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Trees growing through impervious surfaces use shallower water sources: A stable isotope study

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Trees growing through impervious surfaces use shallower water sources: A stable isotope study

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ABSTRACT

Impervious surfaces account for a large proportion of urban land surface. However, little is known about tree water use in impervious surfaces. Here, we compared the water sources of trees growing through impervious and pervious surfaces using oxygen and hydrogen isotopic compositions from stem water and other potential water sources before and during the wet season. The proportion of topsoil water in the water source, calculated using a simple linear mixing model, showed that trees growing through impervious surfaces took up more water from shallow layers than control trees before the wet season. An IsoSource model applied in the wet season confirmed that trees growing through impervious surfaces took most of their water from depths of around 20 cm, while control trees took the greatest portion of their water from a depth of 70 and 100 cm. These findings could improve urban hydrological cycle models and suggest that urban trees growing through impervious surfaces might be more vulnerable to drought.

Keywords: impervious surface, stable isotope, IsoSource, tree water sources, ecohydrology

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TABLE OF CONTENTS

LIST OF FIGURES

1. Introduction

Trees growing through impervious surfaces play important roles in urban hydrology by increasing ground permeability to water and reducing runoff [*Sanders*, 1986]. Trees may mitigate the impacts of impervious surfaces, which block water exchange between soil and environmental components above the surface [*Arnold and Gibbons*, 1996] and soil beneath the surface [*Lerner*, 2002]. However, it is unclear what water sources are used for trees grown in impervious surfaces, which form a key hydrological component, transpiration.

Rooting depths affect soil moisture distribution [*Canadell et al.*, 1996], soil water pool, runoff, drainage [*Kleidon and Heimann*, 1998], groundwater table depth [*Leung et al.*, 2011], and soil organic carbon stocks [*Bae and Ryu*, 2015]. Despite its importance, few studies have investigated the root depth of urban trees growing through impervious surfaces. *Nicoll and Armstrong* [1998] and *Reichwein* [2003] analyzed root development under impervious surfaces. After removing the surface material, they found that roots had developed in a sideward-dominant manner. *Morgenroth* [2011] showed that seedlings growing on unpaved plots grew deeper roots than seedlings growing in plots covered with either impervious or pervious materials.

Seasonal changes in tree water sources are useful for understanding the role of plants in the hydrological cycle [*Zencich et al.*, 2002]. In monsoon regions, which experience a highly uneven distribution of annual rainfall, the seasonal distribution of water sources for plants is important for understanding the hydrological cycle and water management. Most studies considered water source distribution among seasons under natural conditions [*Dawson and Pate*, 1996], but little is known of the relationship between plants and water sources under impervious surfaces, which have distinct environments due to their lack of rainfall permeation.

Hydrogen and oxygen isotopes have been used to estimate the depths of plant water sources [*Brooks et al.*, 2010]. This approach provides information on active rooting depth [*Dawson and Ehleringer*, 1991], which helps to elucidate changes of actual hydrological flows more effectively than directly investigating rooting distribution. Moreover, the isotopic approach is non-destructive and does not damage the urban infrastructure.

In this study, we estimated the depths of water sources for trees growing at sites paved with impervious surfaces (impervious sites: IPS) and at sites covered by grass and soils (pervious sites: PS) both before and during the wet season, using stable isotopes.. First, we analyzed isotopic compositions of hydrological components of study sites before and during the wet season. Then, we examined effective water source depths for trees growing in PS and IPS by applying mass balance models.

2. Material and Method

2.1 Site Description

This study was conducted at the Seoul National University (SNU) campus (37.4586N, 126.9547W) located in Seoul, Republic of Korea (Fig. 1). The Korean Peninsula experiences four distinct seasons and has a summer monsoon climate. The mean annual temperature and annual precipitation at the study site between 1981 and 2010 were 12.5°C and 1450.5 mm, respectively (Korea Meteorological Administration, www.kma.go.kr), with approximately half of the annual precipitation occurring in July–August. We selected ten *Ginkgo biloba L.* trees, five growing in IPS and five in PS. Trees in IPS were located along roadsides with a 75 cm-radius semicircle tree pit. Trees in PS were located on a mixture cover of bare soil and grass. All trees were transplanted about 40 years ago having diameters at breast height (DBH) in the range of 30 to 40 cm and were located within a 50-m radius. There was no subsoil-pipe installation under IPS and PS which can limit tree root growth [*Jim*, 1998]. The soil texture at both sites was sandy loam.

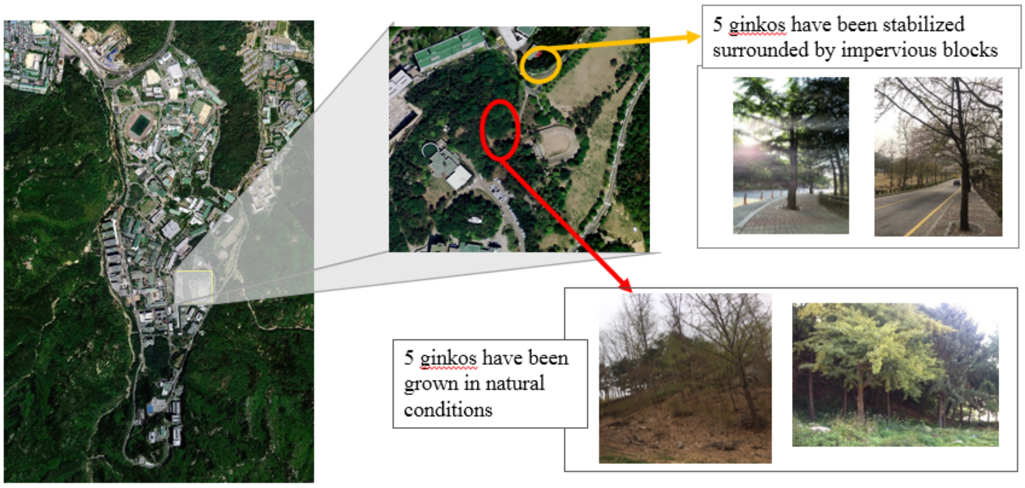

Figure 1 Site location in Seoul Nation University campus

2.2 Sampling and Isotope Analysis

We collected stems on June 9 (before the wet season) and August 2 (during the wet season). We removed three suberized stems (about 0.5 cm diameter) from each tree using 3 m long pruning scissors. Leaves and green stems containing water that might have been isotope-enriched through evapotranspiration were removed [*Dawson and Ehleringer*, 1993]. Once excised, stems were cut into 0.5–1 cm lengths, immediately placed in vials, sealed with Parafilm, and then frozen for storage. Soil samples were collected with a soil auger (auger kit; AMS, USA) from the top soil layers on June 9 and at depths of 0–5, 10–15, 20–25, 40–45, 70–75, and 100–105 cm at each site on August 2 because complicated soil isotopic variation is expected during wet season. We collected rainfall during each of 6 heavy (more than 20 mm) rainfall events that occurred between the two stem sampling dates.

Soil and rain samples were likewise placed in vials, wrapped with Parafilm, and frozen immediately.

For isotope analysis, we extracted stem and soil water using a cryogenic vacuum distillation line following established protocols [*Ehleringer et al.*, 2000; *West et al.*, 2006]. The $^{2}H/^{1}H$ (D/H) and $^{18}O/^{16}O$ ratios of stem water, soil water, and precipitation were measured using an isotope ratio mass spectrometer (Isoprime model, GV Instruments Ltd., UK) at the Korea Basic Science Institute (KBSI). Oxygen and hydrogen isotope data were reported in conventional delta notation relative to Vienna-Standard Mean Ocean Water (V-SMOW) [*Gonfiantini*, 1978].

2.3 Water Sources Estimation

We performed statistical analyses using R version 3.1.3. (R Development Core Team 2015). Two-sided *t*-tests were used to compare stem water isotopic values and water source depth between IPS and PS. Significant differences were reported at $P < 0.05$. To estimate tree water sources, we applied a two-end member mixing model that gives the proportions of each end member in a mixed sample. To use the two-end member mixing model, stem water was considered a mixture of possible water sources. This mixture was assumed to have occurred along a straight line between the most isotopically enriched and most isotopically depleted waters. As deep and top soil water were the end members, water source was expressed as a proportion of deep soil water in the mixture calculated using the equation [*Thorburn et al.*, 1993]:

$$P_t = \frac{\sqrt{(X_s - X_d)^2 + (Y_s - Y_d)^2}}{\sqrt{(X_s - X_t)^2 + (Y_s - Y_t)^2}}$$

where P_t is proportion of top soil water, X is $\delta^{18}O$ value, Y is δD value of the samples, and *s*, *d*, and *t* represent stem water, deep soil water (originally denoted groundwater), and top soil water, respectively.

The two-end member method for estimating water use pattern assumes that trees tap into groundwater. It also assumes that the isotopic composition of soil water is most enriched with heavy isotopes at the top and enrichment gradually decreases with depth [*Dawson et al.*, 2002]. When these assumptions are violated, the model may return confounded results [*Phillips and Gregg*, 2001]. Due to potential confusion from the two-end member method, we used the IsoSource model [*Phillips and Gregg*, 2003] with data from the wet season because complex isotopic variations with depths caused by rainfall events were observed several times [*Liu et al.*, 2011]. The IsoSource model gives all feasible source contributions (that sum to 100%) in small increments (1% in this study) based on linear mixing models for systems whose source contributions cannot be determined because the number of potential sources exceeds the number of isotope groups observed [*Phillips and Gregg*, 2003; *Phillips et al.*, 2005]. Both δD and $\delta^{18}O$ values of soil water sampled at each 7 soil depth were used as endpoints.

3. Results and Discussion

3.1 Isotopic Composition of Rainfall, Stem Water, and Soil Water

Because rainfalls were sampled only during the study period, we used a LMWL (Local Meteoric Water Line) that was established in a previous study ($\delta D = 8.05\ \delta^{18}O + 12.7$ from *Lee and Chung*, 1997) to interpret data collected on June 9. For wet season data, a LMWL was constructed using the data collected in this study ($\delta D = 7.69\ \delta^{18}O + 5.68$). In Fig. 2 and Fig. 3, LMWLs were located to the left (before wet season) and right (during wet season) of the GMWL (Global Meteoric Water Line: $\delta D = 8\ \delta^{18}O + 10$ [*Craig*, 1961]). This is because our data only represented the sampling period while the LMWL from Lee and Chung (1997) was based on annual precipitation data. The isotopic compositions of precipitation in South Korea varied significantly with seasons due to differences in air masses by seasons, with cold and dry continental Siberian air mass in winter and hot and humid maritime Northern Pacific air mass in summer [*Lee and Kim*, 2007]. This resulted in right side-shifted LMWL in the summer compared to annual LMWL, in the same manner as the results.

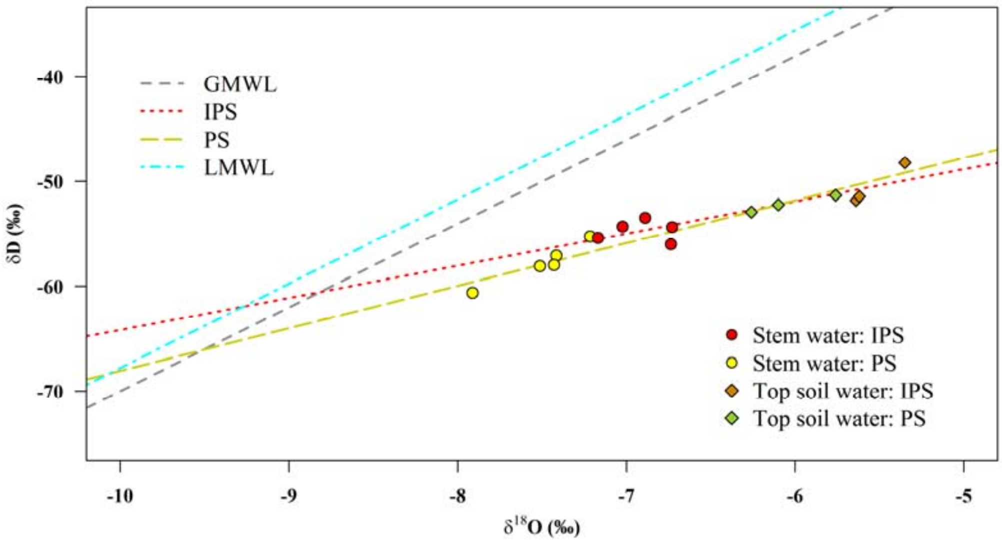

Figure 2. Isotopic (δD and $\delta^{18}O$) composition of stem water and soil water sampled before wet season. Linear regressions of stem water, soil water, and rainfall isotopic composition are shown with GMWL ($\delta D = 8\ \delta^{18}O + 10$).

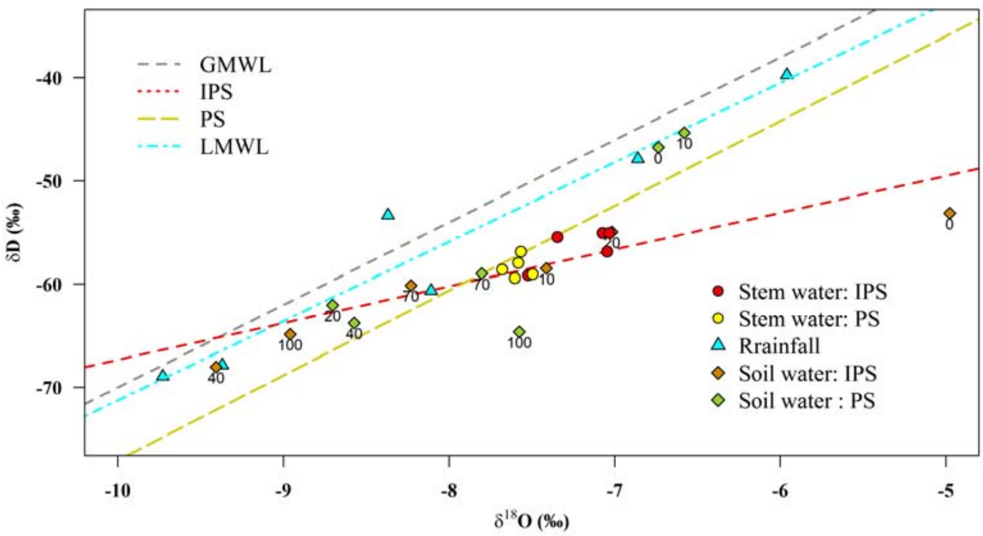

Figure 3. Isotopic (δD and $\delta^{18}O$) composition of stem water, soil water, and rainfall sampled during wet season. Linear regressions of stem water, soil water, and rainfall isotopic composition are shown with GMWL ($\delta D = 8\ \delta^{18}O + 10$). Numbers under points of soil water isotopic composition represent depth of each sample.

Before wet season, the trees in PS had significantly lower $\delta^{18}O$ and δD values in their stem water than the trees in IPS (Fig. 2) (–6.9‰ *vs*. –7.5‰ for $\delta^{18}O$ and –54.7‰ *vs*. –57.8‰ for δD at IPS and PS, respectively; $P < 0.05$). All stem water δ values were further right from the GMWL, showing evaporative enrichment in the water sources of all trees [*Brooks et al.*, 2010]. Top soil water and stem water isotopic compositions at each group showed linear relationships ($\delta D = 3.07\delta^{18}O$ - 33.45 ($r^2 = 0.78$) for IPS and $\delta D = 4.06\delta^{18}O$ - 27.42 ($r^2 = 0.95$) for PS) (Fig. 2). This indicates that trees used a soil water pool whose isotopic composition has evolved through evaporation. These regression lines correspond to local evaporation lines (LEL, [*Gibson et al.*, 1993]) that had smaller slopes than that of the LMWL. The intersects between LELs and LMWL are assumed to represent the initial isotopic composition of soil water that was not affected by evaporative enrichment [*Gat and Matsui*, 1991]. These intersects were used as one of the end members for implementing the two-end member method.

During wet season, the stem water of trees in IPS was more enriched with heavy isotopes than the stem water of trees in PS, just as before the wet season (Fig. 3). The difference in isotopic composition between IPS and PS groups was significant only for oxygen isotopes (–7.2‰ *vs*. –7.6‰ for $\delta^{18}O$ and –56.3‰ *vs*. –58.4‰ for δD at IPS and PS, respectively; $P < 0.05$). Stem water isotopic compositions were located further right from the LMWL, showing evaporative enrichment similar to before the wet season. A regression line for IPS did not change significantly (δD = $3.56\delta^{18}O$ - 31.71) compared to before the wet season (red dashed lines in Fig. 2 and 3). However, a regression line for PS changed significantly ($\delta D = 8.22\delta^{18}O + 5.14$) (yellow dashed lines in Fig. 2 and 3). This implies the divergence of soil water isotopic patterns between groups after heavy rainfall events.

There was a significant difference in topsoil water isotopic compositions between groups during the wet season, giving evidence for a difference in the impact of rainfall (Fig. 3). Rainfall had been blocked by the impervious surface at IPS and the isotopic composition of soil water was not immediately influenced by rainfall. Conversely, topsoil water at PS was directly influenced by rainfall, thereby retaining the isotopic composition of recent rainfall unaffected by evaporation [*Shuster et al.*, 2005]. Higher soil moisture (0~20 cm) at PS during the study period (Fig. 4) was likely to support divergent isotopic compositions of topsoil water between the two groups.

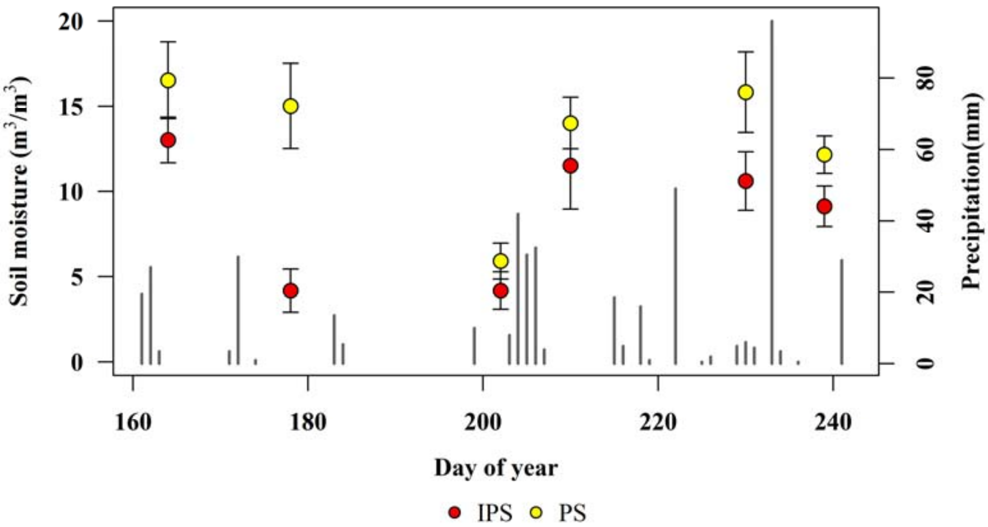

Figure 4. Soil moisture (0 ~20cm) of both groups during study period

Rainfall led to complicated soil water isotopic variation with depth during the wet season (Fig. 3). Fig. 3 shows that the isotopic composition of soil water, except that of topsoil waters at PS, varied along the LELs but did not necessarily follow the expected isotopic enrichment with depth, with the most enriched water at shallower depths and least enriched water at deeper depths. This pattern is clearly shown in Fig. 5. The depth profile of soil water isotopic compositions showed complex variability, contrary to an exponential decrease from top to deep soil observed in arid regions [*Allison and Hughes*, 1983]. This result is consistent with those of a previous study that showed complicated isotopic variability with soil depth in a temperate region during the wet season [*Tang and Feng*, 2001].

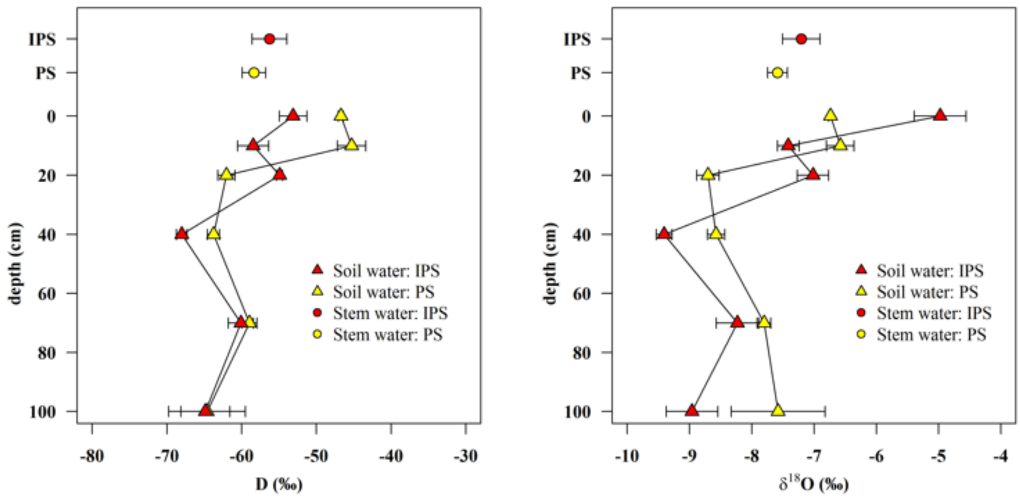

Figure 5. Vertical distribution of isotopic composition of soil water and stem water for both (a) $\delta^{18}O$ and (b) δD during wet season. Soil was sampled from depths of 0–5, 10–15, 20–25, 40–45, 70–75, and 100–105 cm.

A shift in stem water isotopic compositions before and during the wet period only appeared in IPS trees, providing insight into water source differences between the two groups (Fig. 6). Previous studies reported that across seasons, soil moisture and soil water isotopic compositions vary greatly at shallower depths and are relatively stable at deeper depths [*Fravolini et al.*, 2005; *Tang and Feng*, 2001]. This implies that plants with shallower rooting depth may show greater variations in stem water isotopic compositions across the season compared to plants with deeper rooting depth. The apparent shifts of stem water isotopic compositions in IPS trees were likely caused by their shallower rooting depth (see Section 3.2), which was more influenced by rainfall. *Schwinning* [2008] also observed larger shifts in the stem water isotopic composition of understory plants between rainfall events than in overstory plants, consistent with our results.

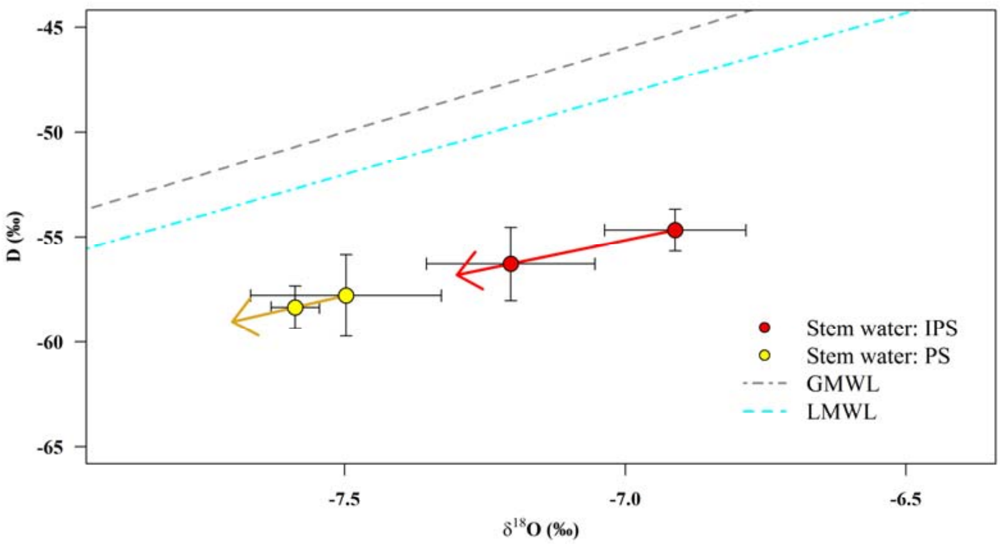

Figure 6. Shifts in stem water isotope composition observed before (29 June) and during (2 August) wet season. Arrows represent directions of change.

The direction of shift in stem water isotopic compositions suggests that trees in IPS used a mixed water source of event water (rainfall) and pre-event water (stagnant soil water) during the wet season (Fig. 6). A separate water source pool consisting of mobile water and relatively immobile water bound tightly to soil particles has been observed [*Good et al.*, 2015; *Klaus and McDonnell*, 2013]. If trees in IPS only used rainfall as their water source, stem water isotopic compositions would be expected to be located along the LMWL [*Li et al.*, 2007].

However, stem water isotopic values in IPS trees were still located further right from the LMWL after rainfall events. Those values represent isotopic depletion approaching a source water isotopic value. This suggests that trees in IPS partially used event water as their water source, rather than using only event or pre-event water created by piston flow.

3.2 Water Sources

The two-end member method showed that before wet season, trees growing through IPS used more top soil water (74±5% for IPS, 61±13% for PS). This is in line with previous studies that found shallower rooting depths under impervious surfaces [*Morgenroth*, 2011; *Viswanathan et al.*, 2011]. The intercept of the soil water regression line and the LMWL was set as one end member. This intercept represented the least enriched soil water isotopic composition, which is assumed to exist at a deeper layer of soils [*Gat and Matsui*, 1991]. We assumed that soil water isotopic compositions varied by depth with expected exponential changes in isotopic composition forming straight lines from least enriched deep water to most enriched top soil water before the wet season [*Barnes and Allison*, 1988].

The two-end member method was inappropriate to apply during wet season. During wet season, multiple rainfalls might result in significant isotopic heterogeneity of soil layers, which could distort exponential decreases in isotopic compositions with soil depths [*Klaus and McDonnell*, 2013] (Fig. 5). Vertically heterogeneous isotopic compositions of δD-$\delta^{18}O$ were observed at a drainage basin of Barogo in West Africa during the wet season [*Mathieu and Bariac*, 1996]. In this case, sampling of soil waters and isotopic measurement at varying depths is needed to derive a more reliable estimation of tree water sources.

The IsoSource model used to estimate water source depth during wet season revealed shallower water sources for IPS trees (Fig. 7). The IsoSource model calculated that trees growing at IPS extracted much of their source water from 20 cm soil depth (73%). PS trees extracted the largest proportion of their source water from 100 cm soil depth (35%), although source proportions were somewhat evenly distributed among depth classes. These results stemmed from the isotopic compositions of vertical soil water profile and stem water (Fig. 5). The isotopic composition of stem water from trees at IPS corresponded very closely with that of soil water at 20 cm for both isotopes. For trees at PS, the isotopic compositions of stem water were similar to those of soil water at 100 cm for oxygen isotopes and 70 cm for hydrogen isotopes. This implies a higher source contribution at both 70 and 100 cm depths at PS.

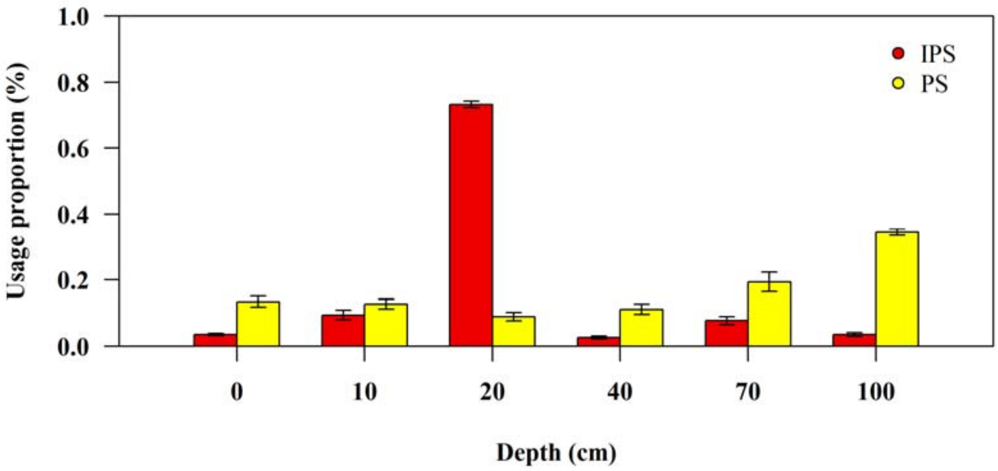

Figure 7. Relative contributions of each soil water depth as water sources for both tree groups calculated from the IsoSource model [*Phillips and Gregg*, 2003].

Both the two-end member model and IsoSource model showed shallower water sources for IPS trees. Shallower water sources under impervious surfaces that limit water input suggest the potential susceptibility of IPS trees to severe drought. This information could be used to improve urban tree management. Data on shallower root zones with limited source reservoirs in impervious urban areas could be used to improve urban hydrological models. The Urban Forest Effects-Hydrology (UFORE-Hydro) model [*Wang et al.*, 2008] coupled with TOPMODEL [*Beven et al.*, 1995] uses root zone depth to estimate evaporation and soil water balance. *Nystrom and Burns* [2011] noted that the calculated water balance in TOPMODEL was sensitive to root zone depth. Also, *Nourani et al.* [2011] reported that root zone depth affects run off and soil water balance outputs in TOPMODEL. This suggests that implementation of shallower root zones in urban hydrology models might make output more realistic.

3.3 Potential reasons for water source results

We observed soil temperature, moisture and bulk density for testing whether these factors can be the reason for difference in water sources.

3.3.1 Soil bulk density

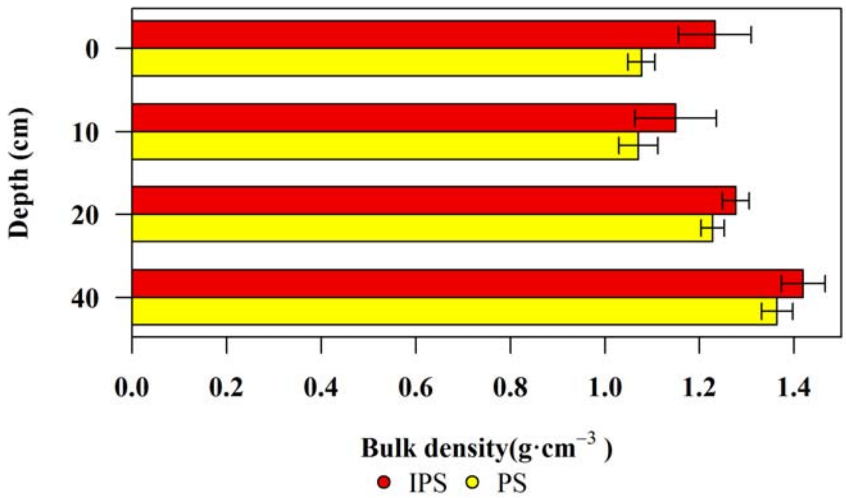

Figure 8. Soil bulk density

Soil bulk density didn't represent significant differences between two sites except for the top soil (Fig. 8), which was different from what we expected. Urban soil compaction is widely assumed due to structural strength or use of heavy equipment

[*Gregory et al.*, 2006]. But, it has been revealed that there is spatial and temporal variability in urban soils properties. *Pouyat et al.* [2007] and *Randrup and Dralle* [1997] showed that bulk density varies depending on the land use or construction method. *Edmondson et al.* [2011] and *Scharenbroch et al.* [2005] examined that bulk density decreased over time, deceasing influence of disturbance and increasing biological activity.

Reichwein [2003] assumed that the urban soil compaction could be the reason for lateral root development under the impervious surface, however, we couldn't verify that. Moreover, *Morgenroth* [2011] showed shallower rooting depths under the impervious surface regardless of the soil compaction, which confirms the low validity of bulk density for the cause of shallower water sources of trees in IPS

3.3.2 Soil temperature and moisture

Fig. 4 shows soil temperature and moisture that were measured during the study period. Soil temperature was higher in IPS, which was confirmed from previous studies [*Asaeda and Ca*, 2000; *Celestian and Martin*, 2004; *Wagar and Franklin*, 1994]. *Volder et al.* [2009], however, identified no significant difference in soil temperature between the impervious and control plot except in certain short periods. In their study, the higher soil temperature under control plot was measured at 5 cm depth in certain short periods. Because all studies we referred measured soil temperature deeper than 20 cm and we measured soil temperature at 20 cm depth as well, it might be not appropriate to compare our results with the results from 5 cm depth. Also, it can be assumed that soil temperature under 5 cm depth has a less effect on the root than that of under 30 cm depth.

Soil moisture was lower in IPS in dry season (Fig. 4), which could be expected as the isotopic composition of IPS implies evaporative enrichment by locating far right from GMWL (Fig. 2 and Fig. 3). Our result is similar with *Morgenroth et al.* [2013] and *Volder et al.* [2009] showed lower soil moisture under impervious plot only at deep soil, and opposite result was shown from Wagar and Franklin [1994]. These differences seem to be due to the soil texture: the soil texture of the study of *Wagar and Franklin* [1994] were clay, while the soil texture of our site was the sandy loam. Because clay soil allows lower drainage [*Cosby et al.*, 1984; *Siyal and Skaggs*, 2009], soil water tends to remain under the impervious surface being impeded evaporation by those barriers. An influence of lateral flow also could be the reason for the different results. Unlike our site which was covered broadly by an impervious surface, the experimental site of *Morgenroth et al.* [2013] was covered by 2.3 x 11.5m strips (5 plots) without a barrier for blocking lateral flow. Water that was input from the unpaved plot could affect the soil moisture distribution of the paved plot by remaining under the impervious surfaces.

We couldn’t identified the soil temperature and moisture as the potential reason for the isotopic results. *Morgenroth* [2011] who examined shallower rooting depths under impervious surfaces suggested the relatively stable soil moisture and temperature that can give a favorable environment for root growth can be a potential reason for that, based on the results of their previous study [*Morgenroth and Buchan,* 2009]. However we couldn't find the evidence that supports his suggestion, rather, our results implies that the lack of water sources under impervious surfaces for trees showed lower soil moisture at IPS. We observed the predawn water potential to examine the water stress of trees in IPS due to shallower rooting depth, which showed no significant difference between the two groups (Fig. 9). Since we measured the predawn water potential during the wet season, we measured again after 50 days and still we couldn't identify any significant difference (data not shown). This results might suggest the possibility of sufficient water source for trees in IPS, which was opposite to the soil moisture result. One possible reason for contrasting results is distillation and condensation. If distillated soil water at daytime condenses at nighttime near the surface due to cooling of the impervious surface, it can become the water source for trees in IPS. Since we measured the soil moisture around at noon, we couldn't observed that symptom. Additional observations may help us get insight of the reason for shallow roots under the impervious surface.

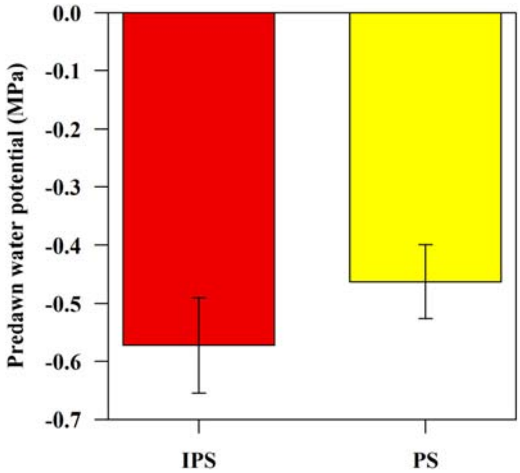

Figure 9. Predawn water potential

4. Summary and Conclusion

We investigated the water source depths of trees growing through impervious and pervious surfaces using stable isotopes (*D* and ^{18}O). Isotope data showed that the source waters for trees at IPS were more enriched with heavy isotopes due to evaporation than those for trees at PS both before and during the wet season. The calculated proportions of topsoil water usage indicated a shallower water source for trees at IPS before the wet season. During the wet season, the two-end member method was inapplicable due to complicated soil layer isotopic compositions caused by recurring rainfall inputs with distinct isotopic composition. The IsoSource model, used only in the wet season, calculated that IPS trees took water from a soil depth of ~20 cm while PS trees took the largest portion of their water from a depth of 100 cm. We also measured soil bulk density, temperature and moisture to examine reasons for a shallow rooting depth of trees growing through the IPS, which was suggested by previous studies. However, we could not explain the reason. Additional studies can help understanding ecohydrological processes under the impervious surface. In conclusion, trees growing through IPS developed shallow roots, implying the vulnerability of urban trees to drought. The findings in this work will be useful to improve urban hydrological models through better parameterization of root zone depths.

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국문 초록

불투수층은 현재 지표면의 많은 부분을 차지하고 있고 점점 늘어나고 있다. 하지만 불투수층 내의 수목의 물 사용에 대해서는 알려진 바가 거의 없다. 이에 우리는 산소와 수소 안정 동위원소를 사용하여 불투수층에서 자라는 수목과 투수층에서 자라는 수목의 수원을 장마 전과 장마 중 두 번에 걸쳐 관측 및 비교하였다. 단순 선형혼합모델을 사용하여 계산된 표토수 사용 비율은 불투수층에서 자라는 수목이 그렇지 않은 수목에 비해 장마철 전에 더 얕은 물을 많이 사용하고 있음을 보여주었다. 장마 중의 물사용 계산을 위해 사용된 IsoSource 모델은, 불투수층에서 자라는 수목은 20 cm 에서 가장 많은 물을 사용하고 있으며, 투수층에서 자라는 수목은 70과 100 cm에서 가장 많은 비율의 물을 사용하고 있음을 시사했다. 이와 같은 결과는 도시 수문 순환 모델을 향상시키는데 사용될 수 있으며, 가로수들이 가뭄에 더 취약할 수 있음을 시사한다.