USING STABLE ISOTOPES OF WATER TO TRACE PLANT WATER UPTAKE

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Abstract

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The stable isotopes of water (^{2}H, ^{18}O) are apparently not fractionated as plants take up water, as has been shown in laboratory and glasshouse studies. The authors verify this for a field situation in a semiarid area of southeast Australia in which *Eucalyptus* spp. are growing on a sand dune. No fractionation implies that the stable isotopes of water in the conducting tissue of plants can be considered to be the sum of stable isotopes from the various soil water reservoirs from which the plants may be extracting. If there are large enough natural variations in the isotopic composition of the soil and groundwater, the stable isotopes in the plant conducting tissue can be used to assess the source of the water used by the plant. The authors have developed a method for doing this. For the vegetation investigated there was no significant difference between the isotopic compositions of heartwood and sapwood. Nor was there a trend in isotopic composition of sapwater from the base of the trunk to the extremities of the twig. This meant that twigs could be used for sampling. Moreover, the isotopic composition of the soil, in which the total suction was not high, matched well with the isotopic composition of the twigs for a range of soil conditions and a range of isotopic values (50‰ for ^{2}H and 9‰ for ^{18}O). On a ^{2}H–^{18}O plot, the twig data lay near the best fit soil line. These results showed that the isotope method was valid for plant water uptake studies in a semiarid field situation.

1. INTRODUCTION

Long term drought and soil salinization are among the factors which contribute to a rapid extension of desertification in semiarid and arid regions of the world. In Australia, as in other dry countries, the natural vegetation is under stress owing to lack of water and/or excess salt. Because of the implications for natural vegetation, agriculture and water resources, it is important to have better information concerning the source of water for plants. Fresh water, essential for the survival of the vegetation, is usually present near the soil surface and in the groundwater. In this paper, we describe how stable isotopes of water (^{2}H, ^{18}O) can be used to find which reservoir of water the vegetation uses preferentially according to the environmental conditions of climate and soil.

The assumption underlying the stable isotope method is that no fractionation of the isotopes occurs during the transfer of water from the soil to the plant. This has been demonstrated in laboratory experiments [1, 2]. The above assumption implies that the isotopic content of the water taken up by the plant should represent a mixture of soil water from various depths. It is well known that fractionation occurs within the leaf, but the degree to which this affects the isotopic compositions elsewhere within the plant appears to vary from no effect [3] to significant variations [4], according to the plant type. If the plant can be sampled for stable isotopes of water so as to avoid the effect of the highly fractionated leaf water, the isotopic method can be used to find the source of soil water. This concept has been used in at least two studies [5, 6]. In the field experiment described in this paper, we provide more detailed soil measurements relevant to plant water uptake than the two studies cited above. In particular, we compare isotopic values of sapwater with soil water isotopic values, as well as soil conditions (dryness and salinity) over a two year period. Thus, we are better able to test the applicability of the stable isotope method in providing information on the use of water by vegetation in a field situation.

2. SITE DESCRIPTION

The study area is near Ouyen, Victoria (35° S, 142° E), in southeast Australia. The mean annual rainfall for the site is 340 mm, with a fairly even monthly distribution ranging from 21 mm in January to 38 mm in October. The rainfall during the first year of sampling was 328 mm with no rainfall event exceeding 30 mm, while for the second year the rainfall was 344 mm with one rainfall event of 71 mm. Class A pan evaporation varies between 1200 and 1500 $mm \cdot year^{-1}$. Extreme temperatures over 40°C often occur during summer and are always associated with a low relative humidity (<20%) due to northerly winds from the arid interior of Australia.

The geology of the region is described in Ref. [7]. Our site consists of a 7 m high dune adjacent to a saline discharge area. The aeolian dune overlies lacustrine clay of about 1 m thickness which in turn overlies the regional Pliocene sand aquifer. The regional groundwater is saline (TDS $\approx$ 40 $g \cdot L^{-1}$). A calcium carbonate layer exists at a depth of 1–3 m near the top of the dune. During the sampling period, there was evidence of perching above the clay layer. The dune is sparsely covered with the native vegetation of the area, a multistemmed form of *Eucalyptus* spp., known locally as 'mallee'. During augering at the site, live roots were found near the water table.

3. METHODS

3.1. Sampling

Sampling was carried out at four sites on the dune with depths to the water table of approximately 0.8 m (denoted HBD), 2.4 m (2HBD), 4.7 m (2HTD) and 6.8 m (HTD). Plant and soil were sampled ten times over a two year period (17 May 1988, 20 June 1988, 17 August 1988, 26 September 1988, 29 November 1988, 2 February 1989, 27 April 1989, 12 October 1989, 13 December 1989 and 1 March 1990). Soil samples were obtained to the depth of the water table using a hand auger and then placed in an airtight 500 mL jar. Generally, twigs were sampled randomly from each tree; the bark was removed from the twig and the twig then placed in a glass distillation flask containing kerosene. For each sampling time two trees were sampled at each site. For the last three sampling times, twigs were not sampled randomly. Samples were obtained from various points of the tree from the trunk, primary branch, secondary branch and twig along the same pathway of sap flow. For each of these points, separate samples were obtained from heartwood and sapwood. Piezometers were installed at the four sites. A rise of 0.7 m in the water table was observed following a large rainfall event (71 mm) on 10 May 1989 but the level was relatively steady otherwise. The depths to the water table quoted earlier represent the highest values observed.

3.2. Soil and plant water analyses

The soil samples were analysed for gravimetric water content, soil matric suction and soil water chloride concentration. The methods are described in Ref. [8]. Water from both soil and plant samples was distilled for isotopic analysis using azeotropic methods [9, 6]. The comparison between azeotropic and other methods of soil distillation is described in Ref. [10], while the azeotropic distillation method is validated for plant material in Ref. [6]. Pot experiments are described in Ref. [6], in which soil and plant isotope values were compared.

4. RESULTS

4.1. Intra-tree comparisons

For sapwood, there was no trend in ^2H values between the bottom of the trunk and the extremity of the twigs. The minima and maxima over the tree were −50 to −51 (HBD sampling 8 (12 October 1989)), −38 to −41 (HBD-9), −31 to −33 (2HTD-8) and −28 to −34 (2HTD-9). (All isotope values quoted are in ‰ relative to V-SMOW. The precision of the analyses is 2‰ for ^2H and 0.2‰ for ^{18}O.) These results are different from those in Ref. [4], in which a significant trend was found for the bean plant. There was in general no significant difference between heartwood and sapwood. The average values for heartwood and sapwood were, respectively: −50.8, −50.1 (HBD sampling 8); −32.2, −32.1 (2HTD-8); −42.3, −39.7 (HBD-9); −31.2, −30.5 (2HTD-9).

4.2. Soil results — Comparison with twig data

Results of soil sampling from site 2HBD (depth to water table ~2.4 m) are shown in Fig. 1. Only the results for sampling times 4, 7 and 8 are shown but these represent the range of soil conditions. Both the soil matric suction and osmotic suction (as represented by the chloride concentration) influence the uptake of water by plants. As a rough guide, 35 $g \cdot L^{-1}$ of chloride would be equivalent to an osmotic suction of 4.5 MPa from the NaCl in the soil solution. This is relevant to our data as chloride represents over 90% of the anions in the groundwater solution. In general, the vegetation appears to dry the soil to a total suction of 3–4 MPa. While there is ample water in the capillary fringe, the water there is saline.

For the following discussion, the soil matric suction is categorized as low (<1 MPa), intermediate (1–2.8 MPa) and high (>2.8 MPa). Likewise, the soil water chloride concentration is categorized as low (<10 $g \cdot L^{-1}$), intermediate (10–20 $g \cdot L^{-1}$) and high (>20 $g \cdot L^{-1}$). For sampling 4, the chloride concentration in soil solution is low for depths of 0–0.4 m while the soil matric suction is low below 0.1 m. The δD values in the 0.1–0.4 m depth range vary from +2.8 to −1.7‰, compared with −1.3 and −1.7‰ for the twigs. Only one soil sample in this range had enough water for ^{18}O analysis. This gave a value of −0.88‰, compared with the twig values of −1.6 and −0.6‰.

For sampling 7, the soil matric suction is high for depths of 0–0.5 m, intermediate for 0.5–0.7 m and low below 0.7 m. The chloride concentrations, on the other hand, are low to a depth of 0.7 m, intermediate for depths of 0.7–1.0 m and high below this. The δD values in the soil solution in the depth range 0.5–1.0 m vary from −23 to −28.5‰, compared with the twig values of −26 and −29‰.

For sampling 8, the soil matric suction is high for depths to 0.5 m and low below this. The chloride concentration is low to a depth of 0.5 m, intermediate from

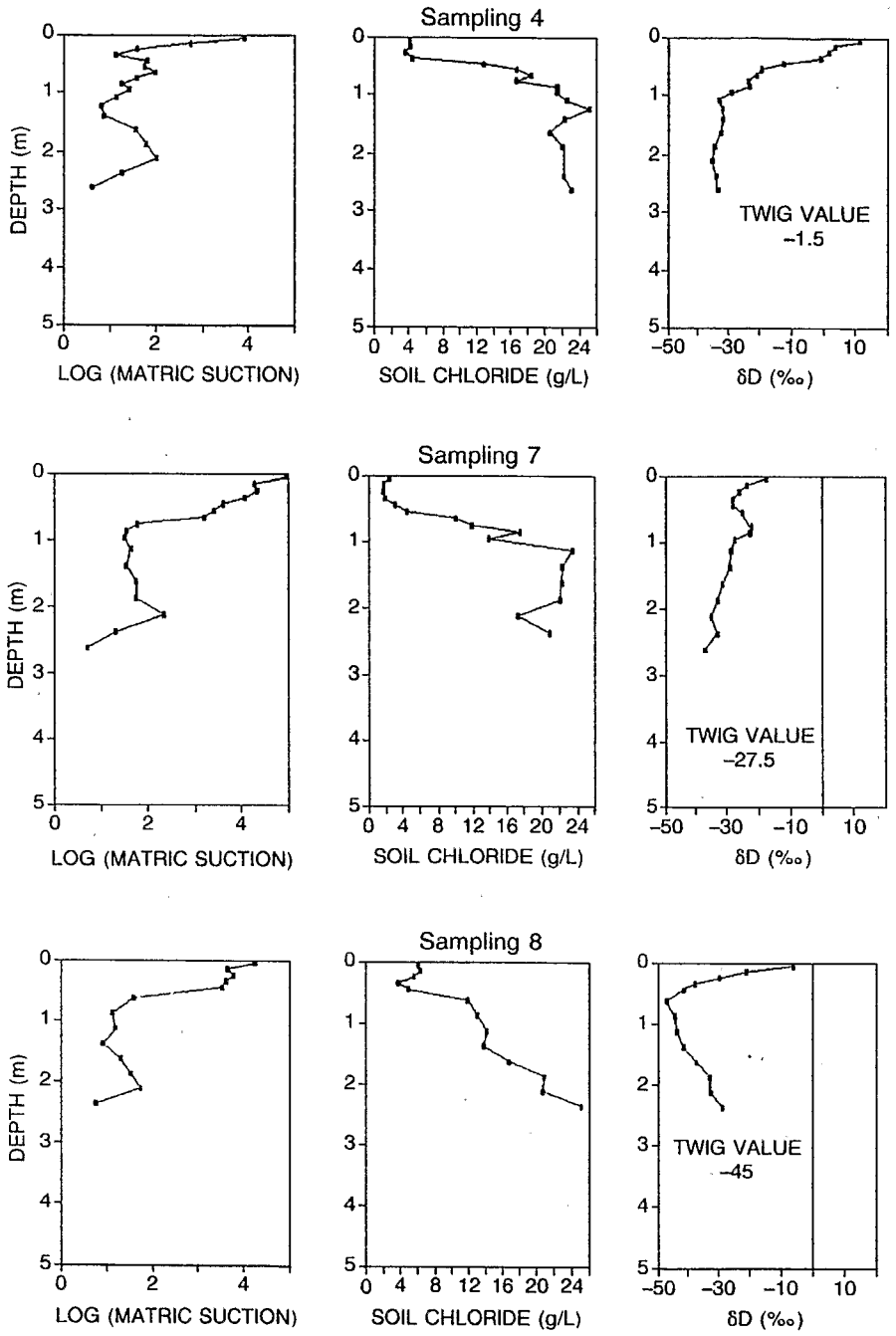

FIG. 1. Depth profiles of soil matric suction, soil water chloride concentration and soil water deuterium values for site 2HBD at sampling times 4, 7 and 8.

0.5 to 1.75 m and high below this range. The δD values in the depth range 0.5–1.75 m vary from −48 to −38‰, with the twig values in exactly the same range.

The results of this comparison show that the isotopic composition of the soil layers with low to intermediate matric and osmotic suction is similar to that found in the twigs. For the three sampling times, the deuterium concentration in the twig varied from −48 to −1‰, but this was still consistent with the soil isotopic values.

4.3. Deuterium–Oxygen-18 plots

The ^{2}H–^{18}O plots for both soil and twigs for all sites at samplings 4, 6 and 8 are shown in Fig. 2. The best fit line to the soil data is also shown in Fig. 2. If the twig water is a mixture of soil water from various depths, it should lie close to the line approximating the soil data for ^{2}H–^{18}O. For sampling 4, all the twig data lie above the best fit soil line. For samplings 6 and 8, the twig data lie about the best fit soil line (lower layer). The reason for the difference in sampling 4 is probably due to the soil water being derived from recent rainfall and this lies above the general best fit soil line (closer to the meteoric water line). Relatively few of these samples would have been analysed for ^{18}O owing to the lack of water. Since, in general, there does not appear to be a bias in the twig samples relative to the soil data and the difference for sampling 4 is relatively small for the purpose of the isotope method, the investigation of this difference has not been pursued further.

A second feature of the ^{2}H–^{18}O plots is the position of the twig data relative to those of the surface soil and the groundwater. For sampling 4, the twig data are close to the surface soil values. The surface soil was relatively wet. For sampling 6, the twig data are close to the groundwater values. Sampling 6 is the driest of all the profiles shown (soil matric suction almost identical to that of sampling 7). Finally, there are two groups of twig data for sampling 8, one isotopically depleted, presumably corresponding to the heavy rainfall some months earlier, and another group close to the groundwater values. On closer inspection of the soil data for this second group, it appears that the sampled water, rather than being groundwater uptake, was a mixture of that same rainfall event and antecedent soil water.

A final feature of the ^{2}H–^{18}O plots is the change of the slope of the best fit soil line and consequently the twig data. The lower part of the soil data remains approximately the same for all sampling times. The slope of the upper part is lower for samplings 6 and 8 than for 4 and is probably associated with evaporation from the soil surface [11].

5. DISCUSSION AND CONCLUSIONS

The data set associated with this field exercise represents one of the most comprehensive soil and plant isotope studies for a field site over a substantial period of

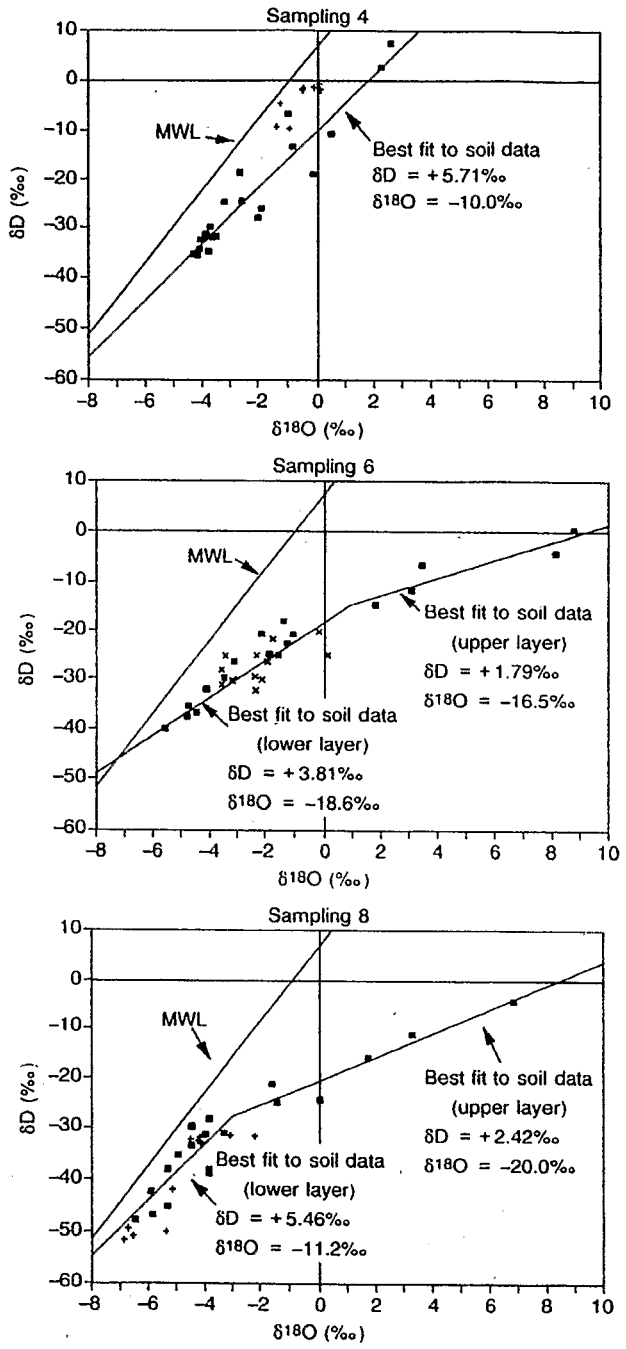

FIG. 2. ^{2}H–^{18}O plots for sampling times 4, 6 and 8. The local meteoric water line (MWL) and best fit line for the soil data are also shown. The soil data are represented by squares and the twig data by crosses.

time. This includes a range of soil moisture conditions of which some representative samplings have been described here. Over the study period, the twig isotope values varied by about 50‰ for deuterium and about 9‰ for ^{18}O. These very large ranges could be adequately explained by the soil matric suction, chloride and isotope data. If one makes the reasonable assumption that the plant will not take up water from soil for which the soil matric suction was very high and/or the soil salinity was high, one finds that the isotopic composition of the soil at the remaining depths is similar to that in the twig water. The fact that the twig data were consistent with the soil data for such a range of conditions and isotope values is the strongest evidence that the assumption of no fractionation in root uptake is valid under natural semiarid conditions for such vegetation.

There has been no attempt in this study to quantify the plant uptake or the soil water or isotope balance. However, it is possible with the present type of sampling to partition two different sources of water. Had the groundwater been fresh, as in the study described in Ref. [5], the water taken up by the plant would probably have been a mixture of the groundwater and soil water. For such circumstances, the ^{2}H–^{18}O plot could be used to define the relative contributions of soil water and groundwater.

In this type of study, the soil sampling is essential for partitioning water uptake. In some circumstances, the sampling of only rainfall, sapwater and groundwater (as in Ref. [5]) could be ambiguous. For example, in sampling 8 for the two higher sites, the isotopically depleted water from a previous rainfall event mixed with isotopically enriched soil water resulted in water of similar isotopic composition to groundwater. In the absence of soil isotope data, this may have been interpreted as the tree starting to use groundwater after the reserves of rainfall derived soil water had been depleted.

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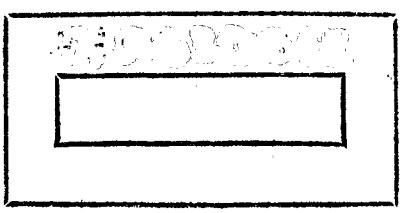

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