Application of seasonal variations of deuterium excess to the estimation of water sources of trees in humid areas like Japan

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Abstract:

Although the depths of water uptake by plants can be estimated by comparing oxygen 18 or deuterium in stem water with that of possible water sources in semi-arid regions, it is difficult to apply this technique to investigations of water use in relatively humid areas because the vertical profile of the isotopic ratio in soil water in such areas is more complicated than that in arid and semi-arid regions. However, the d-excess (deuterium excess) of rainfall in Japan shows clear seasonal variations. Therefore, we attempted to utilize seasonal variations of d-excess to estimate water sources of 20-year-old Japanese cypress (Chamaecyparis obtusa) and Japanese cedar (Cryptomeria japonica). Source water could be distinguished based on differences in their seasonal pattern of d-excess. The seasonal variations of d-excess in the stem water of both species were similar to those of shallow soil water (<1.0 m), but different from those of other water sources, indicating that the main water source was shallow soil water.

KEYWORDS deuterium excess; deuterium; oxygen 18; stem water; plant water uptake

INTRODUCTION

Stable water isotope analyses of source water (e.g. rain, soil water and groundwater) and plant tissue water have provided new insights into the patterns of plant water use. Such studies are based on the fact that fractionation of isotopic forms of hydrogen or oxygen does not occur when roots take up water in the soil (Dawson and Ehleringer, 1991; White, 1988). These studies have primarily been conducted in the field of ecology since the 1990s (e.g. Dawson and Ehleringer, 1998). Dawson and Ehleringer (1991) found that mature streamside trees growing in or directly next to perennial streams used little or none of the surface stream water. Thorburn and Ehleringer (1995) measured stable isotope ratios in root water and assessed the water uptake patterns and root functions. This technique has also shown that water sources for plant uptake change seasonally in Utah (Donovan and Ehleringer, 1994; Ehleringer et al., 1991); Texas (Schwinning, 2008), Western Australia (Dawson and Pate, 1996; Zencich et al., 2002) and Yakutsk (Sugimoto et al., 2002). Additionally, this technique has revealed competition for water and partitioning (Flanagan et al., 1992; Jackson et al., 1995; Kojima et al., 2003; Midwood et al., 1998; Ohte et al., 2003), as well as the removal of water via hydraulic lifting by plants (Dawson, 1993). The majority of these studies have been conducted in arid and semi-arid environments because the vertical distributions of isotope values of soil water in such regions are usually simple and consistent due to the strong evaporation effect at the surface layer (e.g. Barns and Allison, 1988). Thus, this technique provides a substantial benefit to investigators in terms of cost when compared to actual root surveys.

In contrast, it is generally difficult to apply this technique to investigations of the water sources of plants in humid areas such as Japan because isotopic values of soil water change greatly in the surface following each rainfall event, ultimately converging at a constant value with increasing depth (Hsieh et al., 1998), although Yamanaka et al. (2006) revealed water source separation between pines (Pinus densiflora) and oaks (Quercus myrsinaefolia) in Japan. Conversely, there is remarkable variation in deuterium excess (d-excess) in precipitation in Japan, with low values in summer and high values in winter (Kondoh and Shimada, 1997; Waseda and Nakai, 1983). Indeed, deuterium excess produces a more robust signal than oxygen 18 or deuterium in Japan, Korea and eastern China (Yoshimura and Ichiyanagi, 2009), and has often been applied to estimate the mean residence time of stream water (Asano et al., 2002; Kabeya et al., 2007, 2011; Kawaraya et al., 2000).

In this study, we investigated the seasonal variation of d-excess in stem water and possible water sources, and attempted to use these signals to estimate plant water sources. The objective of this study was to verify whether seasonal variations of d-excess in stem water and possible source waters can be used to estimate the depth of water uptake by plants. We selected Japanese cypress (Chamaecyparis obtusa) and Japanese cedar (Cryptomeria japonica) because they account for 25% and 44% of the species planted in artificial forests in Japan, which comprise 40% of the total forest area in the country. These trees were also selected because their root distribution and water absorption have already been investigated in detail by Karizumi (1957, 1976, and 1985).

MATERIALS AND METHODS

This study was conducted within the 0.88 ha Hitachi Ohta Experimental Watershed located on the east side of the main island of Japan at a latitude of 36°34’N and a
was later increased. Based from 25 July 2006 and the number of trees sampled approximately 40 mm and the bark was removed. The stem naturally, after which they were cut to a length of approximately 500 mm were collected for analysis. Prior to analysis, the frozen twigs were defrosted with Parafilm to prevent evaporation. The twig samples were subsequently stored in a freezer in the laboratory until sparsely tested with the vacuum distillation method (Ehleringer et al., 2000; Iizuka et al., 2004; Sugimoto et al., 2002; Yamanaka and Shimada, 1997). However, we used the squeezing method because a sufficient amount of water for analysis was easily obtained from softwood using this method, and invalid values of deuterium in stem water extracted by the vacuum distillation method have occasionally been reported (Sugimoto et al., 2002; Iizuka et al., 2004).

Throughfall was collected using a funnel with a diameter of 210 mm and then stored in a 10-L Poly bottle at the site as shown in Figure 1. Silicon oil was added to the bottle to prevent evaporation from the water surface. Throughfall was collected approximately every two weeks and stored in glass vials. Soil water was collected approximately every two weeks with suction lysimeters at the site as shown in Figure 1. During this period, we were always able to collect soil water; thus, the collected water would be the same as that taken up by trees if the source water is soil water. Samples were collected from depths of 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0 m. Soil depth was measured at the point at which the suction lysimeters were constructed and found to be 2.01 m. Additionally, a penetration test was conducted at throughout the basin with the same geographical features and geology within the Hitachi Ohta Experimental Watershed and an average soil depth were 1.61 m ± 0.90 m (Tsuboyama, 2006). Each suction lysimeter consisted of a porous cup 17 mm in diameter, a glass collection bottle and a connecting tube 2 mm in diameter. A suction force of approximately 80 kPa was established in the bottle and tube. Base flow was collected as groundwater samples at the outlet of the catchment approximately every two weeks (Sklash, 1990).

Oxygen and deuterium stable isotopes were analyzed by mass spectrometry (Finnigan MAT 252). Oxygen samples were prepared using the CO$_2$-H$_2$O equilibration method and deuterium samples were prepared using the H$_2$-H$_2$O equilibration method with a Pt catalyst (Ohba and Hirabayashi, 1996). The Pt catalyst used here was a 1–2 mm diameter spherule containing 1-wt% Pt black. The isotopic concentration was expressed as parts per mil (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW), according to the following equation:

\[
\delta = \left( \frac{R_{\text{sample}}}{R_{\text{V-SMOW}}} - 1 \right) \times 1000 \text{‰},
\]

where \( \delta \) is the sample $^{18}O$ or $D$ concentration in ‰ and \( R \) is the ratio of $^{18}O$ or $D$/$H$. The accuracy of $\delta$D was generally ±1.0‰, while that of $\delta$18O was ±0.2‰. The $d$-excess was calculated from $\delta$D and $\delta$18O using the following expression:

\[
d = \delta D - 8\delta^{18}O.
\]

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Figure 1 Map of the Hitachi Ohta Experimental Watershed showing the sampling sites for throughfall, soil water, and stream water during base flow and for twigs.
RESULTS AND DISCUSSION

The δD and δ18O of stem water, throughfall, soil water and groundwater observed in 2006 and 2007 are shown in Figure S1. The δD and δ18O in the throughfall differed greatly among rainfall events. The isotopic ratios in the stem water of *Ch. obtusa* and *C. japonica* were similar at almost all times, and their changes were small. The isotopic ratios of soil water samples collected from the surface to 0.4 m also differed among rainfall events. The isotopic ratios of soil water samples collected from 0.4 to 1.0 m tended to vary seasonally and were higher from April to July and lower from August to November. This is probably because rainfall with a lower isotope ratio than soil water was added to the system by rainfall during the rainy season (from May to July) and by typhoons from July to October, while the isotopic ratio became higher as a result of evapotranspiration during other periods. The isotopic ratios of soil water samples collected at depths of more than 1.5 m (deep soil water) and groundwater did not change significantly in response to rainfall. The δD and δ18O of possible source waters could not be distinguished from each other, especially from December to July.

The seasonal variations of d-excess in throughfall, stem water, soil water and groundwater are shown in Figure 2. In throughfall, the seasonal variations were large, ranging from 4‰ to 29‰. The d-excess in shallow soil water showed clear seasonal variations and ranged from 8‰ to 19‰. Conversely, the amplitude of seasonal variation of d-excess in deep soil water was small and the phase shifted from those of shallow soil water (surface to 1.0 m) and stem water. The seasonal variation of d-excess in groundwater was smaller than that of deep soil water, which showed almost no seasonal variation. Thus, we were able to distinguish the pattern of seasonal variations in possible water sources between throughfall, shallow soil water, deep soil water and groundwater. The correlation of the d-excess of stem water and that of possible source waters was measured and the correction coefficients are shown in Table SI. The stem water was strongly correlated with soil water from 0.2 to 1.0 m in both *Ch. obtusa* and *C. japonica*. Thus, the main water source of *Ch. obtusa* and *C. japonica* was assumed to be shallow soil water. However, this result was not consistent with the results shown in Figure S1 (g) and (h) if the main water source was always shallow soil water. The seasonal variation of δD and δ18O in stem water of *Ch. obtusa* and *C. japonica* was small, and tended to be even smaller than the average from August to November, suggesting that the isotopic ratio of stem water was affected by the lighter isotopic ratio of shallow soil water. Moreover, the amount of soil water collected from the surface to 0.6 m was small in August and November of 2007, suggesting that the soil water content was small. Thus, the amount of water absorbed from deep soil may have become large.

Karizumi (1976) investigated the root biomass and its distribution in the ground around several trees including *Ch. obtusa* and *C. japonica* and demonstrated a relationship between the basal area at the breast height of the tree and the maximum depth of the root. The basal area at the breast height of the trees investigated in this study was around 150 cm² for both *Ch. obtusa* and *C. japonica*. According to this relationship, the maximum depth of the roots was

![Figure 2](image-url)
approximately 1.1 m and 1.3 m for *Ch. obtusa* and *C. japonica*, respectively. Karizumi (1957, 1976) reported that most of the fine roots of *Ch. obtusa* and *C. japonica* were distributed from the ground surface to 0.3 m underground. Karizumi (1985) estimated the annual amounts of water absorption from fine roots at each soil depth and found that the fine roots of 20 to 30-year-old *Ch. obtusa* and *C. japonica* obtained more than 80% and 70% of their moisture from up to 0.3 m underground, and almost 100% up to 0.9 m. Thus, the roots of *Ch. obtusa* and *C. japonica* absorbed water most actively from 0 to 0.3 m, and the depth of water uptake was estimated to be up to 1.2 m by excavation investigations. Estimations based on comparisons of d-excess values in stem water to those in possible water sources revealed that *Ch. obtusa* and *C. japonica* absorbed shallow soil water to a depth of 1.5 m, which was consistent with the excavation results.

Thus, most fine roots of *Ch. obtusa* and *C. japonica* are distributed from the surface to 0.3 m, and the main water source for both is shallow soil water. Although, they absorb water from the entire area in which their fine roots are distributed, they absorb relatively more deep soil water than shallow soil water if the amount of shallow soil water is small.

**CONCLUSIONS**

It is generally difficult to estimate the depth of plant water uptake by simply comparing the δD and δ18O values of stem water to those of possible water sources in humid areas because the vertical profile of δD and δ18O of soil water is much more complex in such areas than in arid and semi-arid regions. In this study, we showed that the d-excess calculated from δD and δ18O in stem water and possible source waters showed clear seasonal variation in Japan. We also demonstrated that the combination of the δD and δ18O values in stem water and possible source waters and this seasonal variation of d-excess could provide beneficial information regarding the depth of plant water uptake. This method is likely applicable to other areas in which seasonal trends of d-excess are found as well. However, this method requires observation of δD and δ18O for more than one year. On the other hand, the actual root survey requires also large effort and is destructive. Thus, this method may be useful for investigation of the patterns of plant water use and water separation among plants.

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**SUPPLEMENTS**

Supplement 1: This includes Figure S1 and Table S1.

Figure S1. Vertical profile of δD (filled circles) and δ18O (open circles) for throughfall, stem water from *Chamaecyparis obtusa* and *Chriptomeria japonica* (mean ±SE), soil water, and groundwater collected in 2007. n is the sample size. The numbers of samples differ by day because water could not always be extracted from all of the branches. The date indicates the day of twig collection. Throughfall and soil water were stored in the bottle for approximately two weeks prior to the collection date.

Table S1. Correlation coefficients between the d-excess of stem water and throughfall, soil water, and ground water.

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