沙漠研究 **24**-1, 29-32 (2014)
Journal of Arid Land Studies － DT11 Refereed Paper －

Estimation of Water Sources of Invasive Tree Species in Arid Environments by Oxygen Stable Isotope Analysis

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Abstract: The objective of this study is to estimate water resources of native and invasive tree species in arid environments by oxygen stable isotope analysis. The target trees were *Prosopis juliflora* (invasive) in Sudan and *Tamarix ramosissima* (invasive) and *Prosopis pubescens* (native) in USA. Three sampling sites were established in Khartoum, Sudan and one site was established in Nevada, USA in 2012. Stems of target trees, soils at various depths, groundwater and rainwater were collected in each site. Meteorological conditions and soil-stem water content have been monitored in these sites. For the plant and soil samples, water was extracted using a vacuum distillation system. The δ^{18}O content of the groundwater, rainfall, stem water and soil water were measured using an isotope ratio mass spectrometer. The results from oxygen stable isotope analysis showed that *Prosopis juliflora* in Sudan did not use only groundwater but also used the soil water in the rainy season, although this species is generally thought to use groundwater through deep tap roots. Similar results were shown from stem water content monitoring in the sites. Both *Tamarix ramosissima* and *Prosopis pubescens* in USA used shallow saline groundwater, suggesting that not only *Tamarix* but also *Prosopis pubescens* are salt tolerant species.

Key Words: Invasive species, Mesquite, Oxygen stable isotope analysis, *Tamarix*, Xylem water

1. Introduction

Trees in arid and semi-arid regions have several mechanisms to make efficient use of limited water resources to survive harsh conditions. Recently, approaches using stable isotopes have been developed as a powerful tool for investigating processes in plant-water relations such as recognizing plant water use and response to different types of water sources, better understanding water utilization processes, water use efficiency, and the pattern, mechanism, and ability to adopt to arid environments (Yang *et al*., 2010). In nature, there exist two stable isotopes of hydrogen (^{1}H - protium and ^{2}H - deuterium) and three stable isotopes of oxygen (^{16}O, ^{17}O, ^{18}O). The concentrations of ^{2}H and ^{18}O in meteoric waters exhibit a broad range of variations, both in time and space. The isotopic composition of water within the water cycle varies during phase changes (evaporation and condensation). For example, ^{18}O has two extra neutrons and is a bit heavier than ^{16}O, which results in a preference for evaporating the lighter ^{16}O containing water and leaving more of the ^{18}O water behind in the liquid state (called isotopic fractionation). However, water is not isotopically fractionated when taken up by the plant (Thorburn and Walker, 1994). As a result, water in plant tissues carries the same isotopic signal as the source water (*e.g.* rainwater, groundwater, soil water, etc.) until it reaches the sites of evaporation or transpiration, generally in the leaves. Therefore, the isotope ratio of stem water can be used as a measure of the isotopic signature of the water being utilized (Craig, 1966). The objective of this study is to estimate water sources of native and invasive tree species in arid environments by oxygen stable isotope analysis. The target trees were *Prosopis juliflora* (invasive) in Sudan and *Tamarix ramosissima* (invasive) and *Prosopis pubescens* (native) in US.

2. Materials and Methods

2.1. Target trees

Prosopis (mesquite) is a genus of “multi-purpose” tree, native to South and Central America and the Caribbean, which has been introduced widely into arid and semi-arid regions of the world (Gallaher and Merlin, 2010; Pasiecznik *et al*., 2001). Nilsen *et al*. (1983) reported that *Prosopis*

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(Received, November 10th, 2013; Accepted, February 1st, 2014)
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glandulosa in the Sonoran Desert of southern California avoids water stress under severe drought conditions by tapping water from the groundwater table using deep tap roots, and acquires greater drought tolerance with osmotic or stomatal conductance. Such morphological and/or physiological properties facilitate rapid invasion by *Prosopis* in arid and semi-arid environments, posing a threat to human subsistence (Berhanu and Tesfaye, 2006; Bosu *et al*., 2009; Milton and Dean, 2010; Mwangi and Swallow, 2008).

Tamarix ramosissima (saltceder) is native to Southeastern Europe and Asia and well known as a major invasive species in the Southwestern and arid regions in US, causing biodiversity reduction and increasing risk for wildlife species in riparian zones (Bateman and Paxton, 2010). *Tamarix* is salt tolerant species and rapidly spreading in river systems using shallow saline ground water (Imada *et al*., 2012).

2.2. Site description and sample collection

2.2.1. Sudan sites

Three sampling sites (Al Rawakeeb, Soba and Al Kadaro) for isotope analysis were established in *Prosopis juliflora* (mesquite) communities in Khartoum, Sudan in May 2012. Annual precipitation of the sites is about 150 mm and rainy season is from June to September. The groundwater levels of Al Rawakeeb, Soba and Al Kadaro were about 80, 20 and 23 m, respectively. Two *Prosopis* trees were selected in each site and two stems (or branches) were cut per one tree about every month. The branches were chopped and then placed in glass bottles. Soil (0-30 cm) and groundwater samples were also taken using bottles about every month in each site. Rainwater samples were taken only in Al Rawakeeb site. There were five rainfall events in 2012 in the Al Rawakeeb area and rainwater samples were taken at every event. In Soba and Al Kadaro, monitoring of sap flow, soil-stem water content, groundwater level and meteorological conditions have also been conducted (Saito *et al*., 2013).

2.2.2. USA site

One sampling site (Virgin River) was established in a mixed community of *Tamarix ramosissima* and *Prosopis pubescens* in Nevada, USA. Annual precipitation of the sites is about 400 mm. The site was located near Virgin River and the groundwater level was shallow (about 1 m). In addition, salinity of groundwater was high (electrical conductivity was 18 dS/m) and salt accumulation was observed at the soil surface in the site. Four branch samples from two *Tamarix* trees and two *Prosopis* trees, soil samples at 10, 20, 50 and 80 cm depths, and groundwater samples were taken in April 2012.

2.3. Laboratory analysis and data analysis

For the plant and soil samples, water was extracted using a vacuum distillation system. The ^{18}O content of the groundwater, rainfall, stem water and soil water were measured using an isotope ratio mass spectrometer (DELTA V: Thermo Fisher Scientific) at Tottori University, Japan.

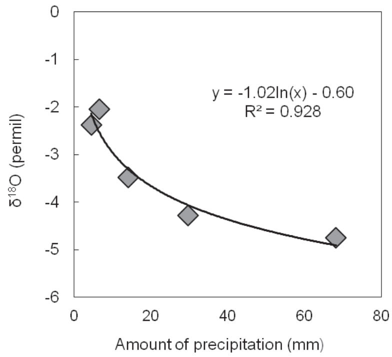

Fig. 1. Relationship between amount of precipitation and $\delta^{18}O$ of rainwater in Al Rawakeeb in 2012. Higher $\delta^{18}O$ value means heavier water. When the $\delta^{18}O$ value is equal to zero, the weight of the water is same as the Standard Mean Ocean Water, V-SMOW.

The isotopic ratio of ^{18}O is expressed by $\delta^{18}O$ (‰) as follows:

$$\delta^{18}O = \frac{R_{sample} - R_{smow}}{R_{smow}} \times 1000 \quad (‰) \qquad (1)$$

where R is the ratio of $^{18}O/^{16}O$ in the sampled water (R_{sample}) or in Standard Mean Ocean Water, V-SMOW (R_{SMOW}), according to the International Atomic Energy Agency (IAEA). Overall analytical precision of the spectrometer was ±0.2‰ for $\delta^{18}O$.

3. Results and Discussion

3.1. Results in Sudan

Relationship between amount of precipitation and $\delta^{18}O$ values of rainwater in Al Rawakeeb was shown in **Figure 1**. The $\delta^{18}O$ contents of precipitation decreased with increase in the amount of the precipitation. This relationship is called the "amount effect" (Dansgaard, 1964).

Variations in $\delta^{18}O$ and amount of precipitation in Al Rawakeeb were shown in **Figure 2**. The $\delta^{18}O$ values of the groundwater were low and almost constant. The $\delta^{18}O$ values of the rainwater were basically higher than those of the groundwater and varied with the amount of the precipitation as shown in Figure 1. The $\delta^{18}O$ values of the soil water were high except for Aug. 9 because light water molecule tends to evaporate and heavy water molecule tends to remain at or near the soil surface. On Aug. 9, the $\delta^{18}O$ value of the soil water was similar to the rainwater because the soil seemed to be filled with low $\delta^{18}O$ rainwater after two heavy rainfall events. The $\delta^{18}O$ value of the stem water on June 25 (before the rainy season) was much higher than that of the groundwater,

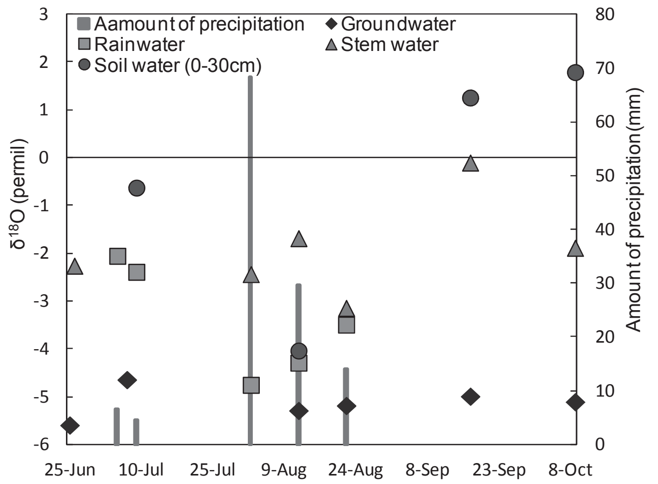

Fig. 2. Variations in δ^{18}O of groundwater, rainwater, stem water and soil water and amount of precipitation in Al Rawakeeb site (Sudan) in the rainy season in 2012.

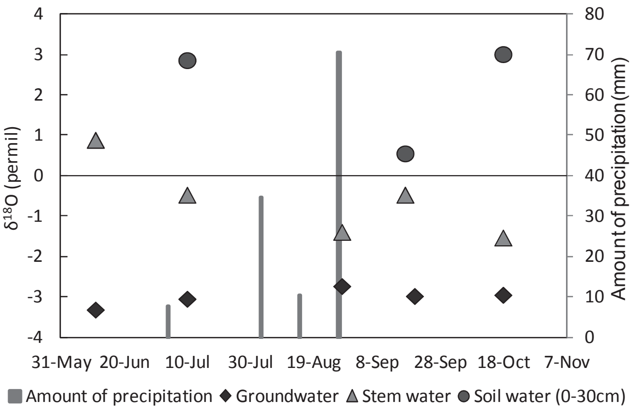

Fig. 3. Variations in δ^{18}O of groundwater, stem water and soil water and amount of precipitation and in Soba site (Sudan) in the rainy season in 2012 .

suggesting mesquite trees do not use only groundwater as their water source even in the dry season. Originally, the groundwater level of this site was about 80 m and it seems to be difficult for trees to use the groundwater. After the heavy rainfall events (on Aug. 24), the δ^{18}O value of the stem water was similar to the rainwater, suggesting mesquite trees used surface soil water.

Similar tendencies were seen in Soba (**Fig. 3**). The δ^{18}O values of the groundwater were low and almost constant. The δ^{18}O values of the soil water were high due to the influence of evaporation. The δ^{18}O values of the stem water were higher than those of the groundwater, suggesting mesquite trees do not use only groundwater even though the groundwater level in this site was sufficiently shallow (about 20 m) for mesquite trees. Similar tendencies were also seen in Al Kadaro site.

To obtain a better understanding of the results from the isotope approach, variations of stem water content, soil water content and daily precipitation in rainy season in 2012 were show in **Figure 4**. We focus on the stem of tree^{-1}. On Jul 30th, 10.4 mm of precipitation was observed and only the soil moisture sensor at 5 cm depth responded to this event; other soil and stem water contents did not respond. On Aug 1st and 2nd, 47.0 mm of precipitation in total was observed and the soil water content at 15 and 30 cm depth drastically increased, and then stem water content of tree^{-1} started increasing. This suggests that mesquite uses soil water below 15 cm depth. The stem water content of tree^{-1} linearly increased with time and the maximum value reached 0.46 m^3 m^{-3} on Aug 29th. The stem water content started decreasing from the next day and the soil water content at 15cm depth of this day was 0.19 m^3 m^{-3}. This soil water content value gives close agreement with the primary wilting point (pF 3.8) obtained from the water retention curve of the soil in this study site. This result indicates that the stem water content started decreasing because root water uptake became difficult due to drying of the soil. The results from both sensor-based approach and isotopic approach suggested that *Prosopis juliflora* used the soil water after the heavy rainfall events. This means *Prosopis juliflora* relies heavily on surface soil water in rainy seasons, although this species is generally regarded as using groundwater through deep tap roots (Nilsen *et al*., 1983).

3.2. Results in USA

The δ^{18}O values of the soil water at 20-80 cm depths were almost constant and similar to the value of the groundwater (**Fig. 5**). This was because the groundwater level of this site was quite shallow (about 1 m) and the composition of the soil water was influenced by capillary rise of the groundwater. The δ^{18}O value of the soil surface (10 cm) was high due to the influence of evaporation. The δ^{18}O values of the stem water of mesquite and *Tamarix* were constant and similar to those of the groundwater and soil water (20-80 cm), indicating both species use the groundwater and/or soil water at 20-80 cm depths. Since the salinity of the groundwater and soil water was high in this site, this result suggests that not only *Tamarix ramosissima* but also *Prosopis pubescens* are salt tolerant species.

4. Conclusion

The water sources of native and invasive tree species in Sudan and America were estimated by oxygen stable isotope analysis. *Prosopis juliflora* in Sudan is generally regarded as using groundwater through deep tap roots. Our studies, however, suggest that *Prosopis juliflora* is not using only the groundwater but also soil water after heavy rainfall. Both *Tamarix ramosissima* and *Prosopis pubescens* in USA used shallow saline groundwater, suggesting that not only *Tamarix*

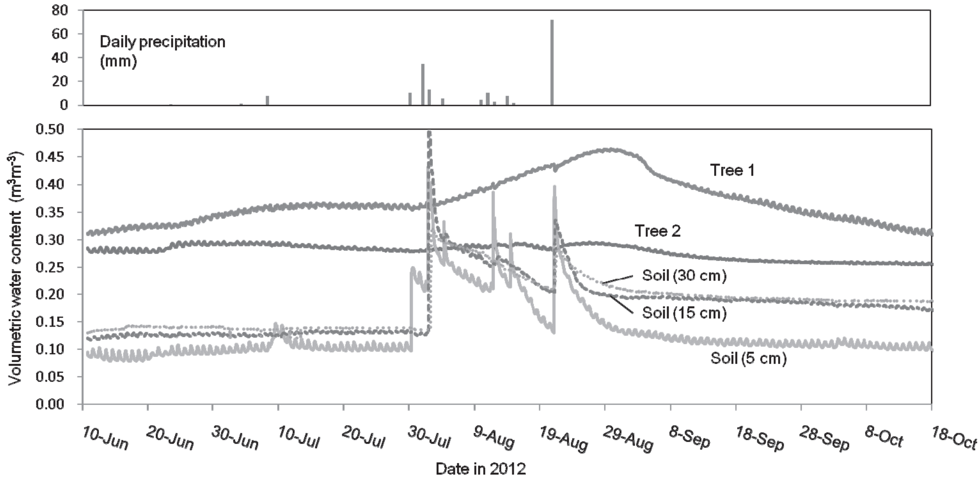

Fig. 4. Variations of stem water content of mesquite, soil water content and daily precipitation in rainy season in 2012 in Soba site, Sudan (Saito *et al.*, 2013). Dielectric moisture probes were installed to two mesquite trees (4 and 7 cm in diameter, respectively). Soil water content was measured at 5, 15, 30 cm depths.

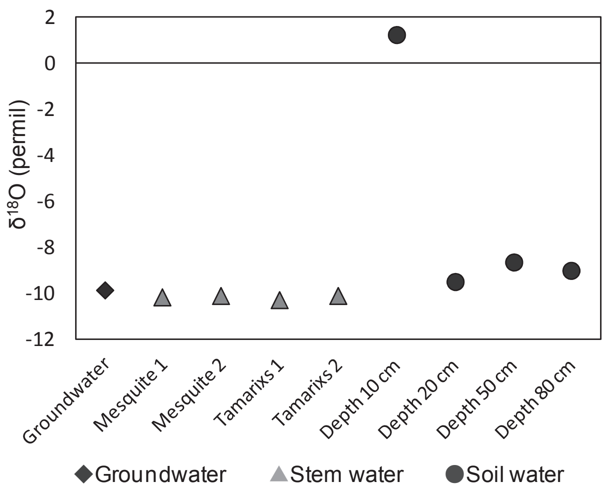

Fig. 5. $\delta^{18}O$ of groundwater, stem water (mesquite and *Tamarix*) and soil water (10, 20, 50, 80 cm depths) in Virgin River site (US) in April 2012.

but also *Prosopis pubescens* are salt tolerant species.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers 24780233, 23404014, and “A Study of Human Subsistence Ecosystems in Arab Societies: To Combat Livelihood Degradation for the Post-oil Era” (Project Leader: Hiroshi Nawata, Research Period: 2008-2013), and Joint Research Program of Arid Land Research Center, Tottori University.

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