through the environmental Kuznets curve. Ecol. Econ. 79, 44–51. https://doi.org/10.1016/j.ecolecon.2012.04.015.

Dawson, T.E., 1996. Determining water use by trees and forests from isotopic: energy balance and transpiration analyses: the roles of tree size and hydraulic lift. Tree Physiol. 16, 263–272. https://doi.org/10.1093/treephys/16.1-2.263.

D'Odorico, P., Bhattachan, A., Davis, K.F., Ravi, S., Runyan, C.W., 2013. Global desertification: drivers and feedbacks. Adv. Water Res. 51, 326–344. https://doi.org/10.1016/j.advwatres.2012.01.013.

Drake, P.L., Froend, R.H., Franks, P.J., 2011. Linking hydraulic conductivity and photosynthesis to water-source partitioning in trees versus seedlings. Tree Physiol. 31, 763–773. https://doi.org/10.1093/treephys/tpr068.

Duan, D.Y., Ouyang, H., Song, M.H., Hu, Q.W., 2008. Water sources of dominant species in three alpine ecosystems on the Tibetan Plateau, China. J. Integr. Plant Biol. 50, 257–264. https://doi.org/10.1111/j.1744-7909.2007.00633.x.

Fleskens, L., Stringer, L.C., 2014. Land management and policy responses to mitigate desertification and land degradation. Land Degrad. Dev. 25, 1–4. https://doi.org/10.1002/ldr.2272.

Geeson, N., Quaranta, G., Salvia, R., Brandt, J., 2016. Long-term involvement of stakeholders in research projects on desertification and land degradation: How has their perception of the issues changed and what strategies have emerged for combating desertification? J. Arid Environ. 114, 124–133. https://doi.org/10.1016/j.jaridenv.2014.12.002.

Giordano, C.V., Guevara, A., Boccalandro, H.E., Sartor, C., Villagra, P.E., 2011. Water status drought responses, and growth of *Prosopis flexuosa* trees with different access to the water table in a warm south American desert. Plant Ecol. 212, 1123–1134. https://doi.org/10.2307/41508799.

Giuggiola, A., Bugmann, H., Zingg, A., Dobbertin, M., Rigling, A., 2013. Reduction of stand density increases drought resistance in xeric Scots pine forests. For. Ecol. Manag. 310, 827–835. https://doi.org/10.1016/j.foreco.2013.09.030.

Jiang, L.L., Bao, A.M., Jiapaer, G., Guo, H., Zheng, G.X., Gafforov, K., Kurban, A., De Maeyer, P., 2019. Monitoring land sensitivity to desertification in central Asia: convergence or divergence? Sci. Total Environ. 658, 669–683. https://doi.org/10.1016/j.scitotenv.2018.12.152.

Kerhoulas, L.P., Kolb, T.E., Koch, G.W., 2013. Tree size stand density, and the source of water used across seasons by ponderosa pine in northern Arizona. For. Ecol. Manag. 289, 425–433. https://doi.org/10.1016/j.foreco.2012.10.036.

Lamoureux, S.C., Poot, P., Veneklaas, E.J., 2018. Shallow soils negatively affect water relations and photosynthesis in two semi-arid Eucalyptus species. Environ. Exp. Bot. 155, 239–250. https://doi.org/10.1016/j.envexpbot.2018.06.037.

Li, Q., Zhang, C.L., Shen, Y.P., Jia, W.R., Li, J., 2016. Quantitative assessment of the relative roles of climate change and human activities in desertification processes on the Qinghai-Tibet Plateau based on net primary productivity. Catena 147, 789–796. https://doi.org/10.1016/j.catena.2016.09.005.

Liu, B., Zhao, W.Z., Liu, Z.L., Yang, Y.T., Luo, W.C., Zhou, H., Zhang, Y.Y., 2015b. Changes in species diversity, aboveground biomass, and vegetation cover along an afforestation successional gradient in a semiarid desert steppe of China. Ecol. Eng. 81, 301–311. https://doi.org/10.1016/j.ecoleng.2015.04.014.

Liu, C.A., Siddique, K.H.M., Hua, S., Rao, X., 2017. The trade-off in the establishment of artificial plantations by evaluating soil properties at the margins of oases. Catena 157, 363–371. https://doi.org/10.1016/j.catena.2017.05.031.

Liu, X.P., He, Y.H., Zhang, T.H., Zhao, X.Y., Li, Y.Q., Zhang, L.M., Wei, S.L., Yun, J.Y., Yue, X.F., 2015a. The response of infiltration depth, evaporation, and soil water replenishment to rainfall in mobile dunes in the Horqin sandy land, Northern China. Environ. Earth Sci. 73, 8699–8708. https://doi.org/10.1007/s12665-015-4125-0.

Liu, Y.Y., Wang, A.Y., An, Y.N., Lian, P.Y., Wu, D.D., Zhu, J.J., Meinzer, F.C., Hao, G.Y., 2018. Hydraulics play an important role in causing low growth rate and dieback of aging *Pinus sylvestris* var. *mongolica* trees in plantations of Northeast China. Plant Cell Environ. 41, 1500–1511. https://doi.org/10.1111/pce.13160.

Matzner, S.L., Rice, K.J., Richards, J.H., 2003. Patterns of stomatal conductance among blue oak (*Quercus douglasii*) size classes and populations: implications for seedling establishment. Tree Physiol. 23, 777–784. https://doi.org/10.1093/treephys/23.11.777.

McDowell, N.C., Allen, C.D., 2015. Darcy's law predicts widespread forest mortality under climate warming. Nat. Clim. Change 5, 669–672. https://doi.org/10.1038/nclimate2641.

MEA, 2005. Millennium Ecosystem Assesment: Ecosystems and Human Well-being: Desertification Synthesis. World Resource Institute, Washington D.C.

Mganga, K.Z., Nyariki, D.M., Musimba, N.K.R., Amwata, D.A., 2018. Determinants and rates of land degradation: application of stationary time-series model to data from a semi-arid environment in Kenya. J. Arid Land 10, 1–11. https://doi.org/10.1007/s40333-017-0036-0.

Musa, A., Zhang, Y.H., Cao, J., Wang, Y.C., Liu, Y., 2019. Relationship between root distribution characteristics of Mongolian pine and the soil water content and groundwater table in Horqin Sandy Land, China. Trees Struct. Funct. 33, 1203–1211. https://doi.org/10.1007/s00468-019-01852-3.

Nie, Y.P., Chen, H.S., Wang, K.L., Yang, J., 2012. Water source utilization by woody plants growing on dolomite outcrops and nearby soils during dry seasons in karst region of southwest China. J. Hydrol. 420, 264–274. https://doi.org/10.1016/j.jhydrol.2011.12.011.

Ohte, N., Koba, K., Yoshikawa, K., Sugimoto, A., Matsuo, N., Kabeya, N., Wang, L.H., 2003. Water utilization of natural and planted trees in the semiarid desert of Inner Mongolia, China. Ecol. Appl. 13, 337–351. https://doi.org/10.1890/1051-0761(2003)013[0337:WUONAP]2.0.CO;2.

Prieto, I., Armas, C., Pugnaire, F.I., 2012. Water release through plant roots: new insights into its consequences at the plant and ecosystem level. N. Phytol. 193, 830–841. https://doi.org/10.1111/j.1469-8137.2011.04039.x.

Ravi, S., Breshears, D.O., Huxman, T.E., D'Odorico, P., 2010. Land degradation in drylands: interactions among hydrologic-aeolian erosion and vegetation dynamics. Geomorphology 116, 236–245. https://doi.org/10.1016/j.geomorph.2009.11.023.

Reynolds, J.F., Stafford Smith, D.M., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M., Walker, B., 2007. Global desertification: building a science for dryland development. Science 316, 847–851. https://doi.org/10.1126/science.1131634.

Seddon, A.W., Macias, F.M., Long, P.R., Benz, D., Willis, K.J., 2016. Sensitivity of global terrestrial ecosystems to climate variability. Nature 531, 229–232. https://doi.org/10.1038/nature16986.

Smits, K.M., Ngo, V.V., Cihan, A., Sakaki, T., Illangasekare, T.H., 2012. An evaluation of models of bare soil evaporation formulated with different land surface boundary conditions and assumptions: models of bare soil evaporation. Water Resour. Res. 48, 12526. https://doi.org/10.1029/2012WR012113.

Song, L.N., Zhu, J.J., Li, M.C., Zhang, J.X., Lv, L.Y., 2016a. Sources of water used by *P. sylvestris* trees based on stable isotope measurements in a semiarid sandy region of northeast China. Agr. Water Manag 164, 281–290. https://doi.org/10.1016/j.agwat.2015.10.018.

Song, L.N., Zhu, J.J., Li, M.C., Zhang, J.X., 2016b. Water use patterns of *P. sylvestris* trees of different ages in a semiarid sandy lands of northeast China. Environ. Exp. Bot. 129, 94–107. https://doi.org/10.1016/j.envexpbot.2016.02.006.

Song, L.N., Zhu, J.J., Li, M.C., Zhang, J.X., Zheng, X., Wang, K., 2018. Canopy transpiration of *P. sylvestris* in a sparse wood grassland in the semiarid sandy region of northeast China. Agr. For. Meteorol. 250–251, 192–201. https://doi.org/10.1016/j.agrformet.2017.12.260.

Souza, A.F., Ramos, N.P., Pizo, M.A., Hubel, I., Crossetti, L.O., 2013. Afforestation effects on vegetation structure and diversity of grasslands in southern Brazil: the first years. J. Nat. Conserv. 21, 56–62. https://doi.org/10.1016/j.jnc.2012.10.002.

Sterk, G., Boardman, J., Verdoodt, A., 2016. Desertification: history, causes and options for its control. Land Degrad. Dev. 27, 1783–1787. https://doi.org/10.1002/ldr.2525.

Teng, M.J., Huang, C.B., Wang, P.C., Zeng, L.X., Zhou, Z.X., Xiao, W.F., Huang, Z.H., Liu, C.F., 2019. Impacts of forest restoration on soil erosion in the Three Gorges Reservoir area, China. Sci. Total Environ. 697, 134164 https://doi.org/10.1016/j.scitotenv.2019.134164.

Tomasella, J., Silva Pinto Vieira, R.M., Barbosa, A.A., Rodriguez, D.A., de Oliveira Santana, M., Sestini, M.F., 2018. Desertification trends in the northeast of Brazil over the period 2000-2016. Int. J. Appl. Earth Obs. Geoinform. 73, 197–206. https://doi.org/10.1016/j.jag.2018.06.012.

UNCCD, United Nations Convention to Combat Desertification, 1994. Elaboration of an International Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa.

Verma, P., Loheide II, S.P., Eamus, D., Daly, E., 2014. Root water compensation sustains transpiration rates in an Australian woodland. Adv. Water Resour. 74, 91–101. https://doi.org/10.1016/j.advwatres.2014.08.013.

Vertessy, R.A., Watson, F.G.R., O'Sullivan, S.K., 2001. Factors determining relations between stand age and catchment water balance in mountain ash forests. For. Ecol. Manag. 143, 13–26. https://doi.org/10.1016/S0378-1127(00)00501-6.

Wang, T., Xue, X., Zhou, L., Guo, J., 2015. Combating aeolian desertification in northern China. Land Degrad. Dev. 26, 118–132. https://doi.org/10.1002/ldr.2190.

Wang, X.P., Schaffer, B.E., Yang, Z.L., Rodriguez-Iturbe, I., 2017. Probabilistic model predicts dynamics of vegetation biomass in a desert ecosystem in NW China. Proc. Natl. Acad. Sci. U.S.A. 114, 4944–4950. https://doi.org/10.1073/pnas.1703684114.

Wei, W., Feng, X.R., Yang, L., Chen, L.D., Feng, T.J., Chen, D., 2019. The effects of terracing and vegetation on soilmoisture retention in a dry hilly catchment in China. Sci. Total Environ. 647, 1323–1332. https://doi.org/10.1016/j.scitotenv.2018.08.037.

Zausen, G.L., Kolb, T.E., Bailey, J.D., Wagner, M.R., 2005. Long-term impacts of stand management on ponderosa pine physiology and bark beetle abundance in northern Arizona: a replicated landscape study. For. Ecol. Manag. 218, 291–305. https://doi.org/10.1016/j.foreco.2005.08.023.

Zheng, X., Zhu, J.J., Yan, Q.L., Song, L.N., 2012. Effects of land use changes on the groundwater table and the decline of *P. sylvestris* plantations in southern Horqin sandy land, northeast China. Agr. Water Manag 109, 94–106. https://doi.org/10.1016/j.agwat.2012.02.010.

Zhu, J.J., Li, F.Q., Xu, M.L., Kang, H.Z., Wu, X.Y., 2008. The role of ectomycorrhizal fungi in alleviating pine decline in semiarid sandy soil of northern China: an experimental approach. Ann. . Sci. 65, 304. https://doi.org/10.1051/forest:2008007.

Zucca, C., Julitta, F., Previtali, F., 2011. Land restoration by fodder shrubs in a semi-arid agro-pastoral area of Morocco. Effects on soils. Catena 87, 306–312. https://doi.org/10.1016/j.catena.2011.06.017.