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RESEARCH ARTICLE

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Scaling-up method for stand water consumption of *Quercus variabilis* water conservation forest

Abstract Single tree's sapwood scattering style and diurnal water consumption rhythm for different diameter classes were studied in a 48-year-old *Quercus variabilis* stand, water protection forest in Beijing. Results showed that the tree's sapwood area was closely related to diameter at breast height (DBH). Single tree's daily water consumption ascended as DBH and sapwood area increased. Daily water consumption of different diameter classes in September ascended steeply in the early morning and reached the peak around 11:00, and then descended slowly to the valley at 18:00. The course of daily accumulated water consumption was in accordance with a typical Richards model (R=0.985,8). Parameters of diameter-time equation for scaling-up can be achieved by parameter-recovering method in the gradient of all diameter classes and at any time of a day, characteristic parameters of the course of daily stand water consumption were calculated from a modulated Richards equation derivative:

$$W_{d_i t_i} = (-7.147 + 1.174^{d_i})[1-(-3{,}025.937 + d_i^{2.175}) \cdot e^{(-0.011 t_j)}]^{\frac{1}{1-d_i^{0.242}}} .$$

Keywords *Quercus variabilis*, water conservation forest, stand (trees) water consumption, scaling-up, Richard's model, forest land water balance

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1 Introduction

The shortage of water resources in recent years has become a major limiting factor in the field of urban development and social progress in Beijing. At present, the area that encompasses various forestry lands in Beijing is about 9.0×10^5 hm^2, out of which 4.6×10^5 hm^2 of forestry land area is for water conservation, with the main tree species consisting of *Quercus* spp., *Pinus tabulaeformis*, *Robinia pseudoacacia*, *Populus davidiana,* and *Platycladus orientalis*, etc.; this area plays an important role in the conservation and protection of Beijing's water resources. Yuan (1999) declared that water resources in Beijing could only accommodate the forest coverage rate of 24.16% (4.036×10^5 hm^2 of forest land area) by using linear programming technique according to the strength of forest water consumption. Undoubtedly, this cannot meet Beijing's requirement of eco-urbanization construction. Therefore, it is imperative to be able to exactly calculate the water consumption of individual trees and forest stands, which will benefit selection of water-saving tree species and the scientific constitution of water conservation forest for the adoption of reasonable silvicultural and forest management measures. So, researchers must pay more attention to how to estimate water consumption both on a single tree scale and stand scale, for the purpose of selection of low water consumption tree species and forest structure configuration.

Conventional method of calculating water consumption of single tree and forest stand is not highly accurate and cannot provide a satisfactory result (Wang and Ma, 2002). Marshall (1958), Swanson (1994), Edwards and Becker (1996), and others successfully created the first-generation integrated tree sapwood flow measuring system on the basis of the results of the research conducted by Huber (1935). Based on the principle of bi-thermocouple checking and thermal dissipation, Granier (1987) developed a thermal dissipation sap flow velocity probe (TDP), which can measure real-time sapwood flow velocity, provide a dynamic description of water consumption law of single tree, and disclose the eco-physiological mechanism (Wullschleger et al., 1998). By using the thermal balance principle instrument of TDP, whole tree water consumption can be measured easily only when getting the cross trunk sapwood area (Granier, 1987). Hereby, stand water consumption can be calculated according to the sapwood distribution, and water consumption scaled up to stand level has been attempted extensively. Ladefoged (1963), Cermark and Kucera (1987), Werk (1988), Hatton and Vertessy (1990), and Vertessy and Hatton (1997) found that canopy scope, cross-section area of basal trunk, and canopy projection area were not appropriate reference variables in the scaling-up research of single tree water consumption. However, Vertessy et al. (1995) and Hatton and Wu (1995) found that leaf area was the optimal credibility variable in water consumption scaling-up from a single tree level to stand level, and they thought that a tree's conduction tissue in xylem area, leaf area, breast diameter and single tree occupation area were all perfect spatial deducing scalars. Sun and Ma (2002) thought that diameter at breast height (DBH) was the most perfect variable in water consumption scaling-up to stand level, because it was easily measured, and closely related to special leaf area and sapwood area.

Based on the research of the growth course simulation of tree species, Xing et al. (1998) considered that the Richards growth equation had the merits of plasticity, flexibility, accuracy, and integrated biological meaning in describing a tree's growth characteristic such as DBH, height, and volume. The course of accumulative daily water consumption of single tree can be described perfectly as a typical "S" type curve, in accordance with the typical form described by Richards biological growth equation (Wang and Ma, 2002).

2 Site description

The study site is situated in the Jiufeng Forest Research station of Beijing Forestry University (39°54′N, 116°28′E). Semiarid and subhumid monsoon climate of warm temperate zone dominates this area with an annual mean temperature of 7–10°C, annual precipitation of 638.8 mm and annual evaporation capacity of 1,800–2,000 mm. Typical soil types are farming cinnamon soil, leached drab soil, brunisolic soil, etc. Forest types include shelter forest and landscape forest. The main natural vegetation types are mountain *Quercus* forest and *Pinus tabulaeformis* forest belonging to the typical temperate deciduous forest belt. The artificial vegetation is mainly *Platycladus orientalis* forest and *Robinia pseudoacacia* forest at the low mountain level and *Pinus tabulaeformis* forest, *Quercus* forest (such as *Q. variabilis*, *Q. acutissima*, *Q. aliena*, *Q. mongolica*, *Q. wutaishanica*) and mixed *Acer truncatum*-*Q. variabilis* forest at the middle mountain level, and *Larix gmelinii* pure forest at the top mountain level. Main shrub tree species include *Amygdalus davidiana*, *Vitex negudo*, *Ziziphus acidojujuba*, *Broussoneta papyrifera*, *Grewia biloba*, and *Spiraea salicifolia*, etc.

The experiments were conducted in *Q. varibilis* artificial forest of Yanzi mountain range of elevation 480 m, where is semi-light slope with slope degree of 18° and soil preparation of terrace. The soil is leached drab soil, with soil depth about 60 cm. Litter thickness is 3–15 cm. Sample tree is 48 years old with average DBH of 19.7 cm and height of 13.5 m.

3 Materials and methods

Individual trees' DBH, height, canopy scope (EW×NS), height under branch were measured in a 20 m×30 m sample plot. Sapwood flow of sample trees of stand and different diameter classes were measured. Cross sapwood area at measuring position was checked with growing tip. At the same time, another tree similar to the sample was selected, cut down and intercepted into discs. The number and width of annual growth ring were investigated from discs to calculate areas of sapwood and heartwood, and to correct the areas acquired with growing tip (Table 1).

Real-time sapwood flow velocities of sample trees of each diameter class were measured with TDP in September, and sap flow fluxes were calculated according to sapwood area. Meanwhile, the environment factors were measured by the automatism micro-weather station, such as air temperature, air humidity, solar radiation, precipitation, wind speed, wind direction above canopy, in the middle canopy and over the ground, and soil temperature and humidity at 5, 20, 40 and 60 cm soil depth. The methods of sap flow velocity, single tree water consumption, and environmental factors' measurement see the paper of Wang and Ma (2002).

Table 1 Sample trees' growth of diameter classes in plot of *Q. variabilis*

No.		1	2	3	4	5
Diameter class /cm		24.0	22.0	20.0	18.0	16.0
Height /m		12.0	11.5	1.25	11.0	10.0
$\overline{D}_{1.3}$ /cm		23.5	22.7	20.7	17.4	16.8
$D_{1.3}$ /cm		24.0	22.8	19.3	18.6	16.3
Trunck height /m		2.8	4.2	4.1	5.5	3.7
Canopy scope /m	E	4.0	3.2	2.5	2.5	4.0
	S	3.7	3.4	2.3	3.5	2.8
	W	2.3	2.1	2.4	2.8	1.9
	N	3.2	2.7	3.3	3.4	3.0
Canopy area /m^2		34.2	25.5	21.6	29.2	26.9
Bark layer /cm		1.5	1.5	1.2	1.2	1.2
Sapwood width /cm		3.9	3.7	3.7	3.5	2.8
Heartwood width /cm		6.5	5.2	4.7	4.6	5.8
Sapwood area /cm^2		207.0	163.8	152.2	131.6	126.6

$\overline{D}_{1.3}$ refers to diameter class mean diameter at breast height in plot; $D_{1.3}$ refers to sample tree diameter at breast of diameter class.

4 Results and analyses

4.1 The relationship between sapwood area and single tree's DBH

Results from Table 1 show that there was a close relationship between DBH and sapwood area (correlation coefficient R=0.915), but correlations of sapwood width and DBH, sapwood width and canopy scope, canopy scope and sapwood area were not significant.

4.2 Water consumption law of single tree along DBH variation

Daily sap flow velocity and sap flow flux (Figs. 1 and 2) ascended steeply from 8:00 to 9:00, and the maximum occurred around 11:00, then descended gradually into the transmission stage around 18:00.

Accumulated single tree water consumption of different diameter classes was obviously different in all daily time segmentations (Fig. 2). The bigger the DHP was, the earlier the sap flow start-time occurred and the faster the sap flow velocity was.

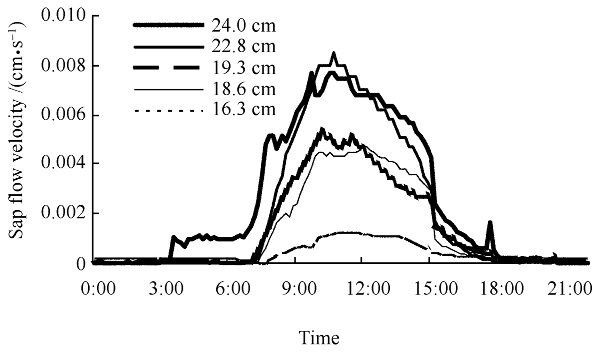

Fig. 1 Diurnal fluctuation of sap flow velocity with different diameter classes of *Q. variabilis* on September 15

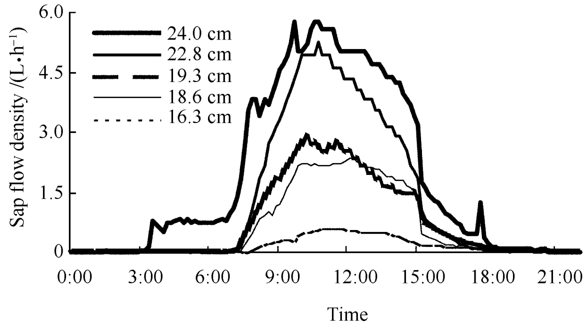

Fig. 2 Diurnal fluctuation of sap flow density with different diameter classes of *Q. variabilis* on September 15

Sap flow of the sample tree with a diameter of 24.0 cm appeared obviously at 4:00, increased quickly at 8:00, peaked at 11:00 and ended at 18:00. Sap flow of sample trees with diameter of 22.8, 19.3, and 18.6 cm started after 8:00, peaked at 11:00, and ended at 18:00 one by one, and their courses were same to the largest sample tree with diameter of 24.0 cm (Fig. 3).

Linear regression analysis of DBH, stem cross-section area with daily accumulated single tree's water consumption showed that DBH, sapwood area, and cross-section area at breast height were all strongly related to single tree's daily accumulated water consumption, mean daily sap flow velocity, and maximum water consumption in a day (Table 2). The relation between single tree daily accumulated water consumption and DBH was significant; based on this relation, diameter classes can be directly used to estimate stand water transpiration, and the scaling-up of water consumption estimation from single tree to stand level can also be achieved.

4.3 Tri-dimensional model of single tree water consumption and calculation of stand water consumption

The objective of sap flow research was to appraise and compare the characteristics of a single tree's water transpiration

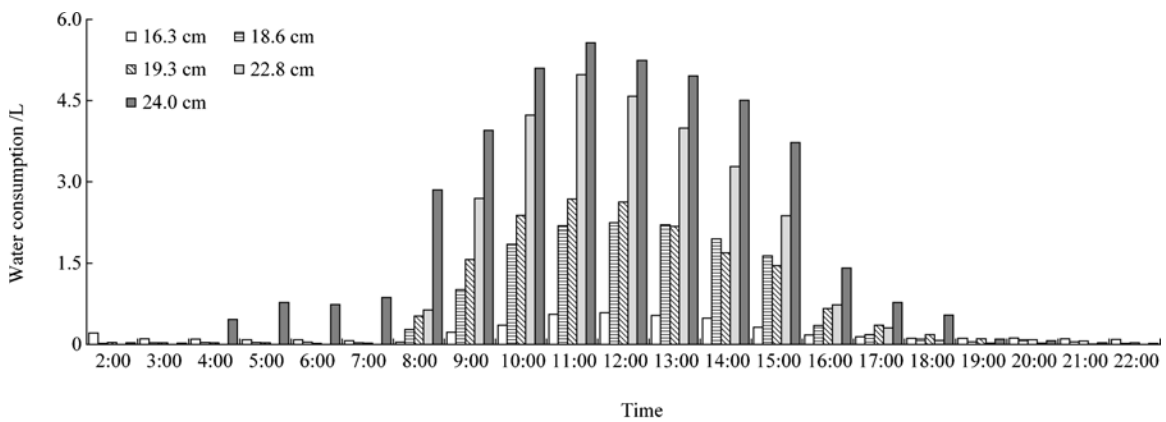

Fig. 3 Daily single tree water consumption with different diameter classes of *Q. variabilis* on September 15

Table 2 Relation between diameter at breast height and single tree daily water consumption of *Q. variabilis*

Independent variable	Dependent variable	Regression parameters		Regression significance F	Correlation coefficient R
		b_0	b_1		
DBH /cm	Mean daily sap flow velocity/cm	-3.420×10^{-2}	2.457×10^{-4}	0.002	0.987***
	Accumulated daily single tree water consumption/kg	−67.708	4.369	0.004	0.977***
	Single tree maximum water consumption in a day /kg	−10.028	0.654	0.000	0.999***
Sapwood area /cm²	Mean daily sap flow velocity/cm	-2.220×10^{-3}	2.369×10^{-5}	0.012	0.953**
	Accumulated daily water consumption/kg	−410.727	0.446	0.001	0.993***
	Single tree maximum water consumption in a day /kg	−6.607	0.062	0.016	0.944**
Cross section area at breast height/cm²	Mean daily sap flow velocity/cm	-10.530×10^{-4}	7.652×10^{-6}	0.003	0.981***
	Accumulated daily water consumption/kg	−24.054	0.138	0.003	0.980***
	Single tree maximum water consumption in a day /kg	−3.481	2.043×10^{-2}	0.000	0.996***

Regression freedom degree is 143. ** refers to 1% confidence probability; *** refers to 0.1% confidence probability.

consumption of different tree species, in different sites, in different forest stand structures, and in different phases of forest growth, and to solve the problem of the selection of tree species and the arrangement and adjustment of the forest structure. Scaling-up method of water consumption was the key.

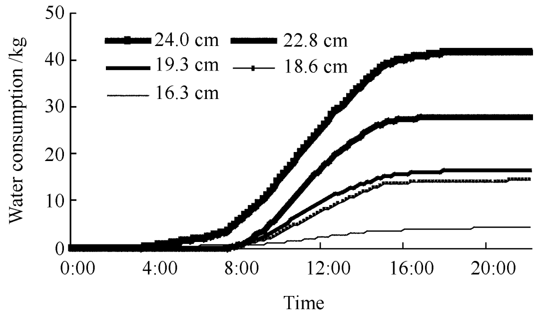

Fig. 4 Daily sample tree accumulated water consumption of diameter classes of *Q. variabilis* on September 15

Figure 4 shows the dynamic curves of the sample tree daily accumulated water consumption of different diameter classes in different time intervals. These dynamic curves, indicated that the course of *Q. variabilis* water consumption occurred characteristic of typical biological growth curve of "S", which can be described by Richards model, so Richards model was selected to calculate daily stand water consumption.

$$Y = b_0(1 - b_1 e^{-b_2 x})^{\frac{1}{1-b_3}} \tag{1}$$

where Y is the total bio-growth increment at t time, b_0 is the theoretic maximum value of growth and temporal ultimate steady state for any bio-growth course, namely the bio-growth upper limit, b_1 is the parameter related to the initial growth value, b_2 is the growth velocity parameter, and b_3 is the unnatural growth velocity parameter deciding the S curve trend. Tree's daily accumulated water consumption course was uniform with the characteristics of bio-growth equation (Fig. 4), so it can be perfectly simulated with the Richards model (Fig. 5). The equation of tri-dimensional forest stand water consumption of the 48-year-old *Q. variabilis* is as follows:

$$W_{d_i t_i} = (-7.147,4 + 1.174,115^{d_i}) \\ (1 - (-3,025.937 + d_i^{2.174,83}) e^{(-0.011,03 t_j)})^{\frac{1}{1-d_i^{0.241,63}}} \tag{2}$$

where $W_{d_i t_j}$ is the accumulated water consumption of the sample tree with diameter of d_i at time of t_j. Parameters were calculated by the parameter-recovering method: $b_0 = (-7.147 + 1.174^{d_i})$, b_1=$(-3,025.937+d_i^{2.175})$, b_2=0.011, b_3=$d_i^{0.242}$, coefficient correlation R=0.985,8.

Any tree's accumulative water consumption with any DBH (cm) at specified time (min) in the same plot in September can be calculated easily with Eq. (2). Characteristic parameters of two groups can be achieved by calculating the differential coefficient of Eq. 2 in the condition of second derivative and third derivative being equal to 0. The first group characteristic parameters were the inflexion points of the equation, referring to the maximum water consumption velocity and appearing time. The second group characteristic parameters were the transition points where sap flow changed its velocity from slow to fast (p_1, under the inflexion) and from fast to slow (p_2, up of the inflexion).

The coordinate of inflexion, q (x, y), is as follows:

$$x = \frac{\ln \frac{-b_1}{1-b_3}}{b_2}, \quad y = b_0 \cdot b_3^{\frac{1}{1-b_3}} \tag{3}$$

The coordinate of stand water consumption velocity altering inflexion, p_1 (x_1, y_1), p_2 (x_2, y_2), is as follows:

$$x = \frac{\ln z}{b_3}, \quad y = b_0(1 - \frac{b_1}{z})^{\frac{1}{1-b_3}} \tag{4}$$

$$\text{where,} \quad z = \frac{b_1}{2(1-b_3)}(2 + b_3 \pm \sqrt{4b_3 + b_3^2}) \tag{5}$$

According to the diameter investigation in the sample plot, water consumption of single diameter class was calculated with the tri-dimensional water consumption equation. The result was 361, 741, 882, 1,016, and 1,816 kg corresponding with diameter classes of 16, 18, 20, 22, and 24 cm with the tree number of 33, 67, 50, 33, 50 per hectare, and the stand total daily water consumption was 4,815 kg/hm² (Table 3).

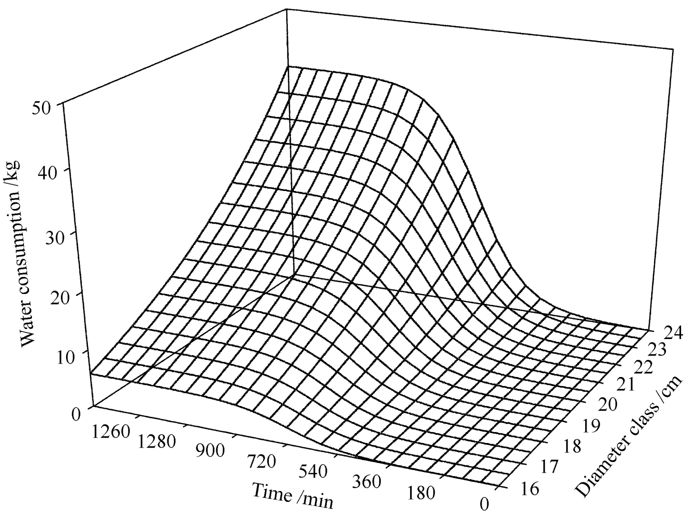

Fig. 5 Water consumption 3-D curve of Richards model of different diameter classes of 48-year-old *Q. variabilis* stand

Table 3 Daily forest stand water consumption of different diameter classes of *Q. variabilis* on September 15

Diameter-class /cm	16	18	20	22	24
Average diameter /cm	16.6	18.1	20.0	22.6	23.5
Tree number per hectare	33	67	50	33	50
Daily water consumption of the mean tree of diameter class/kg	10.83	11.11	17.63	30.50	36.38
Daily water consumption of diameter class per hectare /(kg·hm^{-2})	361	741	882	1016	1816
Daily Water consumption of *Q. variables* forest stand /(kg·hm^{-2})			4816		

5 Discussion

DBH or canopy scope were strongly related to sapwood area, sap flow velocity, and single tree water consumption, which was in accordance with the result obtained by Vertessy et al. (1995), Sun and Ma (2002), Liu et al. (1997), and was in agreement with the idea that scalars were needed in the scaling-up of trees water consumption (Sun and Ma, 2002). DBH was a suitable scalar in scaling-up of stand water consumption, considering its good relationship with sap flow and single tree water consumption, and other traits such as being easily available, intuitionistic, and exercisable.

There were two difficulties in the scaling-up procedure of water consumption from single tree to stand level: First, was the question as to how to obtain a water consumption model of single tree, taking diameter and time as variables. The selection of a suitable model and variables, the relation analysis between variables and water consumption of single tree, and a model solution were the keys in extrapolation of scaling. Usually, the building of a water consumption model of single tree was more difficult than that of tree growth model and management model of artificial forest (Du and Tang, 1997). The research of daily single tree accumulative water consumption showed that the trend was shaped as "S" curve and appeared as a typical bio-growth curve (Wang and Ma, 2002; Sun and Ma, 2002), and can be simulated perfectly by the Richards model (Xing et al., 1998). DBH was selected as the suitable variable of water consumption in scaling-up from single tree to stand level. We got an ideal simulating effect by using the tri-dimensional model in *Q. variabilis* forest stand when water consumption was scaled up to stand level with different diameter classes. Second, was the question as to how to add the main environment factors to the tri-dimensional model, which means water consumption scaling procedures be extrapolated to any environmental condition level from current environmental condition. There were many environmental factors and intricate mechanisms in stand transpiration, so it was difficult to build a feasible stand water consumption model with time variables, DBH, and environmental factors in a short time.

Usually, in water resource balance equation of mountainous water conservation forest, the input item is annual precipitation, the output items are canopy transpiration, canopy interception, and land surface evaporation (surface runoff and leakage need not be considered). In some forest stands made up by specific tree species, canopy interception and surface runoff is closely related to precipitation in certain climatic conditions (Wen and Liu, 1996). The forest stand water released by canopy transpiration, as the remainder item in water resource balance equation, can be calculated by the tri-dimensional model. The calculated water consumption in *Q. variabilis* forest was about 4,815.02 kg/hm^2, and the maximum stand density under the annual precipitation (600 mm) is 1,243 trees/hm^2. In this condition, the forest land water content can satisfy the demand of forest tree growth, and water capacity equals to stand evapotranspiration without runoff generation. The growth will be limited if the stand density exceeds the critical value, whereas the forest tree can grow well with surface runoff generation (ignoring deep leakage).

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