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Short communication

Reduction in soil water availability and tree transpiration in a forest with pedestrian trampling

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Abstract

Many studies have reported tree growth reduction in forests with pedestrian trampling, implying a reduction of tree transpiration in such forests. We undertook observations of tree transpiration based on the heat-pulse method in a forest (*Lithocarpus edulis*) with pedestrian trampling. We prepared trampled and control plots in the forest. Tree transpiration in the trampled plot was reduced compared to that in the control plot after precipitation with a small-precipitation period preceding this. No difference was observed between plots in the small-precipitation period itself; during which tree transpiration was limited in both plots. After the period, tree transpiration recovery was not as complete in the trampled plot as in the control plot. This was caused by incomplete soil matric potential recovery at 20 cm and deeper in the trampled plot due to a lower infiltration rate. We believe this study is the first to report reduction of tree transpiration in a forest with pedestrian trampling.

Keywords: Forest; Pedestrian trampling; Soil compaction; Soil water; Transpiration

1. Introduction

Recently, forests have become not only places for timber production but also one for recreation, which is usually accompanied with pedestrian trampling (Fujimori, 2000). For urban forests, the latter use of forests has become more common than the former.

Recreational use of forests may alter the forest water cycle; for example, pedestrian trampling induced by recreational use may cause soil compaction and therefore limit soil available water of trees (Kozlowski, 1999), resulting in a reduction in tree transpiration.

There have been many studies (Jim, 1993; Ohnuki et al., 1999; Ito et al., 2002) reporting tree growth reductions in forests with pedestrian trampling. Such tree growth reductions are often accompanied with reduction of tree photosynthesis (Greacen and Sands, 1980; Sheriff and Nambiar, 1995; Miller et al., 1996), which suggests tree transpiration reduction because of a close relationship between photosynthesis and transpiration (Campbell and Norman, 1998; Leuning, 1990; Law et al., 2002).

However, there are no studies reporting tree transpiration reduction in a forest with pedestrian trampling. There have been many papers reporting plant transpiration reduction with soil compaction (Scott et al., 2002; Moreno et al., 2003; Sadras et al., 2005). However, most of these papers dealt with grass and crop vegetation

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rather than forest. Though there have been several studies examining the effects of soil compaction on soil, stem and leaf water potential of forests (Sheriff and Nambiar, 1995; McNabb et al., 2001; Gomez et al., 2002); these studies did not examine tree transpiration and focused on soil compaction caused by forestry machinery and irrigation rather than pedestrian trampling.

We performed tree transpiration observations in a forest with pedestrian trampling. The focus of this study is to examine whether tree transpiration reduction caused by pedestrian trampling is observed or not. If observed, we also examine when that reduction occurs. Sheriff and Nambiar (1995) and Gomez et al. (2002) performed tree water potential measurements and reported that soil compaction causes more severe tree water stress during a small-precipitation period when atmospheric evaporation demand exceeds precipitation. (However, none of these studies showed tree transpiration data and the soil compactions were not caused by pedestrian trampling.) This implies that soil compaction intensified tree transpiration reduction during a small-precipitation period. However, soil compaction may cause tree transpiration reductions outside (before and after) a small-precipitation period (i.e., atmospheric evaporation demand does not exceed precipitation). Soil compaction causes changes in soil physical properties such as hydraulic conductivity and therefore changes soil water movement (Wood et al., 1989; Kramer and Boyer, 1995; Kozlowski, 1999). This suggests that soil compaction may intensify soil water deficit outside a small-precipitation period. Thus, this study also focuses on whether transpiration reduction occurs during or outside a small-precipitation period.

2. Materials and methods

2.1. The site

The site was located in the Kasuya Research Forest of Kyushu University, in Kyushu Island, south-western Japan (33°38′N, 130 °31′E, elevation 50 m). The soil at the site was brought from outside of the site in late 1960s. Seedlings of *Lithocarpus edulis* were planted in 1977. During the period between 1977 and 1998, no management was undertaken at this site and very few people entered it (Nagasawa, personal communication). In 1998, when researchers began observations at the site, it was covered with a *L. edulis* plantation forest.

In 1998, canopy height of the forest was approximately 9 m. Surface soil was layered (Imura et al., 2000); the first layer, consisted of humus, ranged between 0 and 25 cm depth; the second layer, consisted of clay (Gleyic dystric cambisols), ranged between 25 and 80 cm depth; the soil layer located >80 cm depth consisted of hard bedrock (Paleogene sedimentary rock). Most tree roots were distributed between 0 and 20 cm depth according to an examination by Hosokawa et al. (2001) performed in 1998. 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, according to an examination by Imura et al. (2000) performed in 1998. The annual mean temperature is about 16 °C and annual total precipitation is about 1800 mm at this site (Hirose et al., 2005). A more complete description of the site is available in Imura et al. (2000), Sato et al. (2003, 2004) and Hirose et al. (2005).

In 1998, researchers began hydrological, ecophysiological and meteorological observations in this forest; carrying out throughfall, tree sap flow and atmospheric condition observations (Sato et al., 2003, 2004; Hirose et al., 2005). It was because of these observations that the forest soil periodically experienced pedestrian trampling.

In 2003, we prepared two plots in the forest, i.e., a trampled and a control plot. The trampled plot was set in the area with frequent pedestrian trampling. The trampled plot had equally experienced pedestrian trampling, because throughfall measurements had been performed all over this plot. Total number of persons who entered onto the plot was about 20 per week. The control plot was set adjacent to the trampled plot but excluding the area with frequent pedestrian trampling. Few people had entered the control plot, though the plot was not fenced. Both plots were 12 m × 8 m in area. The trampled and control plots contained 27 and 36 trees, respectively, with the diameter at breast height (DBH) ≥ 5 cm.

2.2. Measurements

Prior to tree transpiration measurements, we performed soil hardness measurements on June 26, 2003 to obtain evidence of soil compaction in the trampled plot. Soil hardness was measured by Yamanaka System Hardness Sensors (Fujiwara Scientific Company, Japan). Though these sensors are commonly used in Japan, they are not available in other countries. These sensors insert a cone into the soil and measure soil hardness from the depth of the cone entered to the soil. The mechanisms of these sensors are the same as those of the push-cone hardness sensors supplied by Daiki Rika Kogyo, Japan (http://www.daiki.co.jp/PDF/5553.PDF). We selected nine trees randomly from each plot and performed soil hardness measurements at five points 60 cm away from each selected tree in a northern direction. Thus, soil hardness measurements were performed at 45 points for each plot.

Tree transpiration was monitored by sap flow measurements on three trees for each of the trampled and control plots. The measurements were performed between September 6 and December 1 2003; because during this period an autumnal small-precipitation period occurs in this region (National Astronomical Observatory, 2001) and because one of our focuses was on whether transpiration reduction of the trampled plot relative to the control plot was observed during or outside a small-precipitation period. The diameter of breast height (DBH) of the sample trees ranged between 13.6 and 15.3 cm.

Sap flow measurements were performed based on the heat-pulse method (Closs, 1958; Marshall, 1958; Swanson, 1994). Instrumentation for the heat-pulse method consisted of a set of three sensors (HP-3, Hayasi Denko Co., Japan) containing a heater probe and two thermistor probes (diameter: 2.0 mm; length: 60 mm). The three sensors were installed at 120 cm height 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, US).

We simultaneously performed meteorological and soil water condition measurements for data that would be used to interpret the tree transpiration data. Precipitation was measured using a tipping bucket gauge situated in an open space adjacent to the forest. Solar radiation was measured using a pyranometer (MS-42, Eko, Japan) situated in an open space adjacent to the forest. Above-canopy air temperature and relative humidity were measured using a thermistor (VHE, Vaisala, Finland) positioned 14 m from the ground surface. Soil water conditions were assessed by soil matric potential and soil water content. Soil matric potential of at 10, 20 and 50 cm depths was measured at one point for each plot using tensiometers (DIK-3021, Daiki Rika Kogyo, Japan). Soil water content at 15, 25 and 45 cm depths was measured at one point for each plot using a capacitance probe (EasyAG, Sentek, Australia). These meteorological and soil water condition measurements were performed at 10 min intervals and data were recorded with a solid-state memory module (CR10X, Campbell Scientific, US).

2.3. Methods of analysis

We first compared soil hardness between trampled and control plots. Differences in soil hardness between plots were examined using Welch's test with the significance level set at $p = 0.01$.

We then compared daily heat-pulse-velocities (HPVs) between trampled and control plots. Differences in HPVs between plots were examined using Welch's test with the significance level set at $p = 0.05$. Here, we focused on whether significant differences in HPVs between plots were observed during or outside a small-precipitation period when tree transpiration was greatly limited by soil water deficit. Periods with transpiration limits were identified comparing observed HPVs with HPVs calculated by a model assuming no severe soil water limits. This model is based on the simplified Penman-Monteith equation that assumes complete coupling of canopy surface air with ambient air (Granier et al., 1996; Komatsu et al., 2006a). The simplified Penman-Monteith equation formulates transpiration from a canopy as

$$E = G_c \frac{D}{p_a}, \tag{1}$$

where E is the canopy transpiration rate, G_c the canopy conductance, D the vapor pressure deficit (VPD) and p_a is the atmospheric pressure. When expressing G_c as functions of D and air temperature T, the equation is rewritten as

$$E = G_{cmax} f_1(D) f_2(T) \frac{D}{p_a}, \tag{2}$$

where G_{cmax} is the maximum canopy conductance, $f_1(D)$ and $f_2(T)$ are functions expressing responses of G_c to D and T, respectively. When assuming a linear relationship between the HPV and E (Kominami and Suzuki, 1993; Hogg and Hurdle, 1997; Komatsu et al., 2006b), the HPV is written as

$$\text{HPV} = a f_1(D) f_2(T) D, \tag{3}$$

where a is a constant. Note that G_{cmax} and p_a are included in a. This model was used at a daily time step in this study.

Examining relationships between D and HPV and between T and HPV when soil matric potential at 10 cm depth was ≥ -50 kPa, we determined function types of $f_1(D)$ and $f_2(T)$, respectively. We then determined the parameters included in $f_1(D)$ and $f_2(T)$ to minimize RMSE of HPV estimates during periods with soil matric potential at 10 cm depth ≥ -50 kPa. A more detailed description of the determining function types and parameters is available in Komatsu et al. (2006b). Note that the model did not consider the effect of solar radiation on G_c, which contrasts to Komatsu's (2004) and Komatsu et al.'s (2006b) modeling. We found no systematic differences in the relationship between VPD and the daily HPV according to solar radiation classes, indicating that considering the effect of solar radiation on G_c is unnecessary in daily time-step calculations. This agrees with the fact that the effect of solar radiation on G_c is only significant in the early morning and late afternoon when transpiration rates are usually low (Komatsu et al., 2006b).

Lastly, we examined soil matric potential in trampled and control plots. Our focus here was on whether soil matric potential data explained differences in HPVs between trampled and control plots. We also tried to interpret temporal change in soil matric potential based on soil water storage and hydraulic conductivity. We calculated soil water storage assuming soil water content data at 15, 25 and 45 cm depth represented soil water content in soil layers between 10 and 20 cm, between 20 and 35 cm, and between 35 and 55 cm, respectively: $S = 100\theta_{15} + 150\theta_{25} + 200\theta_{45}$, where S (mm) is soil water storage between 10 and 55 cm and θ_{15}, θ_{25} and θ_{45} ($m^3\ m^{-3}$) are soil water content at 15, 25 and 45 cm depth, respectively. Hydraulic conductivity was calculated using an open software, RETC ver.6 (US Salinity Laboratory, US). Users of this software are required to input soil water content and soil matric potential data and select retention-curve and hydraulic conductivity models. As input, we used soil water content at 15 and 25 cm depth and soil matric potential at 10 and 20 cm depth observed during periods when all of these components were available. We selected the van Genuchten's retension-curve model and the Mualem's hydraulic conductivity model. We confirmed that our conclusions were not altered when using alternative models such as the Brooks and Corey's retension-curve model and Burdine's hydraulic conductivity model.

3. Results

The average (±S.D.) soil hardness, as measured using the Yamanaka System Hardness Sensors, was 15.8 (±3.6) mm ($n = 45$) for the trampled plot and 7.0 (±2.9) mm ($n = 45$) for the control plot. These values correspond to 328.0 and 77.0 kPa, respectively. Thus, the soil in the trampled plot was harder than that of the control ($p < 0.01$).

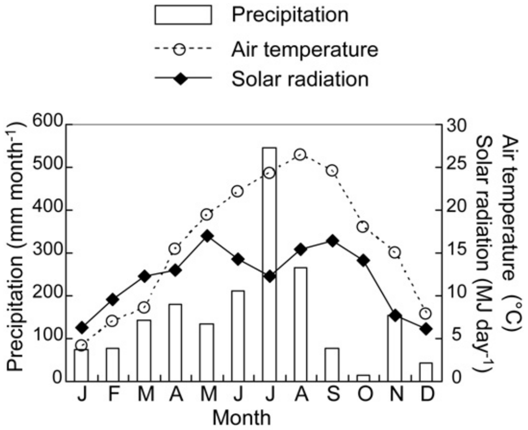

Fig. 1. Precipitation, air temperature and solar radiation of the site observed in 2003.

Fig. 1 shows the seasonal trends of precipitation, air temperature and solar radiation in 2003. Precipitation in September and October was smaller than other months in the growing season. Fig. 2 shows meteorological conditions and daily HPVs at the trampled and control plots. HPVs were normalized by the value on September 6 and then averaged for the sample trees in each plot ($n = 3$). Normalized HPVs showed similar temporal change patterns for both plots (Fig. 2b). However, we observed significant differences in normalized HPVs between each plot after November 5. Fig. 2 b also shows HPV calculated by the model developed from data when soil matric potential at 10 cm depth was ≥ -50 kPa. Model function types were determined as $f_1(D) = 1 - bD$ and $f_2(T) = (T + c)/(30 + c)$, where b and c are parameters. $f_1(D)$ and $f_2(T)$ are normalized at $D = 0.0$ (kPa) and $T = 30$ (°C), respectively, i.e., $f_1(1.0) = 1.0$ and $f_2(30) = 1.0$. Model parameters were determined as $a = 1.5$, $b = 0.41$ and $c = 20$. Before September 30, observed HPVs showed nearly the same value as calculated HPVs in both plots, indicating that the soil water deficit did not greatly limit transpiration in the plots. During the period, between September 30 and November 5, observed HPVs were lower than calculated HPVs in both plots, indicating that the soil water deficit due to small amounts of precipitation in this period (Fig. 2a) limited transpiration in the plots. (Note: During this period, 92% and 86% data showed significant differences between observed and calculated HPVs for trampled and control plots, respectively, according to t-test with the significance level set at $p = 0.05$.) After November 5, observed HPVs showed approximately the same values as calculated HPVs in both plots, indicating that transpiration had recovered due to precipitation at the beginning of November (Fig. 2a). The normalized HPV of the trampled plot was significantly lower than that of the

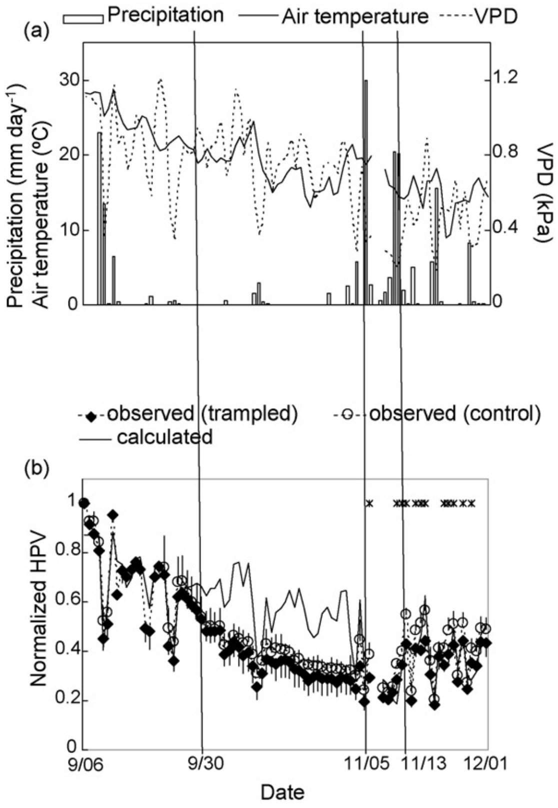

Fig. 2. Meteorological conditions and daily heat-pulse velocities (HPVs) at the trampled and control plots. (a) Precipitation, air temperature and vapor pressure deficit (VPD); (b) observed HPVs for each plot and calculated HPV. Air temperature, HPV and VPD data are missing for November 7 and 8. HPV values were normalized by the value on September 6 and averaged for sample trees at each plot ($n = 3$). Vertical bars indicate standard deviation of normalized HPVs. An asterisk indicates significant difference ($p < 0.05$) in the normalized HPV between trampled and control plots. Vertical dotted lines through (a) and (b) are drawn for readers' convenience. These lines enable to see correspondence between each figure.

control ($p < 0.05$; Fig. 2b). Thus, recovery of transpiration in the trampled plot was not as complete as that in the control. The lower HPV in the trampled plot could not be explained by the difference in tree density between plots, because tree density was smaller in the trampled plot and therefore water competition between trees would be less severe in the trampled plot. Note that such HPV differences were not observed after precipitation on early September due to missing HPV data from the control plot.

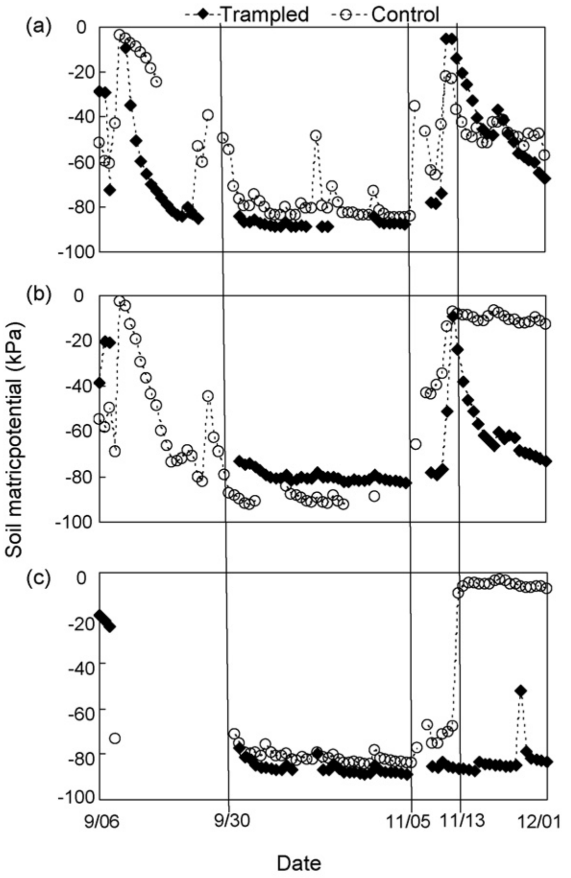

Fig. 3. Soil matric potential for trampled and control plots at (a) 10, (b) 20 and (c) 50 cm. Vertical lines are drawn for readers' convenience. These lines enable to see correspondence between each figure.

The above explanation for the temporal change pattern in normalized HPVs is supported by soil matric potential data. Fig. 3 shows the temporal change in soil matric potential for each plot. Before September 30, matric potential at 10 cm depth was relatively high in both plots. While we could not confirm that matric potential at 20 and 50 cm depth was relatively high before September 30 due to missing data, few tree roots were distributed at ≥ 20 cm depth (Hosokawa et al., 2001), suggesting that soil water at ≥ 20 cm depth did not greatly affect temporal change patterns in the HPVs noted above. During the period between September 30 and November 5, soil matric potential was lower than that in the period before September 30 at both plots. After November 5, soil matric potential was generally higher than that during the period between September 30 and November 5 in both plots. However, we observed differences in the temporal patterns of soil matric potential between plots after November 5. The decreases in soil matric potential at 10 and 20 cm after November 5 were more rapid for the trampled plot than for the control (Fig. 3 a and b), resulting in lower soil matric potential at 10 cm depth in late November and at 20 cm depth throughout the period between November 5 and December 1 for the trampled plot. We observed

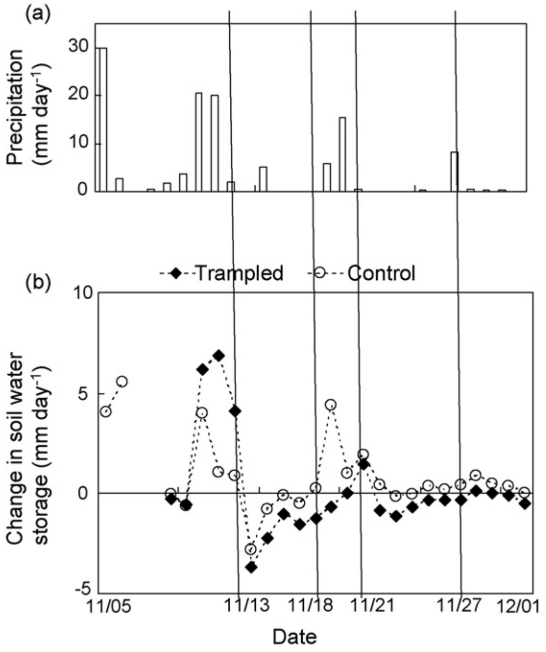

Fig. 4. (a) Precipitation and (b) change in soil water storage between 10 and 55 cm depth in the period between November 5 and December 1. Data were missing between November 5 and 8 for the trampled plot and on November 7 and 8 for the control plot. Vertical lines are drawn for readers' convenience. These lines enable to see correspondence between each figure.

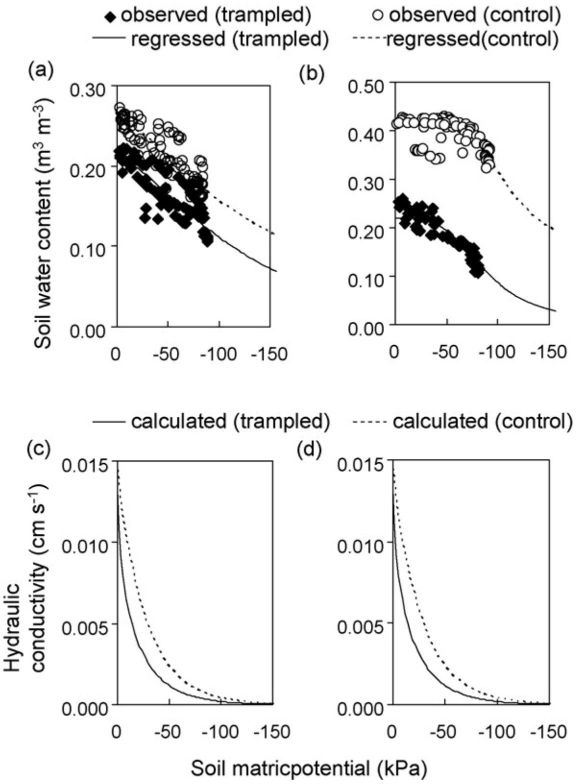

Fig. 5. Relationships (a) between soil matric potential at 10 cm depth and soil water content at 15 cm depth and (b) between soil matric potential at 20 cm depth and soil water content at 25 cm depth. Regression lines in (a) and (b) were determined by RETC. Relationships (c) between soil matric potential at 10 cm depth and hydraulic conductivity calculated from the regression line in (a) using RETC and (d) between soil matric potential at 20 cm depth and hydraulic conductivity calculated from the regression line in (b) using RETC.

nearly no recovery in the soil matric potential at 50 cm for the trampled plot after November 5, in contrast to the case for the control plot (Fig. 3c).

Fig. 4 a and b shows precipitation and changes in soil water storage between 10 and 55 cm for each plot after November 5. The change was positive for both plots on November 11–13 and 21, since relatively heavy precipitations (ca. 20 mm day^{-1}) occurred on November 11, 12 and 20. However, the change was negative or nearly zero for the trampled plot during November 14–November 20 and November 22–December 1. This contrasts to the case for the control plot; though the change in the control plot was negative or nearly zero during November 14–17, the change was positive or nearly zero during November 18–December 1. Thus, soil water storage in the trampled plot was charged only after heavy rainfall (e.g., November 11, 12 and 20), while soil water storage in the control plot was charged after relatively light rainfall (e.g., November 19 and 27) as well as heavy rainfall. This is a plausible explanation for the difference in soil matric potential after November 5 between trampled and control plots (Fig. 3). We observed more rapid decreases in 10 and 20 cm matric potential after November 13 for the trampled plot (Fig. 3 a and b), which would have been caused by the smaller water charge amount compared to water uptake by tree transpiration at the plot. We observed nearly no recovery of the 50 cm matric potential at the trampled plot after November 13 (Fig. 3c), implying that the water infiltration front did not reach that depth because of the smaller water charge amount, and possibly because of lower hydraulic conductivity in the trampled plot.

The above explanation for the difference in soil matric potential between each plot is supported by hydraulic conductivity values calculated from soil water content and matric potential data. Fig. 5 a and b shows relationships between soil water content at 15 cm depth and soil matric potential at 10 cm and between soil water content at 25 cm depth and soil matric potential at 20 cm, respectively. Fig. 5 c and d shows the relationships between soil matric potential and hydraulic conductivity calculated from the relationships in

Fig. 5 a and b, respectively. Hydraulic conductivity values for the trampled plot were smaller than those for the control plots. This result agrees with results from earlier studies: many of which have reported that soil compaction reduces hydraulic conductivity values and therefore infiltration rates (Wood et al., 1989; Kramer and Boyer, 1995; Kozlowski, 1999).

4. Discussion and conclusions

This paper reported the reduction of tree transpiration in a forest with pedestrian trampling. Tree transpiration in the trampled plot was reduced compared to that in the control plot after precipitation with a small-precipitation period preceding this. However, no difference was observed between plots in the small-precipitation period itself; during which tree transpiration was limited in both plots.

Tree transpiration reduction in a forest with pedestrian trampling can be expected from earlier studies that reported tree growth reduction in forests with pedestrian trampling. However, we believe this is the first report of tree transpiration reduction in a forest with pedestrian trampling. The results here should contribute to a more solid and process-based understanding of forest water cycle changes with pedestrian trampling. Further, this study has implications for hydrological, ecophysiological and meteorological observations as it indicates the possibility that these observations can alter the forest water cycle because these observations are usually accompanied with pedestrian trampling from those making the observations. We recommend interpreting hydrological, ecophysiological and meteorological observation data considering this possibility.

We should note the fact that tree transpiration reduction was significant after precipitation with a small-precipitation period. Sheriff and Nambiar (1995) and Gomez et al. (2002) reported that soil compaction intensified tree water stress during a small-precipitation period (Fig. 2 of Sheriff and Nambiar and Fig. 1 of Gomez et al.), implying that soil compaction intensified tree transpiration reduction during a small-precipitation period. Thus, this study suggested another aspect of tree transpiration reduction caused by soil compaction.

It should also be noted that the results of this study are preliminary ones. The main weaknesses of this study are as follows: (1) it was based on short-term data and the reproducibility of the phenomena reported in this study was not confirmed. Thus, we need to perform long-term measurements to confirm the reproducibility. (2) It did not include data of surface runoff. This study suggested that differences in soil matric potential between plots were caused by differences in hydraulic conductivity between plots, which implies differences in surface runoff between plots. Including surface runoff measurements would strengthen the validity of our suggestion. (3) It was based on sap flow measurements of only three trees per plot. Though the mean HPV value of the trampled plot was slightly lower than that of the control plot during the small-precipitation period, we did not observe significant differences in HPV between plots in this period (Fig. 2b). Increasing sample size might result in significant differences in HPV between plots in this period as well as after this period. (4) It measured soil water content and matric potential at one point for each plot. Further measurements are required to confirm whether our results hold after considering spatial heterogeneity of soil water conditions. (5) It evaluated the effect of pedestrian trampling using two adjacent plots. Actually, factors other than soil hardness were different between plots, implying the possibility that those factors might also affect the differences in HPV between plots observed in this study. This uncertainty would be avoided by setting up another plot in the forest that had not experienced pedestrian trampling, and then conducting continuous observations there before and after soil compaction by pedestrian trampling.

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