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RESEARCH ARTICLE

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Sap flow of the major tree species in the eastern mountainous region in northeast China

Abstract This study is based on *Quercus mongolica*, *Fraxinus mandshurica*, *Phellodendron amurense*, *Juglans mandshurica*, *Tilia amurensis*, and *Pinus koraiensis* trees of the same age (12 years) and seedling origin under the same site conditions. The sap flow density, water consumption, and related environmental factors were also measured using thermal dissipation method and ICT-2000TE (Transpiration-Environment) automatic measuring system for tree transpiration and environmental factors. On clear days during the growing season, the sap flow density exhibited mono-peak diurnal patterns, mostly between 10:00 and 14:00, except for *Phellodendron amurense*, whose sap flow showed two peaks during the daytime three times. The photosynthetically active radiation (PAR) and vapour pressure deficit (VPD) were the major factors influencing diurnal changes in sap flow, which explained 60%–74% variations in sap flow density for all species except *Phellodendron amurense*. Maximum sap flow densities for *F. mandshurica*, *Phellodendron amurense*, *Q. mongolica*, *J. mandshurica*, *T. amurensis*, and *Pinus koraiensis* were 516.36, 234.00, 625.93, 945.83, 507.93, and 286.21 $cm^3/(cm^2 \cdot h)$, in July, June, September, August, August, and July, respectively. Water consumption during the whole growing season for *J. mandshurica*, *T. amurensis*, *F. mandshurica*, *Pinus koraiensis*, *Phellodendron amurense*, and *Q. mongolica* was 3,840, 2,820, 2,710, 2,120, 1,470, and 1,390 kg/sapling, respectively.

Keywords major tree species in northeast China, sap flow, temporal dynamics, water consumption

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1 Introduction

Forest transpiration accounts for a large proportion of the annual water loss by combining direct evaporation and transpiration in forest hydrological cycling, whose component and tree density of the stand lead to clear differences (Zhou, 1999). The traditional transpiration measuring methods, such as weighting, porometer, and lysimeter were all limited because of tree size. In the thermometric method the stem of a tree is the most convenient place for measuring xylem sap flow, whose heat is used as the tracer for direct, accurate, and continuous *in situ* estimates of transpiration. Sap flow characteristics of *Populus deltoids* (Liu et al., 1993a, 1993b), *Betula dahurica* and *Acer mono* (Li et al., 1998), *Juglans mandshurica* (Yan et al., 1999), *Platycladus orientalis* and *Pinus tabulaeformis* (Wang et al., 2002), *B. platyphylla* (Sun et al, 2002), and *Larix principi-rupprechtii* (Xiong et al., 2003) have been studied in China. But sap flow of the major tree species in northeast China has been seldom measured.

This study simultaneously measured stem sap flow and related environmental factors of major tree species in the eastern mountainous region in northeast China using ICT-2000TE (Transpiration-Environment) automatic measuring system. The aim is to research temporal dynamics of stem sap flow density of major tree species in this region and related environmental factors, and compare stem sap flow density and water consumption of the different tree species. The results will be used as reference for selecting tree species for afforestation by optimizing stand structure and fully utilizing forest hydrological ecological benefit in the northeast region.

2 Materials and methods

2.1 Site description

Sap flow studies on the main tree species were conducted during the 2000/2001 growing season. The location was the Forest Ecosystem Research Station (45°20′–45°25′N, 127°30′–127°34′E) of Maoershan Experimental Forest belonging to Northeast Forestry University, Heilongjiang Province, China. In the Maoershan range, the highest peak is 805 m, with an average elevation of 300 m. The terrain is made up of undulating slopes generally from 10° to 15°. The soil is dark-brown forest soil, a well-developed soil under natural forest vegetation, with high organic matter content, and good drainage and aeration. Climatic conditions in this area are typically continental temperate monsoon climate. The annual mean temperature is 2.8°C. The annual ⩾5°C accumulated temperature is 2,897°C. Annual sunshine time is 1,850.4 h. Annual mean precipitation is 772.9 mm, with more than 60% concentrated in the 2 months during summer. Annual mean evaporation is 884.4 mm. Annual mean wind speed is 1.5 m/s. The frost-free period is from the end of May to the end of August.

The primary vegetation is dominated by Korean pine mixed with deciduous species such as *Betula* spp., *Larix* spp., *Populus* spp., *Quercus* spp. Since the turn of the twentieth century, the primary forest has been destroyed by large-scale industrial logging and replaced by secondary forests and plantations (Chen et al., 1994).

2.2 Materials

This study selected major tree species such as *J. mandshurica*, *Fraxinus mandshurica*, *Phellodendron amurense*, *Tilia amurensis*, *Pinus koraiensis*, and *Quercus mongolica* as research objects in the eastern mountainous region in northeast China. In spring 1989, one-year-old seedlings of the selected species from the nursery of Maoershan forestry center were planted in the clear cutting area in a small plot with a randomly mixed pattern and an initial spacing of 1.5 m×1.5 m, which gave tree species with same age (12 years) and seedling origin under the same site conditions, in order to compare stem sap flow variations due to the genetic properties of different tree species. The experiment site was south-facing.

According to the size of thermal dissipation probe and typical sampled saplings, each sampled sapling should be healthy, straight, non-stressed, and well-grown. Wooden shelves were erected around the sampled saplings that were as high as the middle-upper portion of the sampled sapling's canopy. Each sampled sapling's height was measured with a diameter tape. The leaf area of each sampled sapling during different foliar expanding periods was determined on the basis of sampled leaf method (Zhou, 1981). The sampled leaf area was measured by Li-3000 portable leaf area meter (Li-COR Co. Ltd., Lincoln, Nebraska, USA). The fully expanded leaves of sampled saplings were selected to make paraffin wax sectioning, and their anatomical structure was observed through the microscope.

The sapwood area of sampled saplings was estimated on the wood cores sampled by the borer from opposite north-south sides of stems at breast height (1.3 m) of trees whose diameter at breast height (DBH) was the same as the sampled saplings under the same site conditions. Five cores of each species were placed in plastic bags immediately after sampling and the radius measured without bark, sapwood, and heartwood directly for *F. mandshurica*, *J. mandshurica*, *Pinus koraiensis*, *Phellodendron amurense*, and *Q. mongolica* whose sapwood and heartwood were distinguished clearly by color. *T. Amurensis*, a diffuse-porous species, was less than 15 years of age, considering that all of the xylem conducted water.

The features of the saplings are listed in Table 1.

Table 1 Basic properties of the sampled saplings

Items	*Pinus koraiensis*	*Tilia amurensis*	*Juglans mandshurica*	*Quercus mongolica*	*Fraxinus mandshurica*	*Phellodendron amurense*
Height /m	5.75	4.64	5.83	4.92	7.60	5.59
DBH /cm	7.70	5.80	8.10	4.50	9.10	5.70
Sapwood area /cm^2	33.96	30.19	23.28	20.23	40.21	19.60

2.3 Stem sap flow and environmental factors

Thermal dissipation method proposed by Granier (1985) was used to measure sap flow rate of the selected sampled saplings. TDP (TDP30, Dynamax, Houston, Texas, USA) consisted of two cylindrical probes of 1.32 mm in diameter that were inserted 0.03 m into the sapwood of the bole, one above the other (0.10 m). The upper probe contained a constantan heating element, which was heated at constantan power. Each probe contained a copper-constantan thermocouple, connected together in opposition, in order to measure temperature difference. The precision in the estimation of the transpiration depends on the accuracy of the differential temperature measurements. The thermocouples must be protected against direct radiation and rain. The following instruments were installed above the tree's crown: RH1 humidity and temperature probe (Vaisala, UT, USA), SKP215 PAR Quantum Sensor (Skye, UK), SKS1110 Silicon Cell Pyranometer (Skye, UK), A100R wind sensor (Vector Instruments, UK), GMP111 CO_2 transmitter (Vaisalar, Utah, USA). STC soil temperature sensor (Delta-T Devices Ltd., Cambrige, UK) and MP406 moisture probe (ICT Ltd., Australia) were used to measure soil temperature and soil volumetric water near the tree's root distribution. Rainfall was measured in the clearing with an ARG100 tipping bucket rain gauge (EM Ltd., USA). TDP（Dynamax, Houston, Texas, USA）and all environmental sensors were sampled every 15 min (ZENO3200, Coastal Environmental Systems, USA).

2.4 Data calculation and analysis

Sap flow rate was calculated with the Eq. (1):

$$Fs = 0.011,9 \times SA \times K^{1.231} \quad (1)$$

where *Fs* is the sap flow rate (l/h); *SA*, the sapwood area at the lever of heated probe (cm^2); and *K*, the flow index (dimensionless):

$$K = [d_{TM} - d_T] / d_T$$

where d_{TM} is the temperature difference between probes without any sap flow and d_T, the temperature difference with sap flow. Stem temperature difference of *Q. mongolica*, *J. mandshurica*, and *Phellodendron amurense* was corrected according to Clearwater (1999) because their sapwood thickness was less than 30 mm. Then sap flow density was calculated using the corrected temperature values with Eq. 1. The probes were installed at 40 cm above the ground because radius at the breast height of *Q. mongolica* and *Phellodendron amurense* was less than the probe length. Sap flow density was converted at DBH with the Eq. (2) for *Q. mongolica* and *Phellodendron amurense*:

$$Js_{1.3} = Js \times As / As_{1.3} \tag{2}$$

where *Js* and *As* are sap flow density ($cm^3/(cm^2 \cdot h)$) and sapwood area (cm^2) at the measurement point, respectively; $Js_{1.3}$ and $As_{1.3}$ are sap flow density ($cm^3/(cm^2 \cdot h)$) and sapwood area (cm^2) at the DBH, respectively. Using Eq. (3) the relationship of sap flow density to sap flow rate can be calculated:

$$Fs = As \times Js \tag{3}$$

where *Fs* is sap flow rate (cm^3/h), and *As* and *Js* are the same as in Eq. (2).

The water consumption was calculated with the Eq. (4): Water consumption per month (10^3 kg/sapling) = average sap flow density per month × 24 × sapwood area × days of the month × 10^{-6} (4)

During the early part (May) and the end (October) of the growing season, the growth days were generally 15 and 20, whereas it was accumulated daily from June to September.

The data statistical analysis was done using EXCEL and SPSS10.1.

3 Results and discussion

3.1 Diurnal changes of stem sap flow

Diurnal courses of sap flow density were different due to the growth rhythm. So the diurnal sap flow changes of different saplings were observed by foliar development phase according to phonological observation (Zhou, 1981) as follows.

3.1.1 Foliar expansion

The buds of *Pinus koraiensis*, *F. mandshurica*, and *J. mandshurica* had just begun to expand, whereas those of *Phellodendron amurense*, *T. amurensis*, and *Q. mongolica* had expanded during the early days of the growing season. The maximum sap flow density of *Q. mongolica* was 43.48 $cm^3/(cm^2 \cdot h)$ at 9:00, which was obviously higher than the others. Maximum sap flow density of *Pinus koraiensis* was half of that of *Q. mongolica*, and higher than one other broad-leaved saplings (Fig. 1a). Water transportation at night and pre-dawn of *Phellodendron amurense* was 22.61% of total daytime transportation, and higher than five other species (about 10%). Average daily sap flow densities for *Pinus koraiensis*, *Q. mongolica*, *J. mandshurica*, *F. mandshurica*, *T. amurensis*, and *Phellodendron amurense* were 7.33, 13.14, 4.13, 3.53, 2.84, and 1.26 $cm^3/(cm^2 \cdot h)$, respectively. The transpiration of *Pinus koraiensis* was higher than the foliar non-expanding broad-leaved trees, except for *Q. mongolica* due to its relatively large leaf area, proper temperature, and soil humidity. However, with the foliar expansion, sap flow density for *Pinus koraiensis* was lower than for one other species (Fig. 1b). The diurnal changes of sap flow density showed as a wide mono-peak pattern, except that *Phellodendron amurense* showed a dual-peak pattern, whose maximum sap flow density occurred at 8:00 and 14:00, and minimum at 11:00. During the foliar expansion period, sap flow density of *Q. mongolica* was higher than that of the other saplings, maybe because it stopped growing in height at the end of May (Zhou, 1981), which resulted in more water consumption.

3.1.2 Full foliar expansion

In clear days during the full foliar expansion period, the sap flow density of the saplings mostly exhibited standard mono-peak or quasi-mono-peak diurnal pattern.

Quasi-mono-peak diurnal pattern is when sap flow density changes with the instant change in PAR. For example, PAR reached a maximum value of 1,351.1 μmol/($m^2 \cdot s$) at 11:00, dropped at 12:00 and 13:00 (1,140.85 μmol/($m^2 \cdot s$)), then increased to 1,348.63 μmol/($m^2 \cdot s$) at 14:00 on June 29 (Fig. 2a). Air temperature and air relative humidity had changed correspondingly with PAR, but VPD varied only a little (Fig. 2b). Sap flow density exhibited a minimum value at 13:00 on June 29 for *T. amurensis*, *J. mandshurica*, *F. mandshurica*, and *Pinus koraiensis* because of the changes in PAR (Fig. 2c).

3.1.3 Foliage falling period

During the foliage falling period on September 26–27 (Fig. 3a) and October 9–10 (Fig. 3b), sap flow density showed mono-peak diurnal pattern, except for *F. mandshurica*, whose mono-peak pattern changed into an irregular one. After mid-October, air temperature dropped to –3.9°C at 8:00, maximum and mean sap flow density of the saplings sharply dropped (Fig. 3c), and the ratio of nighttime to pre-dawn total water consumption increased, i.e., the ratio for *Phellodendron amurense* and *T. amurensis* was 63.88% and 42%, respectively.

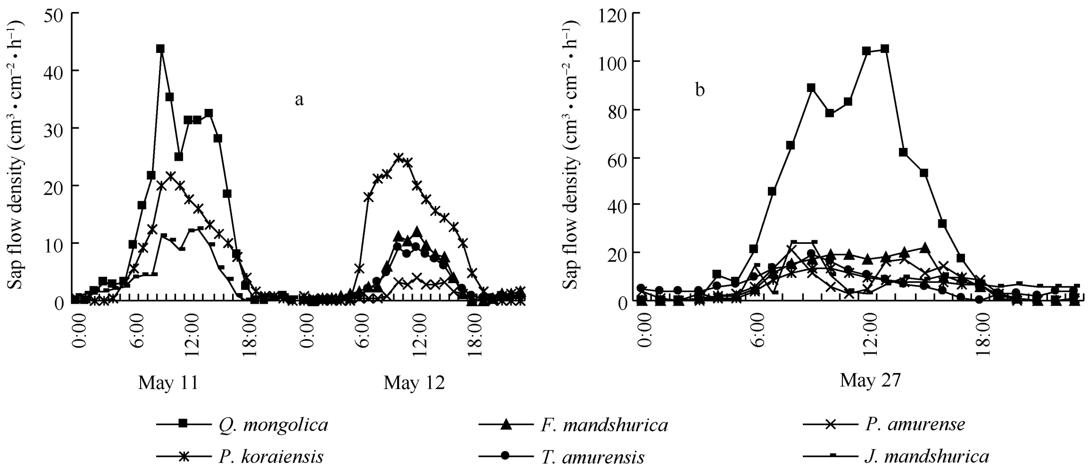

Fig. 1 Diurnal courses of sap flow density during the foliar expanding period

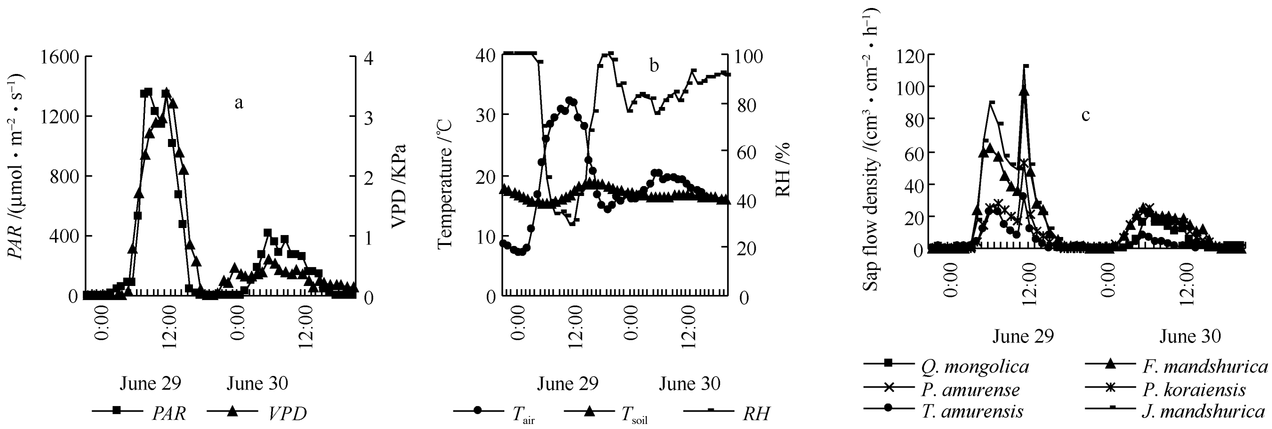

Fig. 2 Diurnal changes of sap flow density and main environmental factors on June 29, 30

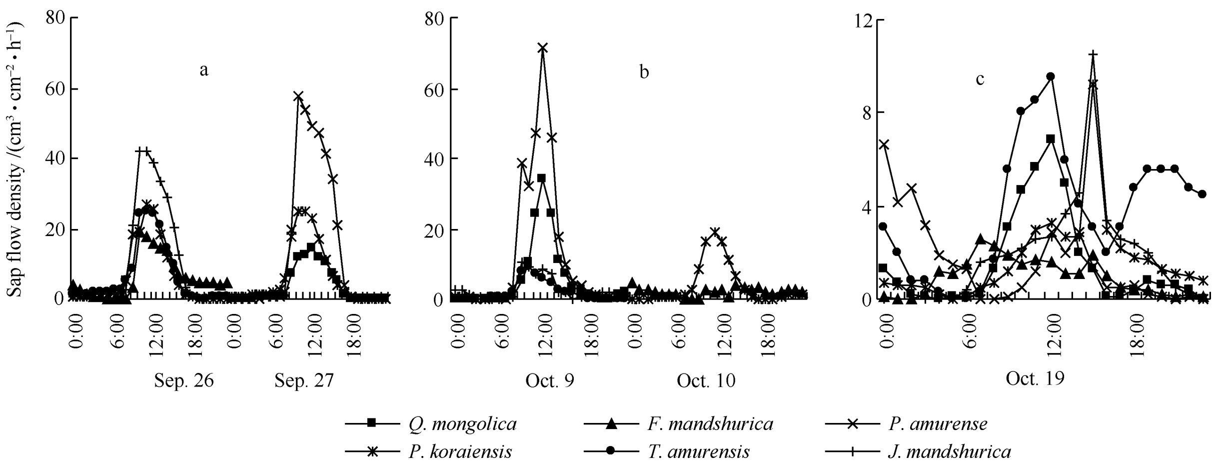

Fig. 3 Diurnal courses of sap flow density during the foliar senescing period

The maximum sap flow densities occurred between 9:00 and 16:00, mostly during 10:00–14:00 (69%–91%) during the measurement. Over the measurement periods, the maximum sap flow densities for *Q. mongolica*, *F. mandshurica*, *Phellodendron amurense*, *J. mandshurica*, *T. amurensis*, and *Pinus koraiensis* were 625.93, 516.36, 234.00, 945.83, 507.93, and 286.21 $cm^3/(cm^2 \cdot h)$, respectively.

3.2 Relationship between sap flow and environmental factors

Step regression standard equations were established to describe the relationships between diurnal changes of sap flow density and significant environmental factors over a monthly measurement period. Partially adjusted determinant coefficients of environmental factors in the equations are given in Table 2. The influence of environmental factors on diurnal sap flow density varied with the tree species and growth period, indicating the complexity in their relationships. Diurnal changes of sap flow density were mainly determined by radiation and VPD (32), whereas soil temperature, wind speed, and soil moisture were not the major factors (4). During the fully growing season (June–August), diurnal changes of sap flow density were explained by PAR and VPD for 60%–74% variations, except for *Phellodendron amurense*, which was explained by VPD for 45%. Generally, diurnal changes of sap flow density were predicted by the models that contain radiation, VPD, and the combination of the above two factors.

Table 2 Partially adjusted determinant coefficients between sap flow density and significant environmental factors

Species	Significant factors ($P < 0.05$)	Month					
		May	June	July	Aug.	Sep.	Oct.
Fraxinus mandshurica	PAR	0.72	0.70	–	–	0.28	0.23
	VPD	–	–	0.69	–	–	0.09
	SM	–	–	–	0.80	–	–
	ST	–	–	–	0.04	–	–
Phellodendron amurense	PAR	0.24	–	–	–	0.09	0.36
	VPD	–	0.75	0.44	0.16	–	–
	SM	–	–	–	–	0.09	–
	Wind	–	–	–	–	0.41	–
Tilia amurensis	PAR	0.56	0.66	–	–	0.54	–
	VPD	0.13	–	0.72	0.74	–	0.23
	ST	–	–	–	–	0.14	–
	Wind	–	–	–	–	0.05	0.38
Quercus mongolica	PAR	0.73	0.72	0.41	–	0.55	0.44
	VPD	–	–	–	–	0.06	0.07
	SM	–	–	0.31	–	–	–
	ST	–	–	–	0.37	–	0.04
Juglans mandshurica	PAR	0.39	–	–	–	0.57	0.43
	VPD	–	0.61	0.56	0.61	–	–
	ST	–	–	–	–	0.08	–
	Wind	–	0.07	–	–	–	–
Pinus koraiensis	PAR	0.81	0.75	0.20	–	0.42	0.66
	VPD	–	–	0.48	0.40	–	0.01
	SM	0.03	–	–	–	–	–
	ST	–	–	–	–	0.14	–

PAR: photosynthetically active radiation; VPD: vapour pressure deficit; Wind: wind speed; SM: volumetric soil water content; ST: soil temperature.

3.3 Seasonal changes of sap flow density

Mean sap flow densities for sunny days during different measurement period are shown in Fig. 4. Seasonal changes of sap flow densities for *Phellodendron amurense*, *Pinus koraiensis*, *J. mandshurica*, and *T. amurensis* exhibited both mono-peak curve and maximum value in June, July, and August, respectively, while *Q. mongolica* and *F. mandshurica* had dual-peak curves. The first seasonal maximum sap flow density for *Q. mongolica* occurred earlier than *F. mandshurica*, maybe due to the different growth rhythm. *Q. mongolica* is a species that grows in height quickly within a short period in the growing season. The last 10 days in May is just the period in which *F. mandshurica* begins its rapid growth in height, while *Q. mongolica* has almost completed its growth. Different growth rhythms lead to the seasonal change of sap flow for *Q. mongolica* earlier than that of *F. mandshurica*. Over the whole season, mean sap flow densities for *J. mandshurica*, *F. mandshurica*, *Q. mongolica*, *Phellodendron amurense*, *T. amurensis*, and *Pinus koraiensis* are 29.44, 17.97, 17.68, 15.27, 14.91, and 12.10 $cm^3/(cm^2 \cdot h)$, respectively.

3.4 Water consumption in the growing season of samples

During the growing season the water consumption for *J. mandshurica*, *T. amurensis*, and *Pinus koraiensis* mainly occurred in July and August; the ratio of water consumption in these 2 months for the above trees was 67.96%, 79.08%, and 63.21%, respectively (Fig. 5). The ratio of water consumption for *Phellodendron amurense* was mainly in June and July at a rate of 61.22%, while for *Q. mongolica* and *F. mandshurica* it mainly occurred in August and September (58.27%), and June and September (72.70%), respectively. In May, the ratio of water consumption for *Q. mongolica* was higher (12.23%) than for *J. mandshurica* (1.30%), *T. amurensis* (1.77%), *F. mandshurica* 3.32%), *Pinus koraiensis* (3.77%), and *Phellodendron amurense* (2.04%), which were all less than 5%. The ratio of total water consumption in October for the samples was less than 4% due to dormancy.

Over the whole growing season the sequence of water consumption was: *J. mandshurica* (3.84) > *T. amurensis* (2.82) > *F. mandshurica* (2.71) > *Pinus koraiensis* (2.12) > *Phellodendron amurense* (1.47) > *Q. mongolica* (1.39) (unit: 10^3 kg/sapling). Among the above saplings, the sap flow density for *Pinus koraiensis* was the lowest, but because its sapwood area was 33.96 cm^2, which is higher than that of *Q. mongolica* (20.23 cm^2) and *Phellodendron amurense* (19.60 cm^2), it resulted in its higher water consumption than for broad-leaved trees such as *Q. mongolica* and

Phellodendron amurense.

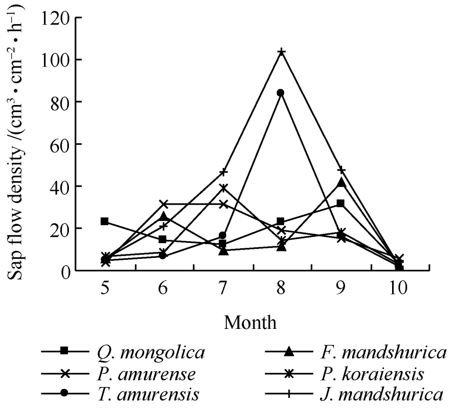

Fig. 4 Seasonal changes in means of sap flow density

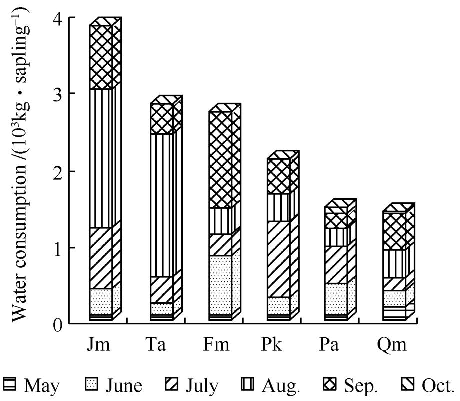

Fig. 5 Water consumption in the growing seasons

The sap flow densities for all selected saplings were determined by their biological properties such as water absorption, transportation, and transpiration systems under the same micro-environmental situation. *J. mandshurica*, *Phellodendron amurense*, and *Q. mongolica* were all deep-rooted species, while *Pinus koraiensis* and *F. mandshurica* were shallow-rooted species. The minimum soil moisture ranged from 19.46% to 19.69% on June 14, June 30, and September 18, and it was higher than 20% on other days during the measurement period. So the root system distribution had little effect on water consumption, while soil water was not a limiting factor.

Table 3 illustrates the strong interactions and adaptations between the water transportation system and transpiration system. For example, as a conifer, the water transportation unit of *Pinus koraiensis* was tracheid, and the flat diameter was the smallest among the six selected saplings. On the basis of Hagen–Poiseuille law, sap flow density is proportional to the fourth power of the conduit radius (Larcher, 1980). In the process of water transportation in the stem of *Pinus koraiensis*, its resistance was the largest and foliar cuticle was thicker, and the maximum and mean stomatal conductance was obviously lower than broad-leaved species, resulting in its sap flow density being the smallest among the selected saplings. However, the tracheid length for *Pinus koraiensis* can reach up to 5,060–6,540 μm, which can compensate for the water transportation efficiency, while the water transportation unit of broad-leaved species was like a vessel. As a diffuse-porous species, the flat diameter for *T. amurensis* was the smallest among the selected broad-leaved species so that its water transport efficiency was lower than the others. But its mean length was 450 μm and it had spiral thickening. Mean stomatal conductance was only lower than *J. mandshurica*, which was the highest in the selected saplings. *T. amurensis* also had such characteristics as thin foliar cuticle, loose palisade tissue, strong vein, and high value of leaf/sapwood area so that its sap flow density was equal to *Phellodendron amurense*. As a ring-porous species, the vessel's flat diameter and mean length for *Q. mongolica* were both higher than those of *F. mandshurica*, but the mean stomatal conductance and the value of leaf/sapwood area for *Q. mongolica* were three fifths and one half of those of *F. mandshurica*, respectively, and the foliar cuticle and palisade tissue of *Q. mongolica* were stronger and tighter than those of *F. mandshurica* so that their sap flow densities were similar. As a semi-ring-porous species, *J. mandshurica*'s vessel flat diameter averaged 140–150 μm and was clearly smaller than ring-porous species. But its longest vessel reduced the resistance for water across different vessels. Its diameter of intervascular pit pair, leaf/sapwood area, and mean stomatal conductance were the highest so that its sap flow density was the highest among the selected saplings under the transpiration pull and small resistance of water conductance.

Table 3 Characteristics of tree water transportation and transpiration system*

Species	Average flat diameter of water transportation unit /μm	Average length of water transportation unit /μm	Diameter of intervascular pit pair /μm	Leaf area/sapwood area /($m^2 \cdot cm^{-2}$)	Mean stomatal conductance /($mol \cdot m^{-2} \cdot s^{-1}$)
Pinus koraiensis	40–45	5,060–6 540	–	0.50	0.02
Tilia amurensis	50	450	6–7.5	0.77	0.32
Juglans mandshurica	140–150	530–600	8–14	1.19	0.44
Fraxinus mandshurica	220	240	4–8	0.89	0.30
Quercus mongolica	250–305	440–540	6–8	0.44	0.19
Phellodendron amurense	210	400	6.2–9.6	0.70	0.22

*Wood anatomical characteristics were cited from "Wood Science" edited by Cheng Junqing (1985).
Mean stomatal conductance was calculated by means of stomatal conductance of the whole day in the growing season of samples.

There existed compensated relations between flat diameter, length of water transportation unit, leaf/sapwood area, mean stomotal conductance, and foliar anatomic properties, which effect the tree considerably to maintain a homeostatic state for adaptation to the environment.

4 Conclusions

On sunny days during the growing season, the sap flow density exhibited mono-peak diurnal curve, mostly from 10:00 to 14:00 (69%–91%), except for *Phellodendron amurense.* Results of statistical analysis indicated that PAR and VPD were the major factors affecting each tree sap flow density on fine days at different points in the growth period. Maximum sap flow densities for *F. mandshurica*, *Phellodendron amurense*, *Q. mongolica*, *J. mandshurica*, *T. amurensis*, and *Pinus koraiensis* were 516.36, 234.00, 625.93, 945.83, 507.93, and 286.21 $cm^3/(cm^2 \cdot h)$, respectively. Seasonal average sap flow density ($cm^3/cm^2/h$) on a fine day during the study period was in the following order: *J. mandshurica* (29.44) > *F. mandshurica* (17.97) > *Q. mongolica* (17.68) > *Phellodendron amurense* (15.27) > *T. amurensis* (14.91) > *Pinus koraiensis* (12.10). Water consumption during the whole growing season for *J. mandshurica*, *T. amurensis*, *F. mandshurica*, *Pinus koraiensis*, *Phellodendron amurense*, and *Q. mongolica* was 3,840, 2,820, 2,710, 2,120, 1,470, and 1,390 kg/sapling, respectively.

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