Original Ariticle

Sap-flow velocity reduction by soil water deficit observed in a *Lithocarpus edulis* forest on Kyushu Island, Japan *

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Abstract

This paper examines transpiration reduction due to soil water deficits observed in a *Lithocarpus edulis* forest on Kyushu Island, south-western Japan. Continuous sap flow measurements were performed on six trees to monitor changes in tree transpiration rates. A reduction in sap flow velocity was observed in the period between late-September and late-October 2003. Precipitation amounts for this period were limited resulting in a corresponding low soil matric potential. A clear reduction in sap flow velocity occurred when soil matric potential at a 10 cm depth was < − 70 (kPa). Sap flow velocity scaled for 1.0 kPa vapor pressure deficit declined by 42 % when soil matric potential at a 10 cm depth was < − 70 (kPa) compared to ≥ − 70 (kPa). In addition, intensive leaf-scale physiological measurements were performed on two days that had contrasting soil matric potentials. The intensive measurements showed lower leaf transpiration rates and stomatal conductance on the day with the lower soil matric potential. This finding suggests soil water deficits caused stomatal closure and therefore reduction in tree transpiration. Sap flow velocity and leaf water potential data showed that stem hydraulic conductance did not decline with low soil matric potential when compared to the day with higher soil matric potential.

Key words: forest canopy; *Lithocarpus edulis* ; sap flow; soil water deficit; transpiration

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* 九州のマテバシイ林で計測された土壌水分減少による樹液流速の低下

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1. Introduction

As forests are the predominant land-cover type in Japan (Fujimori, 2000), examining the forest water cycle is crucial for water resources management (Komatsu, 2007). Forest canopy transpiration is a critical component affecting water yield from forested watersheds (Vertessy *et al.*, 2001; Komatsu *et al.*, 2007b). Thus, numerous researchers have investigated forest canopy transpiration in Japan (Komatsu *et al.*, 2006a,b; Kumagai *et al.*, 2007).

Soil water availability is a factor affecting forest canopy transpiration. Reduction in forest canopy transpiration by soil water deficit has been reported by several international studies (Granier *et al.*, 2000; Law *et al.*, 2001) and is included in forest water cycle models (Granier *et al.*, 1999; Williams *et al.*, 2001). However, very few studies (Hattori *et al.*, 1993; Takimoto *et al.*, 1994; Tanaka *et al.*, 2002) have examined reduction in forest canopy transpiration by soil water deficit in Japan. Furthermore, water cycle models developed in Japan (Kondo *et al.*, 1992; Komatsu *et al.*, 2005, 2007b) usually do not include this phenomenon. Thus, reduction in forest canopy transpiration by soil water deficit may not be a common event in Japan.

Nevertheless, examining the effect of soil water deficit on forest canopy transpiration is significant for the following two reasons. First, soil water deficit could greatly affect forest canopy transpiration during infrequent severe droughts brought on by inter-annual precipitation variability or a possible climate change. Second, examining the forest water cycle during a severe drought is important because water resources management becomes critical. This study examined reduction in forest canopy transpiration by soil water deficit in Japan.

2 Materials and methods

2.1 The site

The experiments were executed in the Kasuya Research Forest of Kyushu University, on Kyushu Island, south-western Japan (33° 38'N, 130° 31'E, elevation 50 m). The study site was located in a 28-year old evergreen broad-leaved plantation forest (*Lithocarpus edulis*) with an approximate canopy height of 9 m. Surface soil was layered (Imura *et al.*, 2000); the first layer, containing humus, ranged between 0 and 25 cm depth; the second layer, consisting of clay, ranged between 25 and 80 cm depth; and the soil layer located > 80 cm depth consisted of hard bedrock. An examination by Hosokawa *et al.* (2001) in 1998 revealed the majority of the tree roots were distributed between the 0 to 20 cm range. The saturated hydraulic conductivity was 1.5×10^{-2} cm s^{-1} for the first layer and 3.0×10^{-5} cm s^{-1} for the second layer as shown in a study by Imura *et al.* (2000) conducted in 1998. The annual mean temperature is about 16 ℃ and the annual total precipitation is about 1800 mm at this site (Hirose *et al.*, 2005). Further details regarding the description of the site are available in research papers by Imura *et al.* (2000), Sato *et al.* (2003, 2004) and Hirose *et al.* (2005).

The site included two plots with differing pedestrian trampling intensity to examine the effect, if any, on the forest water cycle. Our previous study (Komatsu *et al.*, 2007a) found a significant difference in sap flow velocity between the plots. However, this difference did not alter the conclusions of this study. Thus, the data from the two plots were not differentiated.

2.2Measurements

Tree transpiration was monitored by measuring sap flow on six trees. The measurements were performed during the period of September 6 to December 1 in 2003. The diameter at breast height (DBH) of the sample trees ranged between 13.6 and 15.3 cm.

Sap flow measurements (n = 6) were performed based on the heat-pulse method (Closs, 1958; Marshall, 1958; Swanson, 1994). Instrumentation for the heat-pulse method was comprised by a set of three sensors (HP-3, Hayasi Denko Co.) consisting of a heater probe and two thermistor probes (diameter: 2.0 mm; length: 60 mm). The three sensors were installed at a height of 120 cm in holes drilled to a depth of 10 mm. A heat-pulse tracer was released for a duration of 1.5 s every 20 min and the temperature difference between the thermistor probes was measured every 0.25 s. The time delay for the same temperature increase to occur at both thermistor probes was recorded with a solid-state memory module (CR10X, Campbell Scientific).

We measured meteorological and soil water conditions concurrently. This data was used later to interpret the sap-flow velocity data. Precipitation was measured using a tipping bucket gauge situated in an open space adjacent to the forest. Above-canopy air temperature and relative humidity were measured using a thermistor (VHE, Vaisala) positioned 14 m from the ground surface. Soil matric potential was measured at 10 cm depth at two different points using tensiometers (DIK-3021, Daiki Rika Kogyo). These two measurement points were about 18 m apart.

In addition, we took intensive measurements of leaf stomatal conductance and leaf transpiration rates using a porometer (Li-6400, Li-Cor) and leaf water potential using a pressure chamber (Model 600, PMS instrument Co.). These measurements were conducted on two leaves of four different trees, on three of which sap flow measurements were performed. These intensive measurements were undertook on October 7 and November 14, days which displayed contrasting soil water conditions. Data from these measurements were used to examine the processes of transpiration reduction.

3 Results and discussion

Monthly precipitation amounts were 64, 7, and 122 mm for September, October, and November, respectively. Monthly precipitation amounts at the site, averaged for the previous 30 years, were 175, 81, and 81 mm for September, October, and November, respectively. Thus, precipitation amounts in 2003 were much lower than usual in September and October. Figure 1a shows daily precipitation during the period that sap flow measurements were performed. The amount of precipitation was quite small for the period between mid-September and late-October.

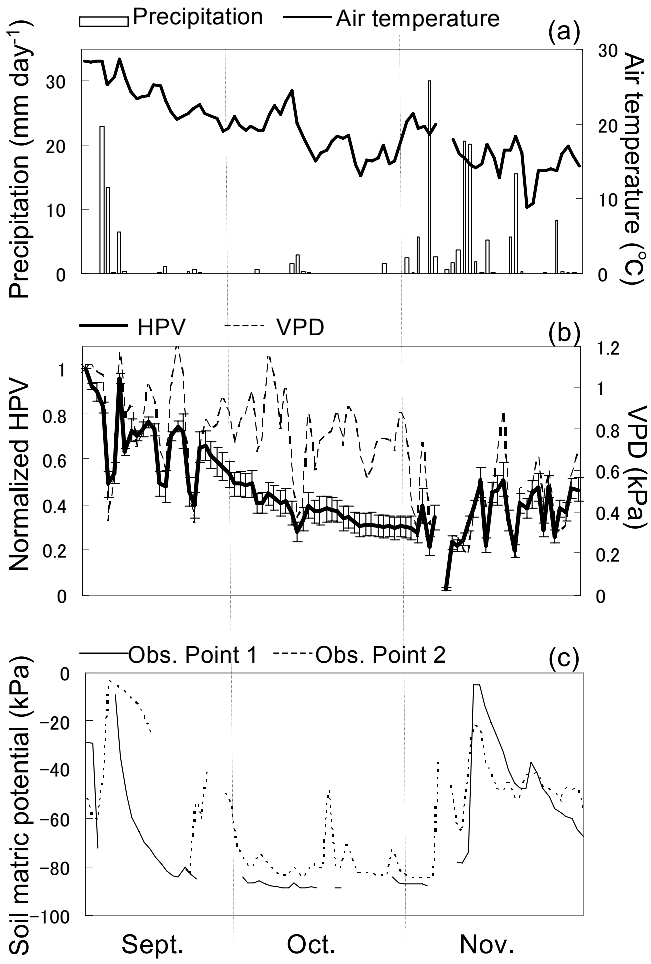

Fig. 1. Meteorological conditions, daily heat-pulse velocities (HPVs), and soil matric potential at a 10 cm depth. (a) Precipitation and air temperature; (b) HPVs and vapor pressure deficit (VPD); (c) soil matric potential at two observation points in the forest. HPV values were normalized by the value on September 6 (i.e. the first day of sap flow measurements) and averaged for the number of sample trees (n = 6). Vertical bars indicate standard deviation.

Figure 1b shows daily heat-pulse velocities (HPVs) and vapor pressure deficit (VPD). HPVs were normalized by the value on September 6 (i.e. the first day of sap flow measurements) and then averaged for the number of sample trees (n = 6). Normalized HPVs corresponded well to VPD in early-September and in November. During the period between late-September and late-October, normalized HPVs did not correspond well to VPD. This implies that soil water deficit limited transpiration during this period and which is supported by the soil matric potential data. Figure 1c displays 10 cm depth soil matric potential at two different observation points. Soil matric potential tended to be lower at both observation points in the period between late-September and late-October.

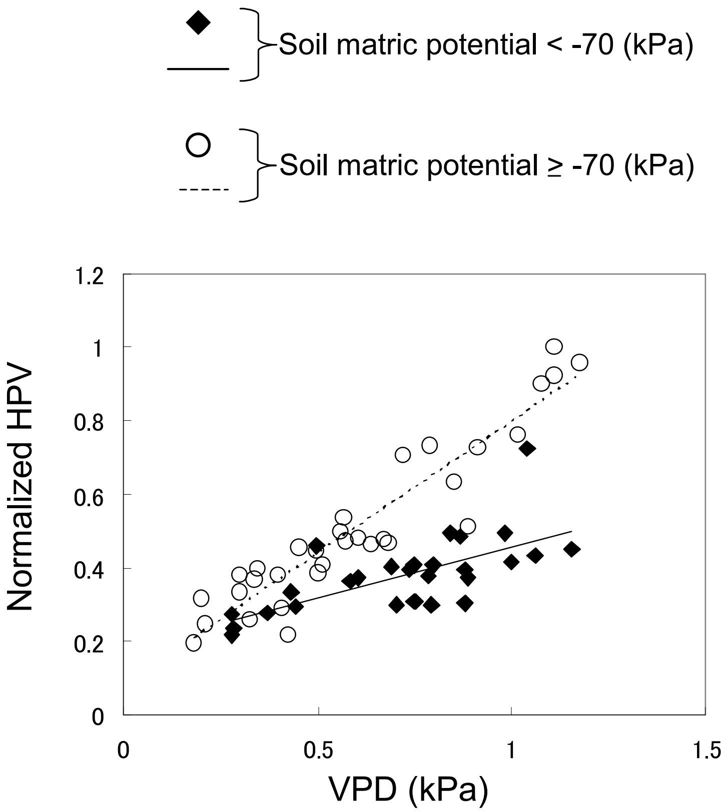

Fig. 2. Relationship between vapor pressure deficit (VPD) and normalized heat-pulse velocities (HPVs) classified according to soil matric potential (average of data from Observation Points 1 and 2).

Figure 2 shows the relationship between VPD and the normalized HPV, classified by soil matric potential (Fig. 1c). Regression lines were determined by the least-squares method. The normalized HPV increased with increasing VPD regardless of soil matric potential class. However, the slope of the regression line was greater when soil matric potential was ≥ −70 (kPa) ($p < 0.001$; t-test). HPV scaled for 1.0 kPa VPD declined by 42% for soil matric potential at 10 cm depth < −70 (kPa). Thus, sap-flow velocity reduction was significant when the soil matric potential was < −70 (kPa). This agrees with Komatsu *et al.*'s (2007a) examination on the relationship between soil matric potential and water content. They showed that reduction in soil water content was drastic when soil matric potential was< −70 (kPa) (Figure 5b of Komatsu *et al.*, 2007a), indicating that available soil water greatly reduced when soil matric potential became <−70 (kPa).

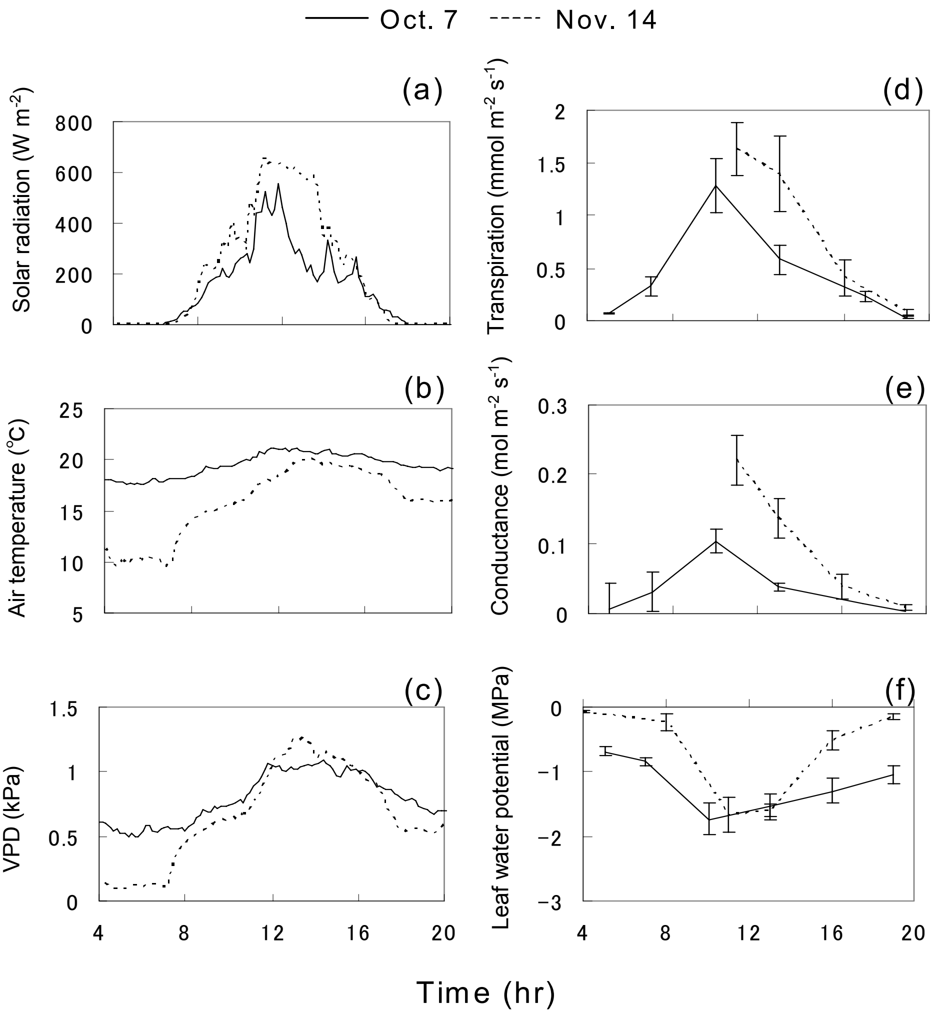

Fig. 3. Diurnal course of (a) solar radiation, (b) air temperature, (c) vapor pressure deficit (VPD), (d) leaf transpiration rates, (e) leaf stomatal conductance, and (f) leaf water potential on October 7 and November 14. Leaf transpiration rates and stomatal conductance were not measured in the early morning of November 14 due to heavy dew. October 7 was in the period with heat-pulse velocity reduction, while November 14 lies outside the period.

Figure 3 shows the diurnal course of meteorological factors (Figs. 3a, 3b, and 3c), leaf transpiration rates (Fig. 3d), leaf stomatal conductance (Fig. 3e), and leaf water potential (Fig. 3f) on October 7 and November 14. October 7 was included in the period with sap-flow velocity reduction while November 14 lies outside this period (Fig. 1b). Transpiration rates were lower for October 7 than for November 14 (Fig. 3d) which is consistent with the HPV data in Fig. 1b. Stomatal conductance and predawn water potential were lower on October 7 than November 14 (Figs. 3e and 3f). This indicates a lower soil water availability caused lower stomatal conductance and therefore lower transpiration rates on October 7.

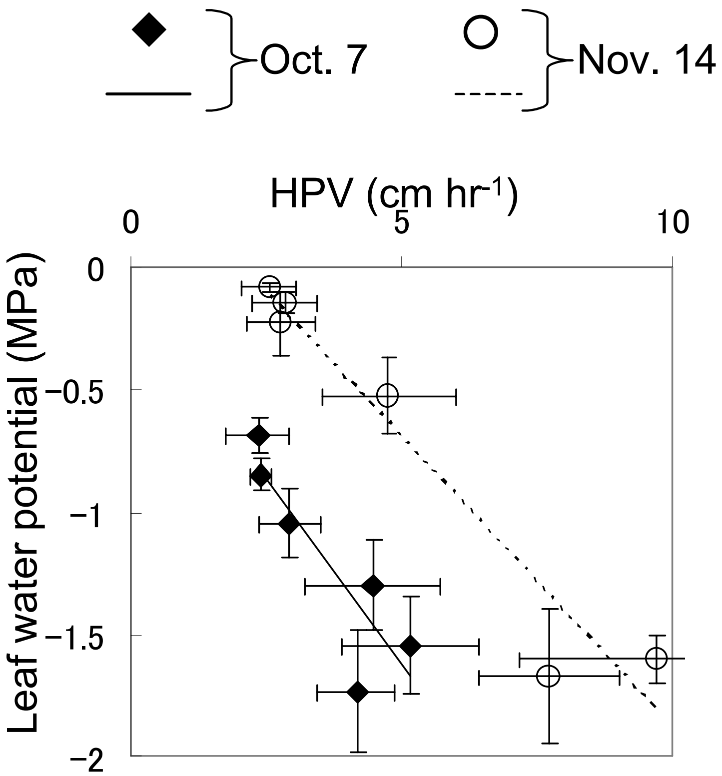

Fig. 4. Relationship between heat-pulse velocities (HPVs) and leaf water potential on October 7 and November 14. October 7 was in the period with heat-pulse velocity reduction while November 14 lies outside the period. Bars indicate standard deviation.

Figure 4 shows the relationships between HPV and leaf water potential on October 7 and November 14. Regression lines were determined based on the least-squares method. The slope for October 7 was not significantly different from that for November 14 (p = 0.39; t-test). This suggests that stem hydraulic conductance did not decline on October 7 compared to November 14.

4 Conclusions

Sap flow was monitored for six trees in a broad-leaved forest on Kyushu Island located in south-western Japan. Sap flow velocity was clearly reduced when the precipitation amount, and therefore the soil matric potential, was low. Reduction in sap flow velocity was significant when the soil matric potential at a 10 cm depth was < -70 (kPa): HPV scaled for 1.0 kPa VPD was reduced by 42% for soil matric potential at a 10 cm depth < -70 (kPa). Leaf-scale physiological measurements suggested tree transpiration reduction was caused by physiological stomatal control due to soil water deficit.

Our study is important as few studies have reported on such reductions in Japan. Further research will clarify the forest water cycle during the infrequent severe droughts that can be brought on by inter-annual precipitation variability or possible future climate change.

Acknowledgements

We would like to thank Dr. Atsushi Kume (Universityof Toyama , Japan) and Dr. Shigeki Hirose (T & F, Japan) for their instruction and assistance in measurements. Thanks are also due to two anonymous reviewers whose comments greatly improved the manuscript. This research was supported by Grant-in-Aid for Scientific Research (#17380096 and #18810023) from the Ministry of Education, Science, and Culture of Japan.

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九州のマテバシイ林で計測された土壌水分減少による樹液流速の低下

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要　旨

本論は，九州のマテバシイ林で計測された土壌水分減少による蒸散低下を調べたものである。蒸散の変化を観測するために森林内の6本の樹木において樹液流計測を行ったところ，2003年9月下旬から10月下旬にかけて樹液流速の低下が認められた。この期間は降水量が少なかったために，土壌マトリックポテンシャルが低下していた。樹液流速の低下は，深度10 cmの土壌マトリックポテンシャルが－70 kPa以下のときに顕著であった。大気飽差が1.0 kPaのときの樹液流速は，土壌マトリックポテンシャルが－70 kPa以下のとき，土壌マトリックポテンシャルが－70 kPa以上のときに比べて42%低下していた。樹液流計測に加えて単葉スケールでの樹木生理計測を，土壌マトリックポテンシャルの異なる2日を選んで行った。その結果，単葉の蒸散量と気孔コンダクタンスは，土壌マトリックポテンシャルが低い日において小さかった。このことは，土壌水分減少が気孔の閉鎖を引き起こし，その結果，樹木の蒸散が低下したことを示唆している。樹液流速と水ポテンシャルの関係から，土壌マトリックポテンシャルの低下による幹の通水コンダクタンスの低下は認められなかった。

キーワード: 森林; マテバシイ; 樹液流; 土壌水分減少; 蒸散