



Use of stable isotopes of water to determine the origin of water used by the vegetation and to partition evapotranspiration. A case study from HAPEX-Sahel

J.P. Brunel^{a,*}, G.R. Walker^b, J.C. Dighton^b, B. Monteny^a

^aORSTOM, 911 Avenue Agropolis, 34 032 Montpellier, France
^bCSIRO, Division of Water Resources, P.B. 2, Glen Osmond, S.A. 5064, Australia

Abstract

At one of the 'Supersites' within the HAPEX-Sahel exercise, soil, vegetation and atmospheric water vapour were sampled for measurement of the concentration of stable isotopes of water. The sampling took place at the beginning of the wet season. The stable isotope compositions, in conjunction with other physical measurements, were used to determine the mixing of rainfall with soil water, the point of extraction of water from the soil profile by the vegetation, and the relative importance of transpiration and evaporation from the soil surface. In the sandy soils of the area, water infiltration from rainfall into the upper parts of the soil profile was rapid. The perennial vegetation of the area, Guiera senegalensis, extracted the water from shallow depths of the soil profile, consistent with its extensive superficial root system. The transpiration from these plants contributed only about 20% of the total evapotranspiration. © 1997 Elsevier Science B.V.

1. Introduction

Stable isotopes of water, 2H and 18O, are now widely used in studies of water transport in the soil-vegetation-atmosphere continuum. For example, stable isotopes of water have been used to determine sources of water used by plants (Dawson and Ehleringer, 1991; Flanagan and Ehleringer, 1991; Walker and Richardson, 1991; Brunel et al., 1991; Ehleringer and Dawson, 1992; Thorburn et al., 1992; Mensforth et al., 1994). They have also been used to estimate local transpiration from vegetation (Brunel et al., 1992;

* Corresponding author.



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Calder et al., 1992), large-scale evapotranspiration (Magaritz et al., 1990) and water balance (Gat and Matsui, 1991). Isotopic fractionation resulting from the change from liquid to vapour phase also provides a tool for studying evapotranspiration processes. This has been developed mainly to estimate long-term bare soil evaporation (Allison and Hughes, 1983; Barnes and Allison, 1988).

It is therefore surprising that isotopes have not been included in more classical studies of evapotranspiration. They would be expected to provide information on mixing processes on a different spatial and time scale from the normal instrumentation. This paper presents results that were obtained in the framework of the HAPEX-Sahel exercise (Goutorbe et al., 1994), for a sparse bush type vegetation in semi-arid climatic conditions. The aims of the study were twofold: (1) to determine possible sources of water used by the perennial vegetation, Guiera senegalensis, the dominant species of shrubs, at the very beginning of the rainy season; (2) to use isotopic signatures of water in soil, vegetation and atmosphere to partition soil evaporation and plant transpiration from total evapotranspiration.

2. Site description

The general field area has been described by Goutorbe et al. (1994). The present field site is the Central-East Supersite, an area of fallow bushland of woody shrubs, Guiera senegalensis. Here, they have an average height of 3.5 m and cover 20% of the land surface with a density of 344 trees per hectare (Karimou, 1993). The soil consists of sand down to a hard crust located between 3.0 and 3.5 m below the surface.

3. Theory and methods

3.1. Theory

3.1.1. Soil-vegetation interactions

Use of stable isotopes of water to determine the possible origins of water used by vegetation relies on the principle that the isotopic composition of water in the plant is the same as that of the source of water used by the plant; this is generally the water in nearby soil, from where it is extracted by the roots. (If there are several possible sources, the isotopic composition of water in the plant should be a mixture of the compositions for the various soil compartments). The approach for using stable isotopes of water to determine water sources of vegetation relies upon a number of assumptions (Brunel et al., 1994), as follows: (1) there is no isotopic fractionation of water when it is extracted by the roots; (2) there is no significant change in the isotopic composition of sap water within the plant except in the vicinity of the leaf; (3) no significant errors are associated with the sampling of isotopes or in the extraction and analysis of water from plants and soil; (4) the isotopic composition of the soil water is laterally homogeneous within the rooting area; (5) the time of sampling was such that time delays associated with transport of isotopes up the plant were not important.

The lack of fractionation in the uptake of water by the roots has been shown in

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laboratory and glasshouse experiments (Walker and Richardson, 1991; Thorburn et al., 1992), and in field conditions (Brunel et al., 1994). The only exception demonstrated is for a mangrove (Lin and Sternberg, 1993).

Mixing of isotopically enriched water presumably from leaf with xylem has been observed in one field study involving alfalfa (Bariac et al., 1983). However, such mixing has not been observed in other studies involving trees, with the sampling procedure described below.

The total error involved in sampling, extraction, analysis and other assumptions for the procedure used in this study appears to be less than 5‰ for ^2H and 1‰ for ^{18}O (Brunel et al., 1994). If the natural variation of the isotopic compositions is greater than this, they are likely to be useful in determining sources of water used by the trees. The sampling procedure for this field study involved a check of spatial heterogeneity of isotopic compositions and hence of assumption (4). Assumption (5), of there being no important time lags in travel of water within the shrubs, was tested in this experiment using heat-pulse devices.

3.1.2. Soil–vegetation–atmosphere interactions

The isotopic composition of atmospheric water vapour can be considered as that of a mixture of water vapour from large-scale circulation air mass and water vapour from land surface evapotranspiration:

$$\delta^a = (1-x)\delta^{ct} + x\delta^*$$

where δ^a is the isotopic composition of atmospheric water vapour near the surface (‰), δ^{ct} is the isotopic composition of water vapour from evapotranspiration (‰), δ^* is the isotopic composition of large-scale circulation air mass (‰) and x is the fraction of water vapour from large-scale circulation air mass.

Water vapour from land surface evapotranspiration is a mixture of water vapour from soil evaporation and plant transpiration:

$$\delta^{ct} = (1-f)\delta_v^c + f\delta_v^t$$

where δ_v^c is the isotopic composition of the soil water vapour (‰), δ_v^t is the isotopic composition of the water vapour from plant transpiration (‰) and f is the fraction of water vapour transpired by the vegetation (‰).

One can rearrange this equation to obtain the following expression for f :

$$f = (\delta^{ct} - \delta_v^c) / (\delta_v^t - \delta_v^c) \quad (1)$$

Of the terms in Eq. (1), only δ^a and possibly δ^* can be measured directly in the vapour phase using appropriate atmospheric sampling techniques; δ_v^c and δ_v^t must be calculated or estimated indirectly.

Estimation of the isotopic composition of water vapour from the transpiration of the vegetation assumes that at steady-state transpiration, the amount of isotope of any species (^2H or ^{18}O) transpired per unit of time in vapour phase by the vegetation must be the same as the amount of isotope taken up in liquid phase from soil water by the roots of this vegetation (there is no change in the isotopic composition of the water during the taking up of water by the roots, nor during the transfer to the leaves. At steady state, enrichment in

the leaves reaches a maximum then constant value (Walker and Brunel, 1990).) In these conditions, isotopic composition of the water vapour transpired can be considered as the same as the composition of the sap water, δ^{tw} :

$$\delta_v^t = \delta^{tw}$$

Assuming that steady state has been reached, the isotopic composition of the water vapour from soil evaporation can be calculated using the Craig and Gordon (1965) equation

$$\delta_v^c = -\eta + \delta^{ef} - \varepsilon + q \frac{\delta^{sat} - \varepsilon - \delta^a}{q^{sat} - q} \quad (2)$$

where q is the specific humidity of the air at the ambient temperature (g kg^{-1}), q^{sat} is the saturated specific humidity at the temperature of the soil surface (g kg^{-1}), δ^{sat} is the isotopic composition of soil water at the evaporative front (‰), ε is the equilibrium enrichment (‰) and η is the diffusion ratio excess (‰).

Isotope composition of the water vapour evaporated from the soil and transpired by the vegetation, δ^{vt} , was calculated using an isotope mass balance:

$$\delta^{vt} = \left(\rho \int_{z_h}^{z_0} \theta_g \delta^s dz \right)_{t_1} - \left(\rho \int_{z_h}^{z_0} \theta_g \delta^s dz \right)_{t_2} / \left(\rho \int_{z_0}^{z_1} \theta_g dz \right)_{t_1} - \left(\rho \int_{z_0}^{z_1} \theta_g dz \right)_{t_2} \quad (3)$$

where t_1 and t_2 are the time interval between two samplings (days), z_0 and z_1 are depth (m), δ^s is the isotopic composition of soil at various depths between z_0 and z_h (‰), θ_g is the gravimetric water content (g kg^{-1}) and ρ is the soil density. In theory, mass balance equations should apply to isotopic ratios, and these equations using delta notation are approximations.

3.2. Methods

3.2.1. Soil and vegetation sampling

Sampling was carried out from 18 July to 30 July 1992 at three sites within 100 m. One main site was sampled in more detail, and the two others were sampled to check for spatial variability. For all the sites, soil was sampled from the surface to 1.20 m at 10 cm intervals, using a hand-auger. At the main site, one deeper sampling was made down to 3.5 m on 24 July, and three detailed samplings of the first 10 cm at 1 cm intervals were made on 24, 27 and 30 July. The samples were placed in hermetically sealed 250 ml aluminium boxes.

At each site, a tree was selected for sampling of twigs. This sampling was designed to check for spatial variability of the isotopic composition of sap water within the selected tree at the main site and between the selected trees within the two other sites. Twig samplings were undertaken once a day around 10:00 h. The selected twigs were 0.5–1.5 cm in diameter, and for each of them the bark was removed, in case it was in isotopic equilibrium with very isotopically depleted atmospheric water vapour. Each twig was cut into pieces of 2–3 cm length and placed in a glass flask containing purified kerosene (this prevents any isotopic exchange and makes the sample ready for the extraction of water by the azeotropic distillation technique using kerosene).

Rainfall was collected 1 km from the sampling site. During the field exercise three

rainfall events occurred, on 18, 22 and 27 July. All rainfall events from May to September 1992 were sampled at Samadey Village, 3 km from the field site.

3.2.2. Sap flow velocity measurements

To estimate the transpiration from *Guiera* using a heat-pulse technique (Swanson and Whitfield, 1981), four probes were set up in two trees at the main site. The averaged cross-section was 35.5 cm^2 . Spatial integration was done using the vegetation survey information of Karimou (1993), who found that the total cross-section for trees having a main branch diameter greater than 4 cm is $4.1 \text{ m}^2 \text{ ha}^{-1}$.

3.2.3. Atmospheric water vapour sampling

Water vapour samples were collected through segments of tubing attached to a mast at three heights above the ground (3, 6 and 12 m) by pumping air slowly at a flow rate of $10^{-3} \text{ m}^3 \text{ min}^{-1}$ through glass traps maintained at approximately -60°C with an electrical refrigeration unit. These traps were similar to that described by Schoch-Fischer et al. (1984). Sampling periods were generally from 08:00–09:00 h to 17:00–18:00 h. Water samples thus collected were then transferred into hermetically sealed 20 ml glass vials and were later analysed using conventional preparation and mass spectrometry techniques. Laboratory methods have been described by Brunel et al. (1991).

3.2.4. Definition of the value of some of the parameters used in Eq. (1), Eq. (2) and Eq. (3)

δ^a , which represents the deuterium composition of the atmosphere, is an average of the daily values measured at the three heights. There were no significant isotopic gradients between the soil surface and 12 m.

δ_v^1 , the deuterium composition of the transpired water, is taken as equal to the value of the sap water according to what has been stated above. In this case, it represents the average of sap water composition measured for Tree 2.

δ_v^c , the deuterium composition of the water vapour from the soil, has been calculated from Eq. (2). This calculation requires knowledge of δ^{ef} , q^{sat} and q , ε and η . Values of ε and η were taken from Merlivat (1978) and Majoube (1971), respectively, and corrected for IR temperature at the soil surface. q and q^{sat} were replaced in the calculation by e and e^s , which are, respectively, the measured water vapour pressure in the air and the saturated water vapour pressure in the air calculated for the measured soil surface IR temperature (T_s). Measured values for e and T_s were obtained from micrometeorological measurements made at a nearby site (B. Monteny, personal communication, 1993). Instantaneous values of T_s and e were made at 9 m height every 10 s and averaged over 20 min, 1 h and daily periods.

δ^{ef} , the deuterium composition of the soil water at the evaporative front, was extracted from the graph in Fig. 7 (below). The chosen values were those corresponding to the isotopic composition of water near the soil surface within the 3–10 cm depth interval, below the surface evaporative profile, where there was no isotopic gradient.

δ^{et} , the isotopic composition of the water vapour from both soil evaporation and plant transpiration, was obtained using Eq. (3). The calculation requires the value of θ_b , which has been measured. Soil density for this very sandy soil was estimated to be 1.4 (range from 1.4 to 1.6 (Le Fèvre et al., 1994)). Integration over depth to determine isotopic mass balance was made from the surface to 50 cm. The reasons for this were as follows: (1) no

change in water content with time was measured below 50 cm (Fig. 3(a) and (b), below); (2) the soil matric potential vs. depth curve (Fig. 4(b), below) shows that there was almost no chance that the vegetation would extract water below 50 cm; (3) one can consider as negligible the contribution from soil layers below 50 cm depth to direct soil surface evaporation over a 1 week period. Integration over time has been done for the period 23–30 July.

4. Results and discussion

4.1. Rainfall

Daily precipitation from 24 May to 14 September 1992 and the corresponding isotopic compositions (J.D. Taupin, personal communication, 1993) are shown in Fig. 1. Two comments can be made: (1) low rainfall events are associated with enriched deuterium values, which indicate evaporative enrichment during the event; (2) rainfall is more depleted in heavy isotopes at the end of the rainy season, which, according to Taupin

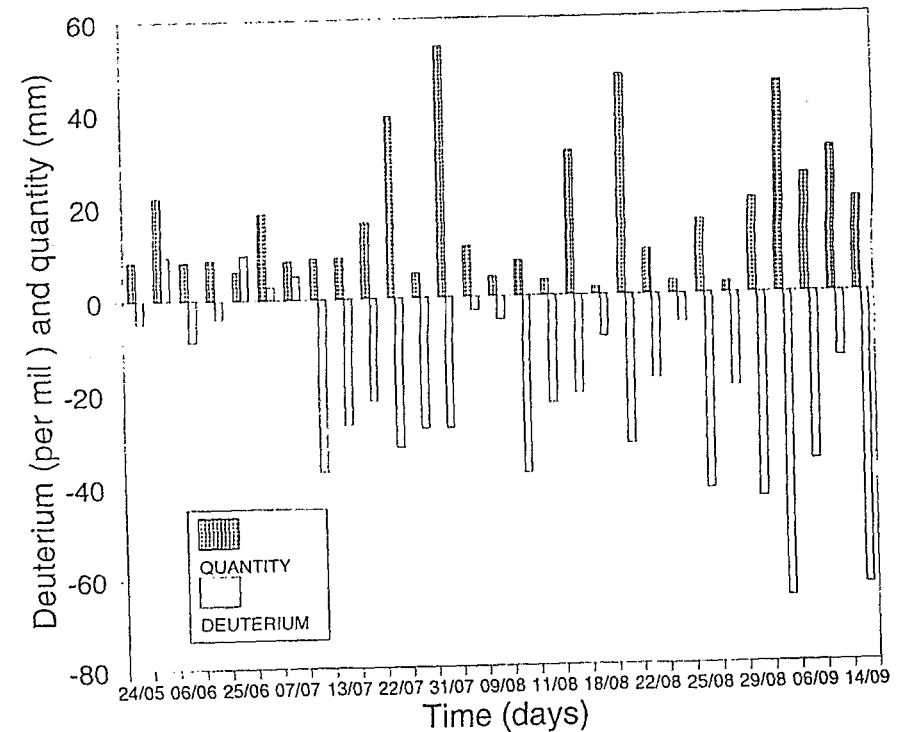


Fig. 1. Rainfall quantity and deuterium composition at Samadey, 24 May–14 September 1992.

Table 1
Rainfall characteristics

Day	Time ^a	$\delta^2\text{H}$ (‰)	$\delta^3\text{H}^b$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^{18}\text{O}^b$ (‰)	P (mm)	P^b (mm)
18/7	01:10	-20.8	-22	-3.74	-3.8	23.0	16.2
22/7	15:45	-31.2	-32	-5.55	-5.3	26.5	38.2
27/7	17:10	-21.2	-28	-3.19	-3.0	15.5	5.2

^a Time when the rainfall event started at Samadey.

^b Values measured at the long-term station Samadey.

(1994), means that it formed from condensation processes at very high altitude, linked to strong convection at the time of the tropical monsoon.

The line of best fit for the ^2H – ^{18}O relationship, the local Meteoric Water Line, can be expressed as follows:

$$\delta^2\text{H} = 6.9\delta^{18}\text{O} + 1.5$$

During the exercise, three rainfall events occurred. The amount of rainfall and isotopic compositions measured at both the field site and the long-term station at Samadey are shown in Table 1 (expressed in ‰).

The previous rainfall (measured at Samadey) was on 13 July: $P = 8.8$ mm, $\delta^2\text{H} = -27$ ‰ and $\delta^{18}\text{O} = -4.5$ ‰. From the start of the rainy season on 24 May to 18 July, cumulative rainfall was 97.0 mm. Except for the rainfall recorded on 11 and 13 July with isotopic compositions being respectively -37 ‰ and -27 ‰ for ^2H and -6.3 ‰ and -4.5 ‰ for ^{18}O , all other events show a relatively enriched isotopic composition, -9 ‰ to $+9.6$ ‰ for ^2H and -1.93 ‰ to $+1.76$ ‰ for ^{18}O .

4.2. Gravimetric water content, soil matric water potential and isotopic composition of water in the soil at the main site (Site 2)

Soil was sampled for gravimetric water content, soil matric water potential and stable isotope analysis on six selected days according to the rainfall events which occurred between 18 and 30 July. These days were 18, 23, 24, 26, 28 and 30 July. Surface soil was sampled on 24, 27 and 30 July. Deep soil sampling was on 24 July.

In Fig. 2(a), the three curves represent the variation of gravimetric water content with depth within the 0–0.1 m depth interval (sampling every centimetre). One can see the effect of rainfall and the rapidity with which the soil surface is responding to the precipitation–infiltration–evaporation process. The corresponding profiles for deuterium, in Fig. 2(b), show a similar pattern for the 3 days, with high enrichment in heavy isotopes from 4 cm depth to the surface, representing soil evaporation.

Fig. 3(a) shows for selected days the gravimetric water content vs. depth within the 0–1.2 m depth interval (sampling every 10 cm), and illustrates the quick response of the top 40–50 cm of soil to infiltration–evapotranspiration. Below that depth, variations seem almost negligible, and gravimetric water contents remain low (less than 3%) and fairly stable. Corresponding deuterium profiles in Fig. 3(b) show an old evaporative front at

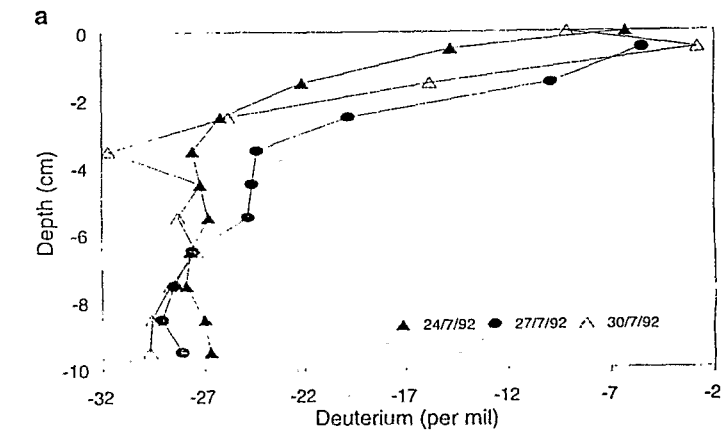
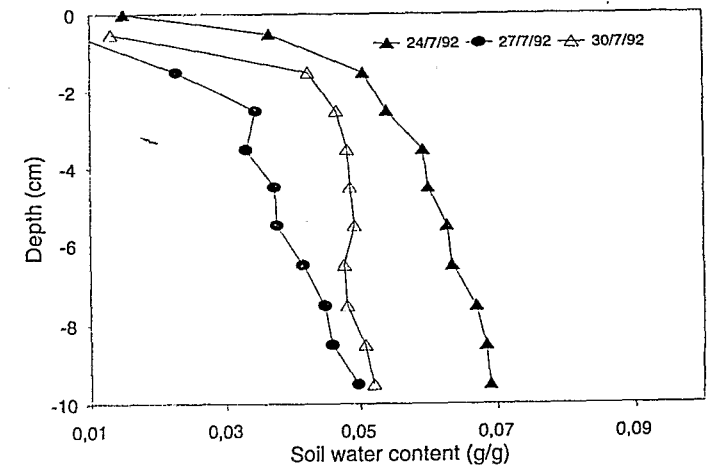


Fig. 2. (a) Surface gravimetric water content (0–10 cm) and (b) surface deuterium profiles (0–10 cm), at Site 2 on 24, 27 and 30 July.

50 cm depth. For the 0–3.5 m depth interval (sampling every 20 cm), data are shown in Fig. 4(a)–(c).

Fig. 5(a) and (b) give an example of the variation of gravimetric water content and deuterium composition of soil water with depth for Sites 2, 3 and 4, on 23 and 26 July. Spatial variability is not sufficient to influence the interpretation of the results.

4.3. Isotopic composition of sap water in trees

Twigs were sampled for isotopic analysis of sap water on 23, 26 and 30 July; the data are shown in Table 2. For each tree at Sites 2, 3 and 4, and for each time of sampling, twigs

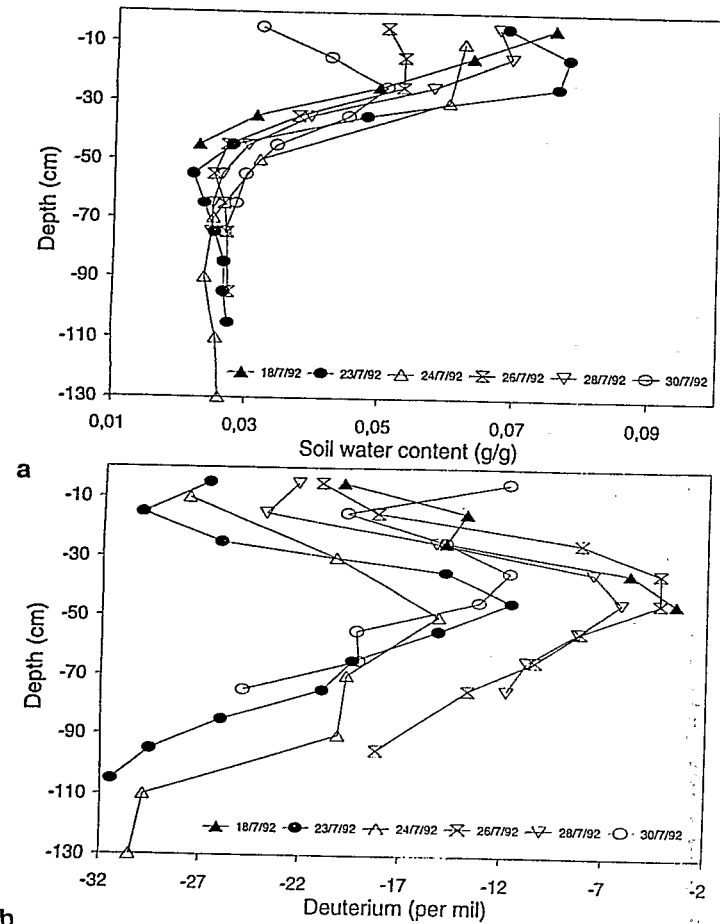


Fig. 3. (a) Gravimetric water content and (b) deuterium profiles at Site 2: time variability.

were generally sampled from the same two main branches denoted a and b. The numbers 1 and 2 denote replicates of the same twig. When there are two numbers in the $\delta^2\text{H}$ column, the second is the value for ^{18}O .

4.4. Determining the possible sources of water used by the *Guiera* trees

The principle of the method consists of finding the depth in the soil at which the isotopic composition of water matches that of the sap water in the tree. The difficulty is that a priori there could be several possible sources. The use of different models has been described by Brunel et al. (1994). In the present case, there is little opportunity for the vegetation to use

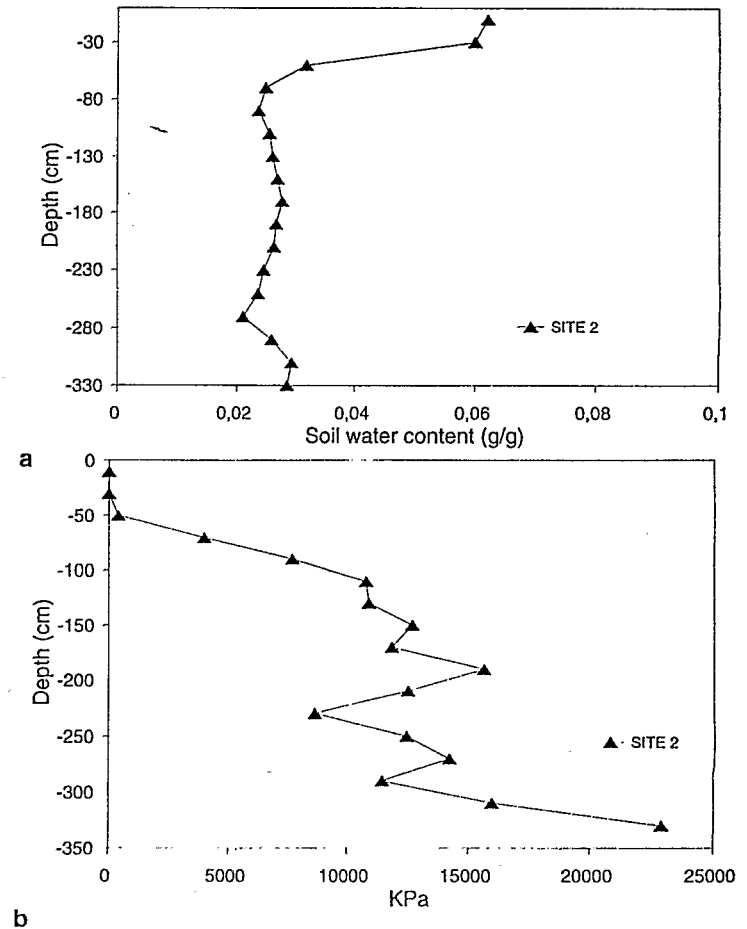
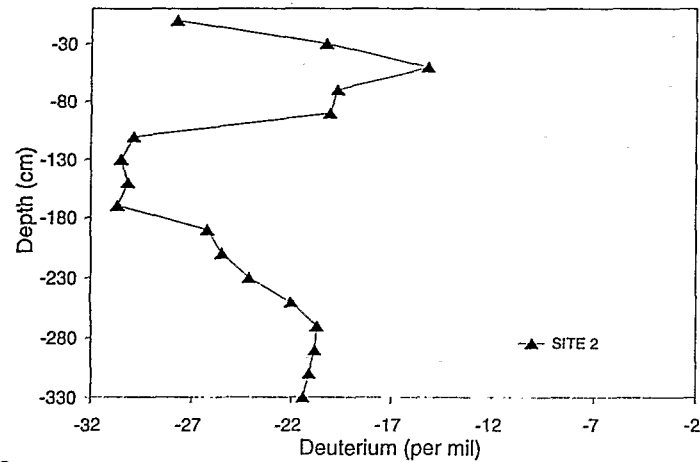


Fig. 4. (a) Gravimetric water content, (b) soil matric water potential and (c) deuterium profile, for the deep soil sampling (24 July 1992).

groundwater, because the water table is at a considerable depth, generally 20–60 m from the surface and probably close to 40 m in the area of the field sites.

As regards the deuterium profiles from the deep soil sampling (0–3.5 m) at Site 2 (Fig. 4(c)), there are three zones in the soil where isotopic composition of soil water matches that of the sap water in the tree; these are at depths between 20 and 30 cm, around 1 m and between 1.9 and 2.5 m. However, the corresponding soil matric water potential data for this profile (Fig. 4(b)) show that the only interval within which water could reasonably be extracted is represented by the first 50 cm of soil. The maximum value of soil matric water potential for water to be extracted by plants seems to be -3.5 MPa (Brunel et al., 1994).



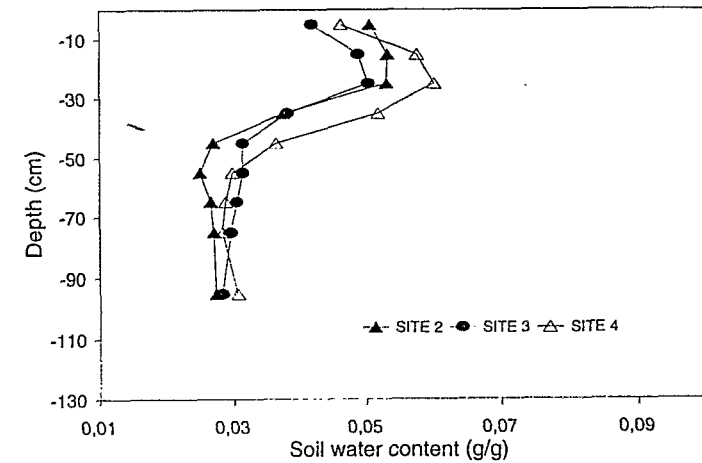
c

Fig. 4. Continued.

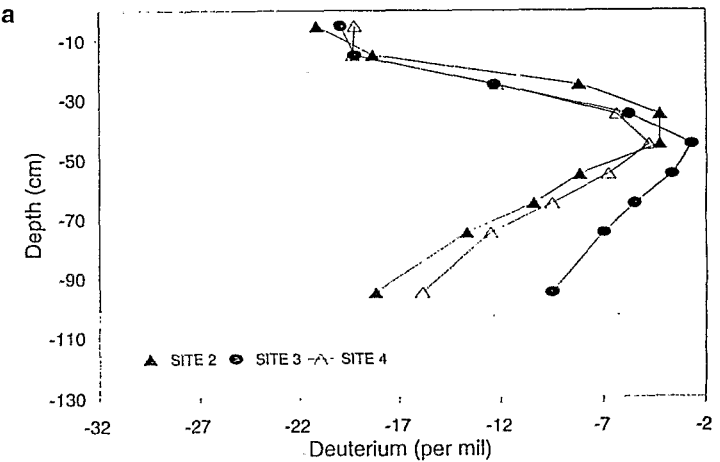
To improve the accuracy of the interpretation, the days for which comprehensive sampling was conducted at Site 2 have been selected. The results are shown in Fig. 6 and Fig. 7. Fig. 6 shows the variation of the isotopic composition of soil water with depth from the surface to 1.0 m for 23 and 26 July (10 cm intervals samplings): the two vertical lines represent the isotopic composition of sap water within the same branch (2a) for the same days. On 26 July, the isotopic composition of the sap water matches that of the soil water at two soil depths: 20–30 cm and 80–90 cm. At soil depths of about 80 cm the soil has been eliminated as a possibility, as the soil matric water potential is too low for the sap water to have originated here. Hence, there only remains the possibility of the soil depth of 20–30 cm. Unfortunately, on 23 July there was no match between the composition of sap water and soil water in this depth range.

Fig. 7 shows the variation of the isotopic composition of soil water with depth from the surface to 10 cm (at 1 cm intervals) for 24 and 27 July. Vertical lines represent the variation of the isotopic composition of the sap water as described in Fig. 6, for 23 and 26 July. The dates of soil sampling were not exactly the same as those of the twig sampling but there was no rainfall on 23 July and the rainfall fell late in the afternoon of 27 July after the soil had been sampled. It can be assumed, then, that the isotopic composition of the soil water on 24 and 27 July was not significantly different from that of 23 and 26 July, respectively.

Fig. 7 shows that the isotopic composition of the sap water matches that of the soil water in a narrow range close to the soil surface, i.e. 2–6 cm. This indicates clearly that the trees were using water from recent rainfall. This is confirmed by examining the ^2H vs. ^{18}O relationships (Fig. 8) for rainfall, soil and plant water, where the sap water data lie on the same line as the soil water data and are close to the soil surface values. This is also confirmed by observations of the superficial but spatially very extended root system seen through the erosion channels.



a



b

Fig. 5. (a) Gravimetric water content and (b) deuterium profiles: spatial variability (26 July 1992).

4.5. Using isotopic signatures of water in soil, vegetation and atmosphere to discriminate soil evaporation and plant transpiration

The results presented in Table 3 show that for the study period the contribution of the *Guiera* trees to the total evapotranspiration is only 20%. The main uncertainties involved in the calculation essentially come from the estimation of δ^{cf} , the isotopic composition of the soil water at the evaporative front. We have verified that a 5‰ change in δ^{cf} (which is the error one can make) would lead to 2% change in the final value for f . Similarly, a 5‰ maximum error on the measurement of the isotopic composition of the atmospheric water vapour would lead to 1% error in the estimation of δ^{cf} . Finally, the influence of the soil

Table 2
Deuterium composition (oxygen-18) of sap water in the trees (in ‰)

Date-site-identity	$\delta^2\text{H}$	Date-site-identity	$\delta^2\text{H}$
23-2-a1	-24.1 (2.49)	26-2-a	-24.1 (3.3)
23-2-a2	-24.8	26-2-b	-28.2
23-2-b1	-26.5	26-3-a	-22.4
23-2-b2	-26.7	26-3-b	-23.2
23-3-a1	-22.1	26-4-a	-26.9
23-3-a2	-23.9		
23-3-b1	-21.1	30-2-a	-21.9 (1.81)
23-3-b2	-22.2	30-2-b	-28.2
23-4-a1	-22.6	30-3-a	-19.8
23-4-a2	-22.4	30-4-a	-21.8
23-4-b1	-23.4		
23-4-b2	-22.3		

density is negligible, as a change from 1.4 to 1.6 (the range of measured values for ρ) would lead to less than 1‰ change in $\delta^2\text{H}$.

Values of actual evapotranspiration for the study site are not available for the measurement period. Hence, the comparison of these results with those obtained by other methods may not be very accurate. Nevertheless, they can provide some indication of the feasibility of the isotopic method.

An averaged value of transpiration measured at Site 2 for the same period was 2.6 l day^{-1} . Spatial integration on the basis of cross-sectional ratios leads to a value of 0.3 mm day^{-1} for tree transpiration. Total evapotranspiration was measured using a Bowen ratio technique at a nearby site, over a millet field. The crop had been sown but had not germinated. The soil characteristics were the same and hence one can assume that measured values of evapotranspiration are representative of bare soil evaporation. The

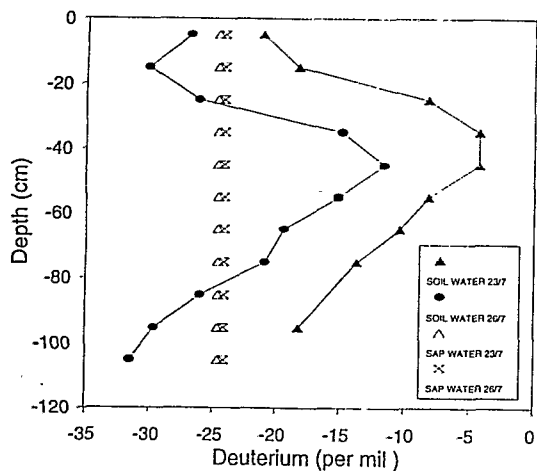


Fig. 6. Deuterium composition in soil (0-1 m) and plant water (23-27 July 1992).

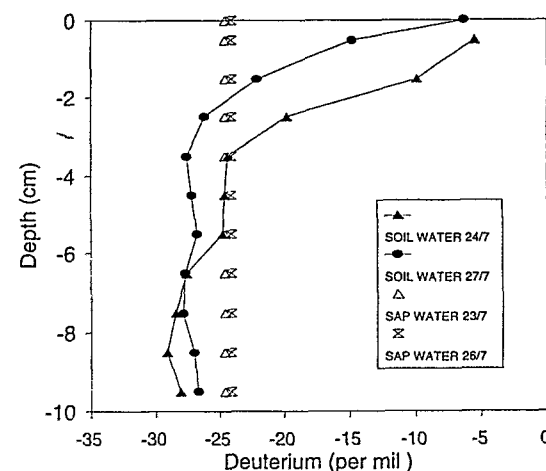


Fig. 7. Deuterium composition in soil (0-1 cm) and plant water (23-27 July 1992).

average value of evaporation for the same period of study was 1.3 mm day^{-1} (B. Monteny, personal communication, 1993). From these data, the contribution of the transpiration of *Guiera* trees to global evapotranspiration can be estimated to be 19% (0.3/1.6).

Other measured values of transpiration from *Guiera* trees and total evapotranspiration have been reported by Tuzet et al. (1994). They were made later during the rainy season. Transpiration was obtained from sap flow measurements (Steinberg et al., 1989), and latent heat fluxes under and above the canopy were measured using an eddy correlation technique. The results show that daily transpiration of *Guiera* trees was close to 0.5 mm

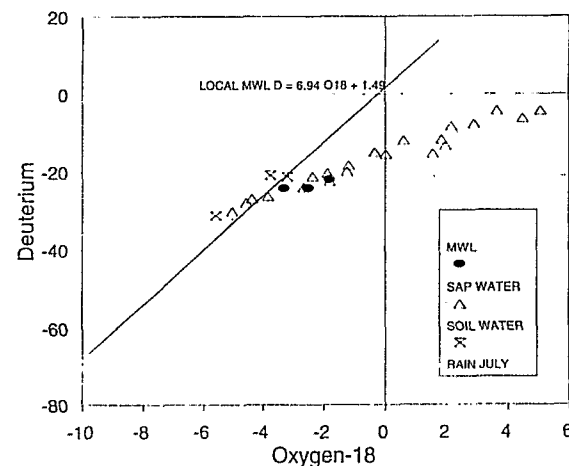


Fig. 8. Rain, soil and sap water: deuterium vs. oxygen-18 composition.

Table 3

Averaged values of the isotopic signatures of water in soil, plant and atmosphere, and calculated value of partitioning factor f

Date	δ^a	δ_v^b	δ_e^c	δ^{ef}	δ^{ef}	$e_s(e_s - e)$	f
23–30/7	-86	-26	-49	-5	-44	2.0	0.21

whereas total evapotranspiration was 2.2 mm. This ratio is similar to that found using the isotopic method.

5. Conclusions

The stable isotopes of water proved to be useful in better defining soil water movement, sources of water for the native vegetation, and the relative contribution from evaporation and transpiration. In particular: (1) rainfall led to rapid movement of water within the upper layer of the soil profile, although the water content was never high; (2) the vegetation used water from recent rainfall that was then resident in the soil within the top 50 cm; (3) the ratio of transpiration to total evapotranspiration for the study period was about 20%. These results are consistent with other results from the HAPEX-Sahel exercise.

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