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A correlation model on plant water consumption and vegetation index in Mu Us Desert, in China

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Abstract

In arid and semiarid regions, development of vegetation is highly limited by scare of water. As a result, the vegetation cover fraction of high water consumption plants is less than that of low water consumption plants. Models in accounting for the relationship between consumption of water and vegetation index can yield basic information in assessment the water balance behavior in arid and semiarid regions. As a case study in Mu Us Desert, in China, leaf transpiration rates of several typical species and leaf area index (LAI) are measured by potometer and LAI Plant Canopy Analyzer respectively. The data is used to analyze the characteristics and controls of desert vegetation transpiration. A statistical model of vegetation water consumption is proposed based on the correlation between leaf area index and leaf transpiration rates. According to the patterns of time varying consumption of water for different plants, an annual transpiration model with average maximum LAI is developed.

Key words: Arid region; leaf area index; transpiration; model; Mu Us Desert

1. Introduction

In water limited area, generally the vegetation cover fraction of high water consumption plants is less than that of low water consumption plants except zones where groundwater is shallow buried. As a result, discharge of groundwater is also partly controlled by the patterns of vegetation distribution, in the form of evaportranspiration. In Northwest China, due to arid climate, vegetation ecosystem is generally weak and sensitive to distribution and variation of groundwater. However, groundwater is also a foundation to promote social development in this area. It leads to a competition of water demands between vegetation

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ecosystem and economy. Then, assessment of necessary water demand of vegetation is an essential topic for sustainable development.

The detail results of dynamic tree transpiration change through objects, locations, time and environment but the basic features of it stay the same. The diurnal variation of transpiration rate is that it is lower at night, increases sharply between 6:00 and 8:00 h, reaches a maximum value between12:00 and 14:00 h, and decreases between 16:00 and18:00 h. As to the annual variation, the transpiration rate similarly rises in the beginning of the growing season, reaches the highest in the vigorous growth period and drops in the end of that [1-3]. The transpiration rate has correlation with natural environment such as vapor pressure deficit, solar radiation, air temperature, wind speed and relative air humidity. The experiential formulas, proposed for the relationship between transpiration rate and whether factors, are restricted to the particular species corresponding to the very environment and may not be generalized to other situations [4-7]. Furthermore, evaluating the characteristic of the theories and methods in the research of transpiration rate which are weighing, lysimeter, steady state potometer, ventilated chamber, water balance, remote sensing, heat-pulse, heat-balance, thermal dissipation, eddy correlation, experiential formula, Bowen ratio energy balance and Penman-Monteith methods [8-11], the potometer method provides the accurate measurement of potential transpiration of an individual tree [12]. The popular heat-pulse technique can determine the transpiration of a variety of tree species successively in their natural habitant. However, it is not accurate under conditions of low xylem flow and inappropriately assumes sapflow velocity to be constant across the sapwood conducting area [13-14]. Scaling up the above determination results in time and space, the annual water consumption of plants which differ in species are considerable [15].

Leaf area index, which refers to the total leaf area per unite land area [16], is an important indicator to simulate the evapotranspiration on canopy [17] or landscape scale [18-19]. Using remote sensing and EPPML, a model of biological biochemical cycle is built to simulate spatial distribution of yearly transpiration of the vegetation in Changbai Mountain and the result shows that transpiration is highly correlated with leaf area index. However, their correlativity is not a simple direct ratio [20]. In the middle reaches of Heihe River, there is a linear relationship between the leaf area index and the water consumption [21].

The above study rarely focuses on the relationship between the leaf area index and the water consumption. The objectives of this study were to:(a) determine the leaf transpiration rate and leaf area index by potometer and LAI Plant Canopy Analyzer respectively; (b) analyze the characteristics and controls of desert vegetation transpiration;(c)propose a statistical model of leaf transpiration rate and LAI; (d) develop an annual transpiration model with average maximum LAI. The above measurements and models should provide basic information for assessing the water balance behavior in arid and semiarid regions.

2. Materials and methods

2.1. Study area

The study was carried out in Mu Us Desert, located in Wushenqi Country, Inner Mongolia Autonomous Region, China. The mean elevation is 1304m, high terrain in the northwest, southeast of low elevation in meters between 1300m and 1400m. Throughout is a warm temperate continental, less precipitation, strong evaporation, ample sunshine and short frost-free period. The mean annual sunshine hours is 295.66h; the frost-free period is about 140~150 days; the mean annual air temperature is 7.10c; the mean maximum temperature and the mean minimum temperature are 22^{0}c in July and -9.4^{0}c in

January; the mean annual degree days above 10^0c is 2621.19^0c; the annual precipitation is 397mm on average , unevenly distributed, ranging from 70% of year-round precipitation in the third quarter; the mean annual open water evaporation is 1055mm and the extinction depth is 2.7m.

The study area consists of two aquifers: the unconfined Quaternary System aeolian sand and the confined Salawusu Group, Cretaceous sandstones. According to aquifer pumping test results, the hydraulic conductivity for the Quaternary System aquifer is about 9m/d, and the specific yield is 0.064. The hydraulic conductivity for the Cretaceous System aquifer is about 0.17m/d, and the storage coefficient is 2.99×10^{-5} /m. In this region, the depth of groundwater is 1~4m.

Soils are dominated by chestnut soil, meadow soil, saline soil and aeolian sandy soil. They are sandy, loose, fine, uniform, weakly alkaline and contain low amounts of organic matter. Correspondingly, the major vegetations in this typical steppe belt area are *Salix psammophila*, *Salix matsudana Koidz*, poplar, *Artemisia ordosica*, *Sabina vulgaris* and *Achnatherum splendens*. As the depth of groundwater increases, low water consumption plants such as *Salix psammophila* and *Artemisia ordosica* will gradually replace high water consumption plants such as *Salix matsudana Koidz* and poplar. When the water table is shallow, *Achnatherum splendens* of salt alkali resistance are pioneer plants. Corn is the dominant crops, widely distributed in the riparian areas.

2.2. Measurements of transpiration rate and LAI

The main cause of water loss from a plant, accounting for 90%, is through the stomata of the leaf known as transpiration. As a result, the volume of water absorbed from the soil approaches to that of water lost through transpiration. They are assumed to be the same in the potometer method, as found in similar studies [22]. It is important for plants in maintaining a transpiration stream that draws minerals into branches, stems and leaves.

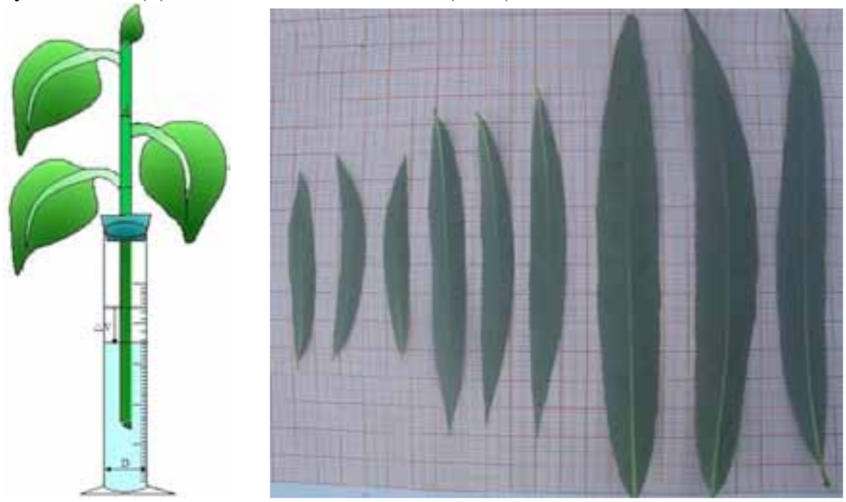
To test the characteristics of desert vegetation transpiration, five typical plants were selected with different growing environments, ranging from moisture, arid to saline-alkali. A self-made portable potometer was used to measure the leaf transpiration rate of *Salix psammophila*, *Salix matsudana Koidz*, poplar, *Achnatherum splendens*, reed and corn. First, the typical branches, possessing thriving stems with several leaves on the top, were cutted from the middle of the canopy using scissors. Then the detached branch was placed in the measuring cylinder of moderate water and recutted below the water surface as soon as possible to prevent air from entering vessels. To inhibit additional evaporative loss from water, the nozzle was filled with wads of cotton. After that, the measuring cylinder was fixed in a box, whose water level was adjusted to an exact level with teat pipette. Last, the volume of water and the corresponding time were recorded at regular intervals. If needed, water was added to the measuring cylinder.

When the water lever kept constant for several minutes, all the leaves were harvested and the diameters of the branches were measured with vernier calipers. These leaves then were divided into three classes according to the size. A 10 leaves subsample, randomly taken from the homogenous, was placed on the graph paper to take pictures (Fig 1b). These photos, utilizing softwares AUTOCAD and SURFER, were used to determine the leaf area. Total leaf area of the same class could then be calculated by multiplying the average leaf area by numbers. Thus, adding the total leaf area of three classes was equivalent to that of the branches. The transpiration rates of five typical plants were monitored during the 2010-growing season: 9-20 July. The records of Hengshan, Yulin and Wushenqi Meteorological Station were collected to get the climatic data including air temperature, relative humidity, precipitation, atmospheric pressure and wind-speed.

The leaf transpiration rate refers to the volume of water lost through transpiration per unit leaf area and per unit time. Fig 1a illustrated the derivation of the variables but more detailed information and the equation for estimating the transpiration rate were as following:

$$T = \Delta V\left(1-\frac{d^2}{D^2}\right)\Big/\left(A\cdot\Delta t\right) \quad (1)$$

where ΔV(ml) is the variation of volume, d(mm) is the diameter of branch, D(mm) is the inner diameter of measuring cylinder, Δt(h) is the time interval and A(mm^2) is the total leaf area of the branch.



(a) (b)

Fig. 1. Schematic representation of the method: (a) drawdown in a potometer induced by transpiration through a branch; (b) photographic record of leaf shape.

The leaf transpiration rate, leaf area, leaf number and transpiration hours were used to compute the amount of water consumption over a day per tree. Applying daily data to the whole month for 30 days, the monthly water consumption could then be determined. June, July and August, contributed significantly to the water consumption of transpiration in a year. Especially, water consumption of July accounted for 23%~35% of that of the year [15]. Thus, the annual water consumption could be estimated by incorporating the average proportion 28% with monthly water consumption. Last, combining it with typical density can derive the annual transpiration rate of each species.

A LAI Plant Canopy Analyzer was used to measure the leaf area index of the canopy of *Salix psammophila*, *Salix matsudana Koidz*, poplar and corn in September 2010, whose value represented the maximum in a year [23-24]. For each species, numerous randomly selected individual trees were measured and then their statistical average was computed. Then, the average maximum LAI of a species in this region can be determined by multiplying the average maximum LAI of individual plant by the corresponding typical coverage.

3. Results

3.1. Leaf area index

The leaf area index of four typical plants ranged from 1.84 for *Salix psammophila* to 5.43 for corn (Table 1). Accordingly, the leaf shape changed from needle to ellipse gradually and the average size of single leaf increased from 2.53 to 220cm^2.

Table 1. Leaf area index of four typical plants

Species	*Salix psammophila*	*Salix matsudana Koidz*	Poplar	Corn
LAI	1.84	2.6	3.43	5.43

3.2. Leaf transpiration rate

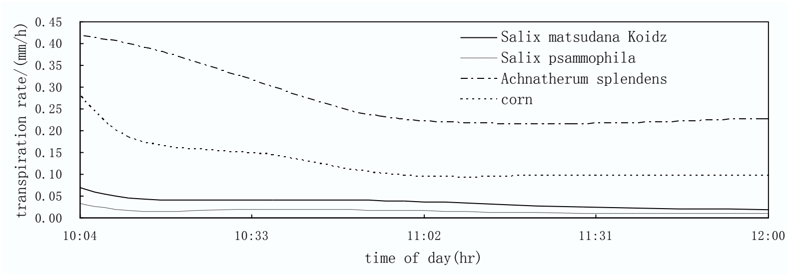
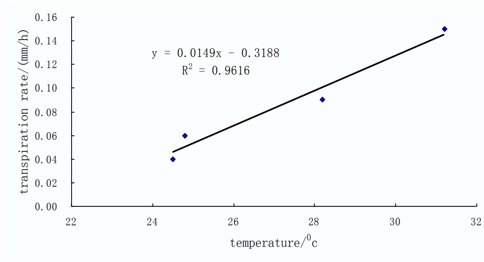


Fig. 2. The leaf transpiration rate over 2h periods between 10:00 and 12:00.

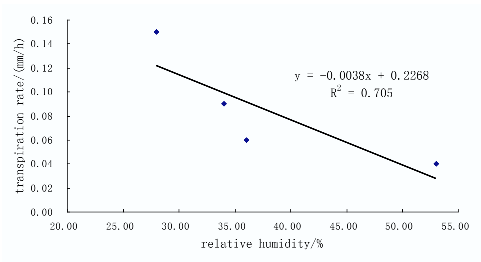
The leaf transpiration rate decreased with time but followed a different decline velocity for different species (Fig 2). The fall of *Achnatherum splendens* and corn in transpiration rate were both larger and faster than the other two. The maximum rate of *Salix matsudana Koidz*, *Salix psammophila*, *Achnatherum splendens* and corn were 0.09, 0.05, 0.44, 0.38 mm/h respectively while their minimum were 0.02, 0.01, 0.22, 0.1mm/h respectively.

3.3. The controls of leaf transpiration rate

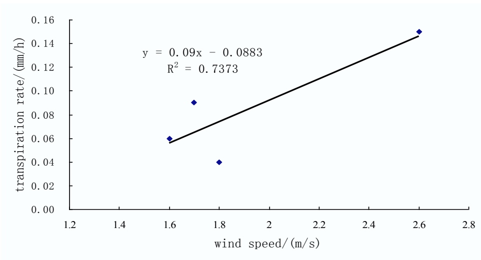
Transpiration rate was subjected to the comprehensive effect of air temperature, relative humidity and wind-speed but their impacts were not the same (Fig 3).



(a)



(b)



(c)

Fig. 3. Environment conditions against the transpiration rate of *Salix matsudana Koidz*. a ,b ,c mean the transpiration rate against air temperature, relative humidity, wind speed respectively. The corresponding regression lines were shown (R^2=0.96, 0.71, 0.74).

The transpiration rate of *Salix matsudana Koidz* had positive correlation with air temperature (Fig 3a) and wind speed (Fig 3c) while it had negative correlation with relative humidity (Fig 3b). However, their relationships were shown to be strong, as derived from the correlation coefficients which were 0.96, 0.74 and 0.71 respectively.

Not only the environment factors but also the vegetation types could bear on the transpiration rate. *Salix psammophila* consumed least water yet poplar, *Salix matsudana Koidz*, reed, *Achnatherum splendens* and corn progressively consumed more (Fig 4). Depending on the field investigations, *Salix psammophila* occurred generally on the top of the dunes while poplar and *Salix matsudana Koidz* appeared extensively around the stream channels. Reeds, known as wetland vegetations, their critical depths of groundwater were less than 0.6m learned by organ. As for *Achnatherum splendens*, drought tolerant, widely spread in saline-alkali land where the groundwater was shallow. Corns, dominate crops, were irrigated once every five days, annual mean fifteen times. A seedling corn which needed less water than ripe ones was selected, so the measured value was underreported. As a result, the transpiration rate of plant, to some extent, could reflect its drought-resistance capacity and the depth of groundwater where it flourished. Moreover, the vegetation cover fraction of *Salix psammophila* was more than that of other species.

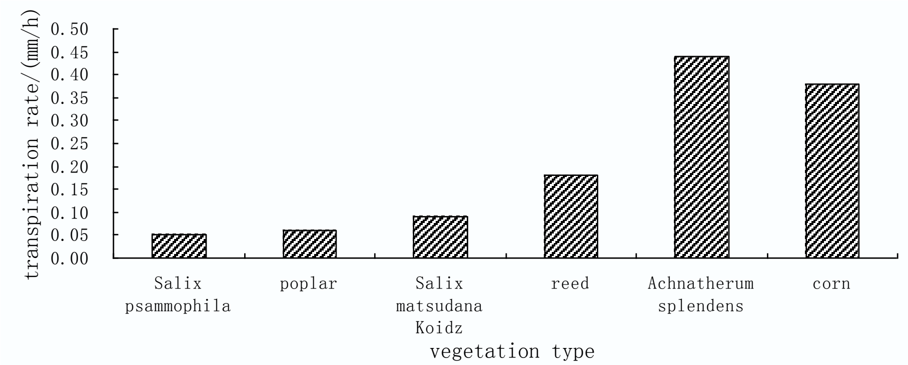


Fig. 4. The relationship between vegetation types and transpiration rate.

3.4. The relationship between leaf area index and leaf transpiration rate

The leaf transpiration rate increased with the leaf area index but not followed a simple direct ratio (Fig 5). Application of a nonlinear regression technique which approximated optimal fit indicated a high correlation between leaf area index and transpiration rate. The corresponding correlation coefficient was up to 0.96 and the fitted equation was as following:

$$T = 0.05 + 0.04(LAI - 1.58)^4 \tag{2}$$

where T (mm/h)is the leaf transpiration rate and LAI is the average leaf area index of an individual tree.

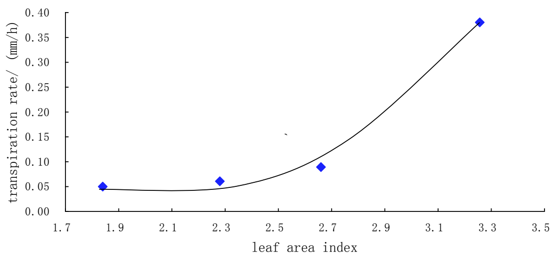


Fig. 5. The relation curve between leaf area index and leaf transpiration rate.

3.5. The relationship between annual transpiration rate and average maximum LAI

The amount of water consumption over a year per tree ranged from 62.70kg for corn belonging to crops to 2668.08 kg for poplar belonging to natural vegetations (Table 2). The corn whose leaf transpiration rate was higher but leaf number was smaller, consumed much less water than vegetations on an individual plant scale. Thus, corn was a crop of high water use efficiency [25].

Table 2. The average maximum leaf area index and annual transpiration rate.

Species	*Salix psammophila*	Poplar	*Salix matsudana Koidz*	Corn
Maximum LAI (individual)	1.84	3.43	2.60	5.43
Typical Density (plants/100 m^2)	11	9	10	900
Annual individual transpiration (Kg)	866.12	2668.08	2005.52	62.70
Typical coverage (%)	21	28	26	100
Average max. LAI	0.39	0.96	0.68	5.43
Annual transpiration rate (mm)	95.27	240.13	200.55	564.30

A logistic regression model was developed to assess the relationship between the average maximum leaf area index and annual transpiration rate (Fig 6). The logistic equation, which indicated the annual transpiration rate kept constant when LAI reached a critical value of 3.5, was as following:

$$T_a = 560/[1+9*\exp(-2.15*LAI_m)] \quad (3)$$

where T_a (mm) is the annual transpiration rate and LAI_m is the average maximum leaf area index. Investigating the leaf shapes, it was found that poplar leaf was relatively elliptic, corn leaf was narrowly oblong and *Salix psammophila* leaf was acicular. Thus, the shape of the leaves could be qualitatively regarded as a good indicator of the water consumption of vegetation.

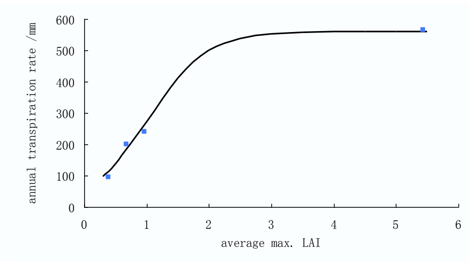


Fig. 6. The relation curve between average maximum leaf area index and annual transpiration rate.

4. Discussion

The potometer method proved to be a feasible method for providing measurable water to plants and reflecting the characteristic of transpiration, although the plants were measured under detached conditions. The organs of branch began to age slowly after separation resulting in the decrease of transpiration rate, despite immersed in sufficient water. However, it is insusceptible to analyze the characteristic of transpiration rate and estimate the annual water consumption of plants.

The transpiration rate was affected by the species and environment including air temperature, wind speed and relative air humidity. It was positively proportional to air temperature and wind speed but negatively proportional to relative air humidity. They all modify the difference of vapor pressure between inside and outside of the leaf to change the transpiration rate. The enlarged differences can improve the transpiration rate, and vice versa. As the air temperature increases, the temperature of leaf is 2~10 degrees higher than that of atmosphere, leading to the increase of vapor concentration of substomatal cavity larger than that of atmosphere. Similarly, that the flowing air takes away the moisture gathering near the leaf surface causes growing differences of vapor pressure to promote water diffusion. On the contray, the humid atmosphere reduces differences of vapor pressure and hinders water diffusion. In additional, the transpiration rate differed in species because every plant has built specific physiological mechanisms to the specific environment during the long-term evolution. The need for the amount of water varied from vegetation to vegetation. In order to adapt to the arid environment of scare of water, the vegetation cover fraction of high water consumption plants is less than that of low water consumption plants. That is why *Salix matsudana Koidz* only appear around the stream channels and *Salix psammophila* extensively spread in Mu Us Desert.

The annual transpiration rate can be predicted to a significant degree using the average maximum leaf area index. On an individual scale, the transpiration rate increased nonlinearly with leaf area index. The high LAI representing the dense canopy generates greater internal shading and lower surface area to volume ratio contributing to decrease the effective exposure area for air movement and irradiance. So the increasing LAI complicates the environment, improves the variability and induces nonlinear changes eventually. On a larger scale, the annual transpiration rate reached a saturation point where it did not increase as the increasing average maximum leaf area index. What is more, the annual transpiration model with average maximum leaf area index proved to be meaningful in this study. When the maximum LAI is measured directly or calculated by NDVI, the transpiration can be derived based on the logistic model proposed.

This study emphasized the potometer measuring the leaf transpiration rate under the detached conditions close to that in natural environment. Combining it with leaf number, leaf area, typical density, typical coverage and transpiration hours, the water consumption of plants in a year was estimated. Though the result was not the most accurate, it was acceptable for providing information for building models and assessing the water balance. Future researches may include the measurement of daily or yearly transpiration of the whole tree in natural environment.

Utilization of the potometer allows to measure and to grasp the dynamic of the leaf transpiration rate. Based on the developed logistic model, the water consumption of plants, hardily measured, can be obtained from the accessible leaf area index. Meanwhile, these procedures can facilitate Ecohydrogeology research and provide scientific basis for the policy of the sustainable development of the arid regions.

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