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Full Length Article

Effects of Irrigation Gradients on Stem Flow Rate of Young *Pinus tableulaeformis* in Feldspathic Sandstone Zones

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Abstract

To investigate the rules of water use by young *Pinus tableulaeformis* in feldspathic sandstone zones, undisturbed soils were collected from the Ordos Feldspathic Sandstone Soil & Water Conservation Demonstration Plot, Inner Mongolia, China. *P. tableulaeformis* trees from the demonstration plot were planted in greenhouses in seedling-raising bags containing undisturbed soils. Then, the young trees were irrigated at different gradients (W1: θ_{FC}25%, W2: θ_{FC}40%, W3: θ_{FC}55%) and the stem flow rates and environmental factors were continuously monitored. The following results were found: (1) at different irrigation gradients, the daily stem flow rates of young trees changed unimodally with time and peak values increased with the irrigation gradient. In particular, the stem flow rates changed, following similar trends in the two cases of W2 and W3, despite their large difference in irrigation volumes. (2) The stem flow rates of young *P. tableulaeformis* were related to environmental factors: the stem flow rates correlated positively with the solar intensity and atmospheric temperature, but correlated negatively with relative air humidity, with correlation coefficients of 0.992, 0.734 and -0.674, respectively. This study offers both a fundamental basis and suggestions for vegetation recovery and eco-construction in the feldspathic sandstone zones of Inner Mongolia.

Keywords: Feldspathic sandstone areas; *Pinus tableulaeformis*; Irrigation gradient; Stem flow rate; Environmental factors

Introduction

Feldspathic sandstone is a specific type of undeveloped mudstone and sand mudstone formed during the Paleozoic Permian, Mesozoic Triassic, Jurassic, and Cretaceous and is mainly distributed along the borders of Shanxi, Shaanxi and Inner Mongolia at the midstream of the Yellow River (Li *et al*., 2015). The feldspathic sandstone zone of Inner Mongolia is one of the regions with the most severe soil erosion in the Loess Plateau or even the world (Wang *et al*., 2013). Feldspathic sandstone can be wind-corroded and intensively freeze-thawed (Xiao *et al*., 2014). It is stiff in water-free conditions, but loosens like mud upon contact with water. These characteristics together with the dry local climate and the harsh annual rainfall complicate the rooting and growth of vegetation; however, the low survival rate of vegetation is the biggest problem for ecosystem restoration in this region (She *et al*., 2014). The consequences are severe erosion and large sand yields in the feldspathic sandstone zones. The annual average mud and sand input from these zones into the Yellow River reached 0.35 billion tons (including 80% of coarse sands), which thus forms the major source of coarse sand in the Yellow River. Moreover, these feldspathic sandstone zones are the major origins of flooding disasters due to the riverbed sediment elevation downstream of the Yellow River (Liu, 2007). Thus, it is urgent to understand the water use rules of adaptive vegetation and the response relations with environmental factors during soil and water conservation in the feldspathic sandstone zones of the Loess Plateau.

Pinus tableulaeformis, also called the Chinese pine, is an evergreen tree with flourishing roots that is cold- and drought-resistant during growth. *P. tableulaeformis* is one of the major afforestation tree species in the soil and water conservation forests of North China. Here, moisture is the major limiting factor for vegetative growth in feldspathic sandstone zones, while water consumption due to evaporation is one of the key processes of water use by vegetation. Specifically, the roots of plants absorb the soil water and then dissipate it through transpiration to the air (Yin, 2010; Liu *et al*., 2011; Zhao *et al*., 2017). Stem flow refers to the transpiration-caused flow of ascending liquid in plants. The soil moisture after absorption by roots flows to the sapwood vessels, where under the driving force of the fluid flow, it passes through the trunk and branches to the leaf blades. More than 99.8% of the moisture is transpires into the atmosphere, thus forming a circulating system (Tian *et al*., 2012). The thermal diffusion method, which is a tree

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sapwood liquid flow measurement system proposed in 1996 (Smith and Allen, 1996), uses a thermal diffusion flow probe that detects heat dissipation by using double thermocouples. It is modified via a heat pulse flow meter based on the pulse lag effect. This method differs significantly from other measuring systems and is capable to monitor liquid flow rates either continuously or at specific time points (Yue *et al.*, 2006). Recently, research has focused on the natural plants from the perspective of evaporation, including afforestation species and economic forest species. By combining the thermal diffusion technique with water balance, researchers have probed into the water consumption rules of plants both under water deficit and water supply conditions (Meinzer and Goldstein, 1995; Liu *et al.*, 1997). Consequently, efficient water use has been achieved under conditions of short water resources. Plant stem flow measurement is significant for building soil-vegetation-atmosphere continuous body models, which can be used to explore laws of moisture supply and demand in forested regions, which can also be used to verify evaporation inhibition and water saving measures.

The existing research focuses on the vegetation under natural growth conditions, but has not yet investigated transpiration and water use by tree species in the harsh environment of feldspathic sandstone zones. As reported, the dominant influencing factor on the liquid flow rate is the soil moisture content throughout the growing season (Jin *et al.*, 2006). Thus, in this study, the water consumption rules of *P. tableulaeformis* were investigated under different irrigation gradients as well as their relationship with relevant environmental factors. The relationship between transpiration-induced water consumption and environmental factors (as determined by the stem heat balance method) provides an important basis for clarifying the water bearing capacity of appropriate vegetation. It can offer a scientific foundation for vegetation recovery in this region. Moreover, the mechanisms underlying the water use dynamics and acclimation factors of *P. tableulaeformis* in the feldspathic sandstone zones were explored. The findings offer a theoretical basis and guidance for suitable *P. tableulaeformis* planting and science-based forest management in feldspathic sandstone zones.

Materials and Methods

Experimental

To facilitate the long-term observation and in-depth research of *P. tableulaeformis* planted in feldspathic sandstone zones, undisturbed soils (interlayers composed of loess, which were matrix-developed yellow surface soil, as well as chestnut soil, which was a matrix-developed feldspathic sandstone) were collected from the Ordos Feldspathic Sandstone Soil & Water Conservation Demonstration Plot of Inner Mongolia, China, in April 2017. The loessic soil surface layer had a thickness of 20 cm. Based on the existing research and field surveys, 3- to 5-year-old *P. tableulaeformis* were found to mainly grow in the 0-30 cm soil layer. Thus, undisturbed soil columns (50 × 50 × 50 cm^3) were collected from typical sections and were put into seedling-raising bags (50 × 50 cm^2). These were then brought to the experimental greenhouse of Inner Mongolia Agricultural University, China. Furthermore, 3- to 5-year-old *P. tableulaeformis* growing in the demonstration plot were planted in seedling raising bags. From the bags, nine trees that were growing normally and similarly were selected and equally divided into three groups according to irrigation gradients. The three irrigation gradients were: 25% (W1), 40% (W2), and 55% (W3) of 2550 mL of field moisture capacity in undisturbed soil. In W1, the withering humidity of chestnut soil in the feldspathic sandstone zones was about 5.5% (Hu, 2003), accounting for 27% of the soil field capacity. The indoor real water consumption of Mediterranean areas was 30% lower than outdoors (Qiu, 2014). Orgaz *et al.*, 2005 found that the water consumption by greenhouse crops was 60-70% that of the same plants outdoors, and the indoor potential evapotranspiration was 60-80% of that outdoors (Orgaz *et al.*, 2005). According to the tested conditions and geographical differences, the greenhouse precipitation rate was set to θ_{FC}25%, which is within the humidity range of withering humidity and growth retardation humidity. The soil moisture content was 7%. In W2: Yang studied the soil moisture contents in the Loess Plateau and found that the deep soil constant humidity was 49-54% of that of field moisture capacity or 9-11% of soil moisture content. This fell within the range of nearly ineffective water (Li, 1983; Yang and Han, 1985; Liu and Wang, 1990). During a simulation of soil deep-layer constant humidity, the irrigation was set to θ_{FC}40% and soil humidity to 10%. W3: Due to the harsh natural conditions in feldspathic sandstone zones, the soil moisture content is lower than the modest valid water (Hu, 2003) (60-80% of field moisture capacity). At a higher soil water content, the correlation between stem flow rate and environmental factors is stronger. To meet the requirement of indoor testing, to guide field exploration and to clarify the differences in stem flow rates between sufficient irrigation and drought stress, the irrigation was set to θ_{FC}55% and the soil moisture content to ~13%. The soil moisture content is lower for a larger soil moisture suction ability, and vice versa; thus, the soil tension index reflects the water-bearing status (Liu *et al.*, 2002). The lower limit of irrigation was set to 0.03 MPa, and two observations were conducted at 9:00 am and 5:00 pm, respectively. When the recording of the tensiometer showed ≥ 0.03 MPa, the soil moisture content reached the withering humidity (~4.56%) and irrigation was required. Basic information of undisturbed soil and *P. tableulaeformis* is shown in Table 1 and 2, respectively.

Measurement of Stem Flow Rate

A packed plant stem measuring system by Yi Ke tai Ecological Technology Co., Ltd., China and an EMS62 portable double-channel plant stem flow meter were used here.

Table 1: Soil properties

Sample No.	Bulk density ($g \cdot cm^{-3}$)	Soil grade (%) Clay	Silt	Sand grain	Gravel
		< 0.002 mm	0.002-0.02 mm	0.02-2.00 mm	> 2.00 mm
W1	1.4	0.27	46.67	53.06	0
W2	1.43	0.25	45.92	53.82	0
W3	1.41	0.29	47.24	52.47	0

Table 2: Basic information of *Pinus tableulaeformis*

Unit (cm)	Plant height	Crown diameter (east to west)	Crown diameter (south to north)
W1	106	35	40
	102	31	36
	108	36	32
W2	102	29	38
	109	38	42
	105	33	36
W3	108	35	35
	110	37	37
	104	39	40

This system is based on the stem heat balance method (SHB): the input energy is equal to the conductive heat due to the increase and dissipation of the stem flow temperature. Its rationale can be expressed as follows (Han *et al.*, 2017).

$$Q = (P - dT \cdot Z) / dT \cdot Cw$$

where Q represents the stem flow rate ($kg \cdot s^{-1}$), P represents the input energy (W), dT represents the temperature difference at the measuring point (K), Z represents the conductive heat loss coefficient at the measuring point, and Cw represents the specific heat of water ($J \cdot kg^{-1} \cdot K^{-1}$).

Given the two types of EMS62 sensors that were used (the 8-12 mm small-sized sensor, and the 12-16 mm large-sized sensor) and to reduce the experimental errors, the appropriate sensor was selected according to the trunk size. Before sensor installation, appropriate trunks were selected and their surface was cleaned from rough bark, which exposed the inner-layer bark. Then, a 2-mm-diameter electric drill was used to drill two 20-mm-long holes as parallel as possible. Probes were inserted into the holes to avoid internal injury. After probe installation, the probes were surrounded by aluminum foil and sealed with insulating tape. The stem flow meter worked continuously for 24 h every day and for 30 min each time and the hourly average was used for further analysis.

Measurement of Environmental Factors

The following environmental factors were measured by a small-sized HOBO weather station (USA): solar radiation intensity, atmospheric temperature, and relative air humidity. The environmental factors were automatically monitored, synchronously with the stem flow rate monitoring (also 24 h every day, 30 min each time). Average hourly data were used for analysis.

Data Processing

Plotting and correlation analyses were conducted with Excel 2007 and SPSS 20.0, respectively.

Results and Analysis

Changing Rules of Stem Flow Rate of *P. tableulaeformis* at Different Irrigation Gradients

The stem flow rates of *P. tableulaeformis* at different irrigation gradients were monitored for seven consecutive days (Fig. 1). Clearly, at different irrigation volumes, the stem flow rates of *P. tableulaeformis* changed between day and night, as the changing trend during the day was generally consistent and typically showed a single-peak curve. Due to the differences of irrigation gradients, the starting time of stem flow rates differed to some extent. The test was conducted in August 2017 when the starting time of solar radiation was very early. The stem flow rates for treatments W1 and W2 both started between 5:00 and 6:00 am, while that for treatment W3 started between 6:30 and 7:00 am. Since the solar radiation intensity enhanced and the environmental factors varied (including temperature increase), the stem flow rates increased rapidly, and the stem flow rates at the day all reached their maximal level between 13:00 and 14:00 pm in all three treatments. After that, the environmental factors (including solar radiation intensity) changed, the stem flow rates started to decline, became very low between 20:00 and 21:00 pm and remained stable and very weak during the night. The average peak values of stem flow rates under treatments W1, W2 and W3 were 0.028, 0.035 and 0.038 kg/h, respectively. Clearly, the peak stem flow rates of *P. tableulaeformis* correlated positively with irrigation volume. The peak stem flow rate increased with increasing irrigation volume.

Then, the stem flow rates at the same time point among the seven days and under the same irrigation gradient were

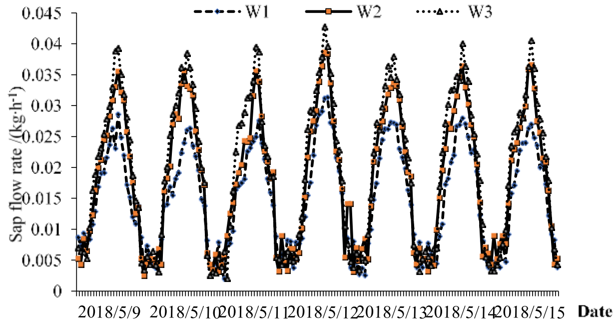

Fig. 1: Changing rules of stem flow rate of *P. tableulaeformis* at different irrigation gradients

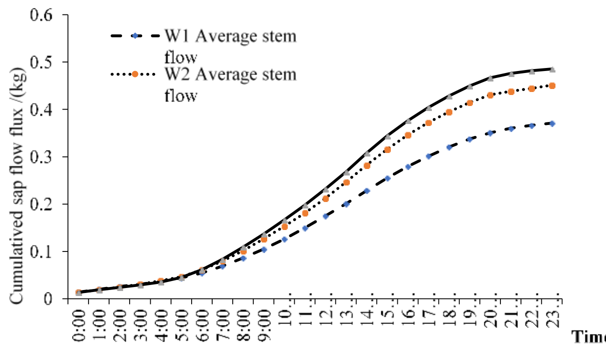

Fig. 2: Daily accumulated stem flow rates of *P. tableulaeformis* for different irrigation gradients

averaged and thus the daily variation of stem flow rate was determined. On this basis, the daily accumulated stem flow rates of *P. tableulaeformis* were analyzed. Fig. 2 shows the changing rules of the daily accumulated stem flow rates of *P. tableulaeformis* for different irrigation gradients. Clearly, the daily accumulated stem flow rates of *P. tableulaeformis* followed an S shape for all three irrigation gradients, and it was positively correlated with the irrigation volume. The slope of the daily accumulated stem flow was basically 0 before 5:00 am, then increased to the maximum at approximately 13:30-14:30 pm and then started to decline again. Basically, 0 was again reached at 20:00-21:00 pm. This changing rule is consistent with that of the daily variation of *P. tableulaeformis*. Clearly, the curves of W2 and W3 are very similar. Analysis indicates that the daily accumulations of stem flow at the three treatments W1, W2, and W3 were 0.37, 0.46 and 0.48 kg, respectively.

Relationship Between Stem Flow Rate of *P. tableulaeformis* and Environmental Factors at Different Irrigation Gradients

The variation of stem flow rates of the vegetation is affected by environmental factors and physiological properties. Many studies reported that stem flow rate is significantly positively correlated with solar radiation (Bužková *et al.*, 2015; Zhang *et al.*, 2015; Xia *et al.*, 2019). In this experiment, changes of stem flow and environmental factors at different irrigation gradients were analyzed and the rules are stated below. The stem flow rates of *P. tableulaeformis* at different irrigation gradients were proportional to both solar radiation intensity and atmospheric temperature; however, rates were inversely proportional to relative air humidity (Fig. 3, 4 and 5). Solar radiation intensity is the dominant influencing factor of the stem flow rate of vegetation. Solar radiation not only regulates the open and close mode of leaf holes, but also affects the atmospheric temperature and relative humidity of the air. Solar radiation started at approximately 5:00 am, then rapidly increased and reached its maximum at 12:00 pm. After that, it declined and reached its minimum at approximately 20:00. The increment of solar radiation intensity affected the atmospheric temperature and relative air humidity differently, and can promote the increase of atmospheric temperature. Solar radiation intensity inhibits the increase of relative air humidity; consequently, the inner and outer vapor pressure difference of leaves increased, thus leading to intensified evaporation and increased stem flow rate. This rule is consistent with the variation of stem flow.

The atmospheric temperature slightly affects the inner and outer saturation vapor pressure difference of leaves, with increasing saturation vapor pressure difference and increasing atmospheric temperature, which thus intensifies the transpiration of vegetation. Atmospheric temperature not only affects the relative air humidity, but also impacts both the leaf temperature and soil temperature to different extents (Xu *et al.*, 2008; Zhang *et al.*, 2013). The vapor content in the air is higher at elevated temperatures. Despite the small gap volume of mesophyll cells, the inner evaporation areas are very large; therefore, with increasing temperature, the gap vapor pressure of mesophyll cells also increases. Due to the increase of daytime atmospheric temperature, when the water evaporated into the atmosphere is deficient, the vapor pressure changes significantly; consequently, the gap vapor pressure of mesophyll cells differs from the vapor pressure of air. Thus, the transpiration rate increases accordingly. Moreover, the increasing atmospheric temperature increases the free energy of water, which accelerates the diffusion of water molecules. This also promotes the water absorption by roots and the water transport inside plants, thus accelerating the stem flow. After reaching a specific level, the atmospheric temperature will inhibit plant transpiration; however, the critical value of atmospheric temperature that inhibited transpiration was not obtained in this study. The atmospheric temperature increased at 8:00-9:00 am, maximized at 13:00-14:00 pm, minimized at 8:00-9:00 pm, and remained stable after that. This is generally consistent with the variation of stem flow rate.

The relative air humidity affects both the physiological properties and growing status of plants through the soil-plant-atmosphere continuum (SPAC). To facilitate transpiration, the relative humidity is not saturated in the substomatic cavity of leaves. Thus, the cell walls of mesophyll cells transform water into vapor to ensure sufficient transpiration.

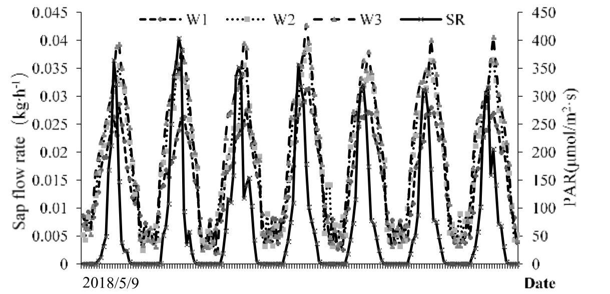

Fig. 3: Relationship between stem flow rate of *Pinus tableulaeformis* and sun radiation intensity for different irrigation gradients

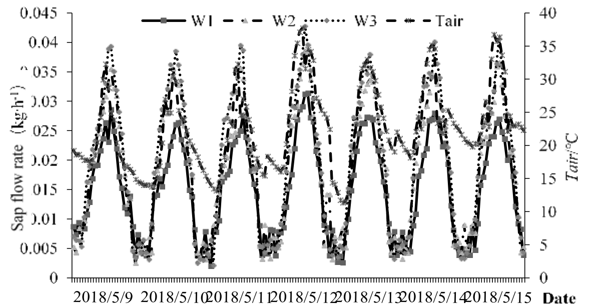

Fig. 4: Relationship between stem flow rate of *Pinus tableulaeformis* and atmospheric temperature for different irrigation gradients

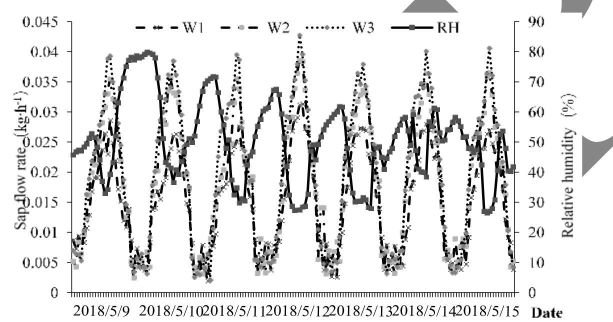

Fig. 5: Relationship between stem flow rate of *Pinus tableulaeformis* and air humidity for different irrigation gradients

When the relative air humidity increases, the air vapor increases accordingly, thus reducing the inner and outer vapor pressure of leaves and weakening transpiration. When the relative air humidity increases, the air water content also increases and thus, the air vapor pressure increases; however, the vapor gradient in the inner cavity decreases, thus decelerating vaporization. Moreover, when the water inside the leaves is nearly saturated and the air is relatively dry, the water inside the leaves diffuses into the air. When the relative air humidity increases, the transpiration weakens. The relative air humidity started to decline around 8:00-9:00 am, was minimal at 13:00-14:00 and increased to its maximum at 2:00-3:00 am, which is the opposite trend to the variation of stem flow.

Table 3: Correlations between stem flow rate of *Pinus tableulaeformis* and environmental factors

	Solar radiation intensity	Atmospheric temperature	Relative air humidity
Correlation	0.992**	0.734**	-0.674**
Significance	<0.001	<0.001	<0.001

The stem flow rates at different irrigation gradients were averaged. Correlations with average stem flow rate, solar radiation intensity, atmospheric temperature, and relative air humidity were analyzed (Table 3).

The stem flow rate of young *P. tableulaeformis* correlates with environmental factors as follows: the stem flow rate is positively correlated with solar radiation intensity and atmospheric temperature, but negatively correlated with relative air humidity. The correlation coefficients were 0.992, 0.734 and -0.674, respectively.

Discussion

This study found that the stem flow rate of *P. tableulaeformis* after irrigation firstly increased gradually and then decreased after reaching a specific level. reported that the stem flow rates of walnut trees under different irrigation gradients first increased rapidly and then slowly decreased after reaching a certain level (Zhao *et al.*, 2015). In comparison, for this study, young trees were collected from the feldspathic sandstone zones, while conducted tests at the fruit and tree test base of Xinjiang Agricultural University, Hongqipo, Aksu, Xinjiang, China (Zhao *et al.*, 2015). The physical properties of feldspathic sandstone differ from other types of soils, since feldspathic sandstone is as hard as rock without water, but is as soft as mud after excessive water absorption. studied the water-holding ability of soil mixed from feldspathic sandstone and sand soil and reported that with increasing feldspathic sandstone mass, the soil water-holding capacity was enhanced (Zhang *et al.*, 2014). Other studies also confirmed the strong water-holding ability of feldspathic sandstone (Wang *et al.*, 2007; Zhu *et al.*, 2007; Han *et al.*, 2012). The difference of this study to the findings of (Zhao *et al.*, 2015) can also be attributed to the unique physical properties of feldspathic sandstone. Thus, the overall effect on the stem flow rate of plants should be studied by combining the soil physical properties and the water-holding ability.

The water needed by vegetation to maintain physiological activities is absorbed by the roots in soils, and soil water conditions directly affect stem flow. As reported, the stem flow of *Schima* correlated well with the soil water potential (Zhou *et al.*, 2011). The stem flow rate of tomatoes was significantly correlated with soil moisture content (Irvine *et al.*, 1998). As found in this study, the daily stem flow of *P. tableulaeformis* declined with the moisture content of soil. No remarkable achievement was obtained in relevant studies concerning *P. tableulaeformis*, but the results are consistent with previous scholars' research results of jujube trees (Li *et al.*, 2016). In addition to the biological properties, physiological characteristics, and soil moisture, the stem flow of vegetation is also affected by other factors, such as solar radiation, air temperature, air humidity and wind speed. Since these factors were all controlled indoors, the effects of these factors can be ignored. This experiment was conducted on sunny days, and the differences of solar radiation at different soil moisture contents were not largely different.

Conclusions

The stem flow rates of young *P. tableulaeformis* trees changed unimodally at all tested irrigation gradients and the peak values increased with increasing irrigation gradient. The starting time and peaking time of stem flow slightly differed due to the different irrigation gradients. In particular, the daily accumulation of stem flow also increased with increasing irrigation gradient. Furthermore, the stem flow rates were similar for both W2 and W3, despite the large difference in irrigation volumes. The irrigation rates of *P. tableulaeformis* correlated with the environmental factors: the stem flow rates correlated positively with the solar intensity and atmospheric temperature, but negatively with relative air humidity. The coefficients were 0.992, 0.734 and -0.674, respectively.

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