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Actual evapotranspiration of a thorn scrub with Acacia tortilis and Balanites aegyptiaca (North Senegal)

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Abstract

The actual evapotranspiration (E_a) was followed from 1989 to 1992 in a thorn scrub stand in the northern Ferlo region (North Senegal, West Africa) for an *Acacia tortilis* grove, a *Balanites aegyptiaca* grove (every grove possessed its characteristic herbaceous layer) and a herbaceous zone outside the tree crown shade (annuals). E_a was derived from the water balance equation method (neutron probe measurements). The soil water profiles (soil water content and potential plotted to soil depth) were established, giving an account of preferential water uptake zones and the rooting depths of trees and annuals.

The mean seasonal actual evapotranspiration of the thorn scrub was 1.92 mm day^{-1} during the rainy season (period 1), 1.62 mm day^{-1} during the 'deferred' season (period 2), 0.62 mm day⁻¹ during the cool dry season (period 3) and 0.09 mm day^{-1} during the hot dry season (period 4). The daily maximal actual evapotranspiration of the groves was higher than that of the herbaceous zone and the *Acacia tortilis* grove's maximal daily actual evapotranspiration was higher than that of the *Balanites aegyptiaca* grove: 5.04, 4.15 and 3.98 mm day⁻¹ (period 1), 4.28, 3.76 and 2.89 mm day⁻¹ (period 2), 1.73, 1.79 and 1.34 mm day⁻¹ (period 3), 0.93, 0.46 and 0.36 mm day⁻¹ (period 4) for the *Acacia tortilis* and *Balanites aegyptiaca* groves and the herbaceous zone, respectively.

For soil depth to 3.5 m taken into account in the water balance equation, by the end of the growing year, soil moisture differed by 20.8 mm between tree and grassland zones in favor of grassland. Had this water been used by trees, this thorn scrub could have produced 13.72–0.8 kg DM ha⁻¹ year⁻¹ more wood.

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1. Introduction

The Sahelian thorn scrub is composed of a continuous graminoid layer and a discontinuous shrub-tree layer (30-80% tree canopy cover according to Cole (1986)). Evapotranspiration studies of sparse plant canopy cover ought to take into account (1) the spatial structure of plant community units, i.e. groves, herbaceous zones and bare soil areas; (2) the relative contributions of these units, which vary throughout the day and season, to produce the total actual evapotranspiration (Massman, 1992). The model of Nizinski and Saugier (1989), adapted for use in sparse vegetation, was used. The key factor of this model, inspired by the Penman-Monteith study (Monteith, 1965), was the surface resistance (Monteith, 1981; Shuttleworth and Wallace, 1985) which was assessed from transpiration, potentials and stomatal resistances of the trees and herb species and corresponding soil water potentials. The data required to validate and update the model are provided from the water balance method (soil water content) and from the Bowen ratio method (actual evapotranspiration). The quality of the model's validation is dependent upon the choice of natural vegetation and soil units, which should be carefully considered in view of the complexity of this ecosystem (Sivakumar and Wallace, 1991) which comprises sand dune formation with four main topographic units: (1) top of the dune; (2) slope; (3) low slope; (4) hollow; and for each topographic unit, a sparse vegetation.

This paper deals with actual evapotranspiration of the thorn scrub stand in the northern Ferlo region (North Senegal, West Africa). Actual evapotranspiration was derived from the water balance equation method (neutron probe measurements). We chose a slope zone representative of a large part of the thorn scrub surface (according to Cornet, 1981), 40% of the total area), this slope zone contains purely herbaceous surfaces, herbaceous surfaces having isolated shrubs or trees, and shrub and tree grove surfaces.

2. Site description and measurements

2.1. Study site

The study area is a Sahelian zone in the northern Ferlo region (North Senegal, West Africa). The climate of the region is dry tropical with mean annual precipitation (1918-1990, Dagana) of 282.4 mm year⁻¹.

The rainy season, which lasts about 80 days, starts in July and ends in September; the mean annual temperature is 28.7° C, the potential evapotranspiration is 2031 mm year⁻¹ (Anonymous, 1988).

According to Le Houérou (1989) the Ferlo belongs to the ecoclimatic Sahel– Sahelian subzone sensu stricto: this Mimosaceae thorn scrub has three main vegetation layers: a herbaceous layer (mainly composed of annual grasses) dominated by shrub and small trees layers (Poupon, 1980). The landscape is typically a gently undulating surface composed of low magnitude non-oriented dunes that end in small hollows.

Field work was carried out on a 1 ha plot situated on a dune's rise (including the dune's crest and hollow with 1.6% slope). The plot was located near Souilène, about 400 km from Dakar and 20 km from Dagana (16°20'39"N, 15°25'40"W).

The overstorey canopy is mainly 20 year old *Acacia tortilis* (Forsk.) Hayne ssp. raddiana (Savi) Brenan and 25 year old *Balanites aegyptiaca* (L.) Del; stand density is 151 trees ha⁻¹ and the total basal area is $3.87 \text{ m}^2 \text{ ha}^{-1}$. On the 1 ha plot we selected a grove with *Acacia tortilis*, a grove with *Balanites aegyptiaca* and a herbaceous zone outside the tree crown shade (without trees). Mean height of *Acacia tortilis* and *Balanites aegyptiaca* trees was 6.60 m and 6.40 m, respectively, and mean stem diameter at soil level was 0.56 m and 0.61 m. The ages of selected trees, (20 (Mariaux, 1975) and 25 years (Poupon, 1980), respectively) correspond to the most important populations in the pyramid-shaped diagrams representing the populations of *Acacia tortilis* and *Balanites aegyptiaca* by age-groups. Every grove possessed its characteristic herbaceous layer (annuals).

The plot's soils belong to the brown subarid sandy soils (French taxonomy) which are slightly acid (pH 6-6.5) and poor in clay, organic matter, nitrogen and phosphorus.

The study zone is a rangeland with average annual primary production of the herbaceous layer (2895 kg DM ha⁻¹ year⁻¹) being 10% lower than the actual demand of the grazing livestock (livestock of Dagana Department is 35791 TLU, Tropical Livestock Unit) (Akpo, 1992). The continuous livestock presence destroys the crust at the soil surface and promotes infiltration of rainfall. The study plot was fenced off in May 1989 (livestock exclusion); towards the end of the rainy season a crust formed on the soil's surface under rain drop impact (Lamachère, 1991). In this case there was little opportunity to recover the germination of annuals the following year (Cornet, 1981); so, the study plot was weeded before the rainy seasons of 1990 and 1991.

3. Material and methods

3.1. Water balance equation method

The water balance of an element of the soil (direct or surface run off and water table can be neglected in the present context) can be expressed as

$$Pi = E_{a} + D + dS/dt \quad (mm \ day^{-1})$$
(1)

where

$$E_{\rm a} = E_{\rm t} + I_n + E_{\rm s} \quad (\rm mm \ day^{-1}) \tag{2}$$

and

$$I_{\rm n} = Pi - (P_{\rm n} + P_{\rm s}) ~({\rm mm}~{\rm day}^{-1})$$
 (3)

where Pi is rainfall (mm day⁻¹); E_a is actual evapotranspiration (mm day⁻¹); D is drainage (mm day⁻¹); dS is change in soil water content (mm); dt is time resolution

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(day); E_t is transpiration (mm day⁻¹); I_n is net interception (mm day⁻¹); E_n is evaporation from soil (mm day⁻¹); P_n is throughfall (mm day⁻¹); P_s is stemflow (mm day⁻¹).

The soil water content, rainfall, throughfall and stemflow were measured; drainage and actual evapotranspiration were derived: when the actual soil water content exceeds its field capacity (S_{FC}), drainage occurs and the actual evapotranspiration equals the potential evapotranspiration ($E_a = E_p$). When the soil water contents lower than field capacity it is assumed that no drainage occurs; thus, drainage and actual evapotranspiration can be quantitatively expressed as follows

if
$$S \ge S_{FC}$$

then

$$E_{\rm a} = E_{\rm p}$$

and

$$D = Pi - E_{\rm p} - {\rm d}S/{\rm d}t \quad ({\rm mm} \ {\rm day}^{-1})$$

if
$$S < S_{FC}$$

then

D = 0

and

$$E_{\rm a} = Pi - {\rm d}S/{\rm d}t \ ({\rm mm} \ {\rm day}^{-1})$$

The assumption that no drainage occurs when the soil water content is lower than field capacity ($S < S_{FC}$) is valid for sandy soils; the sandy texture promotes a rapid decline of the hydraulic conductivity with decreasing soil water content (Marshall and Holmes, 1988). A soil depth of 4.75 m was taken into account in the water balance equation.

3.2. In situ water balance measurements

3.2.1. Soil water content (S)

The neutron probe ('Solo') was made at the Centre d'Etudes Nucléaires in Cadarache. The neutron probe calibration was established using the gravimetric technique. The sampling system (Fig. 1) comprised 15 permanent access tubes: three access tubes in the *Acacia tortilis* grove (tubes 1, 2 and 3), three access tubes in the *Balanites aegyptiaca* grove (tubes 4, 5 and 6), five access tubes in the herbaceous zone outwith the tree crown shade (tubes 7, 8, 9, 12 and 13) and four access tubes in edge zones (tubes 10, 11, 14 and 15); all 15 permanent access tubes were situated at similar contour lines. Measurements were made in each tube every 0.10 m from the soil surface until a depth of 1 m was reached then every 0.20 m until 2 m depth and subsequently every 0.50 m until 5 m depth was achieved. The soil water sum

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(5)

(4)



Fig. 1. Map of study plot (area: 10000 m^2 , slope: 1.6%, elevation: 5 m above see level); \blacksquare , meteorological station (rainfall, mean air temperature, dew point temperature, soil temperatures (at 0.5, 1.0 and 1.5 m depth), air humidity, solar radiation, net radiation, wind speed); \star neutron probe access tube; \bigoplus , raingauge; \bigcirc , stemflow collar; $\Box\Box$, psychrometer thermocouple.

(expressed in millimetres) summed for each layer of the tube amounts to the tube (profile) soil water content.

The field capacity (S_{FC} , matric potential equal to -0.01 MPa) and permanent wilting point (S_{WP} , matric potential equal to -16.00 MPa) were measured in situ. Six access tubes were combined with 19 psychrometer thermocouples (ceramic chambers set up every 0.10 m from the soil surface to 1 m depth, then every 0.50 m until 4 m depth) in an area 1 m in diameter which was delimited by a metal infiltrometer ring (Marshall and Holmes, 1988). The ring infiltrometer (1 m in diameter, 0.20 m height), was pressed 0.10 m into the soil, to help limit the lateral spread of water, thus maintaining infiltration under a constant hydraulic head and ensuring approximate homogeneity of water contents in the soil profile throughout

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the whole range of water contents and potentials between field capacity and the permanent wilting point (dry season).

The difference between field capacity $(S_{\rm FC})$ and the permanent wilting point $(S_{\rm WP})$ is the 'available water content' $(S_{\rm AW})$ amount in each soil layer and the sum of each layer's 'available water content' made up the 'available water content' of the soil profile (tube).

The soil water contents of each grove, of the herbaceous zone and of the thorn scrub are the arithmetic means of the water contents of the access tubes combined within them (as for 'available water content').

3.2.2. Rainfall (Pi)

The rainfall data came from a meteorological station situated at the center of the study plot (ARG100 Campbell raingauge, Campbell Scientific Inc., Shepshed, UK; collecting area 510.7 cm²).

3.2.3. Throughfall (\mathbf{P}_n)

The throughfall measurements were made using 17 recording rain gauges (The Bendix Corp., Baltimore, MD) (Fig. 1), with collecting areas of 323.6 cm²: five rain gauges were placed in the *Acacia tortilis* grove, five in the *Balanites aegyptiaca* grove, three in the herbaceous zone outside the tree crown shade and four rain gauges in edge zones. The throughfall of each grove and of the thorn scrub are the arithmetic means of the throughfalls from the rain gauges contained within them.

3.2.4. Stemflow (P_s)

An Acacia tortilis trunk was surrounded with a plastic stemflow collar; the volume of the collected water divided by the surface of the vertical tree's canopy projection onto the soil surface (25.63 m^2) gives the stemflow, expressed in millimetres of water.

3.2.5. Potential evapotranspiration (E_p)

The potential evapotranspiration was calculated by Penman's (1948) formula, modified by Van Bavel (1966)

$$E_{\rm p} = (D \ R_{\rm n} + qc_{\rm p} \ de/r_{\rm a})/L(D+c) \quad (\rm mm \ day^{-1})$$
(6)

where D is slope of the saturation vapour pressure vs. temperature curve (bar K⁻¹); R_n is net radiation (W m⁻²); qc_p is heat capacity of air at constant pressure (J m⁻³ K⁻¹); de is saturation pressure deficit of air (mb); c is psychrometric constant (mb K⁻¹); L is latent heat of vaporization of water (J kg⁻¹; 2.46 × 10⁶); aerodynamic resistance, r_a (s m⁻¹), was calculated from the formula given by Monteith (1965) as $r_a = [1/(k^2 u)][\ln(z-d)/z_o]^2$ where k is Von Karman's constant (0.39); u is wind speed (m s⁻¹); z is height above ground (m); z_o is roughness height (m) and d is zero plane displacement height (m). In the absence of wind profile data, d and z_o , the surface roughness parameters, were estimated according to an empirical formula which relates both parameters to mean vegetation height (Thom, 1971): d is 0.75h and z_o is 0.1h where h is mean vegetation height (m).

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3.2.6. Data collection

Measurements of soil water content, soil water potential, rainfall, throughfall and stemflow were made (from 10 August 1989 to 2 July 1992) weekly during the rainy season and every 20–30 days during the dry season; rainfall, mean air temperature, dew point temperature, air humidity, soil temperatures (at 0.5, 1.0 and 1.5 m depth), total air pressure, solar radiation, net radiation and wind speed were recorded hourly from May 1990 on a 21X Datalogger (Campbell Scientific Inc., Logan, UT).

4. Results and discussion

4.1. Water balance

Our results concern the period from 9 August 1989 to 2 July 1992. According to Le Houérou (1989), there are four main seasons in the annual cycle in the ecoclimatic Sahel–Sahelian subzone: period 1, from mid-June to mid-September (rainy season); period 2, from September to November ('deferred' season: it has stopped raining, annuals still alive); period 3, from November to February (cool dry season); period 4, from March to May (hot dry season). The annual rainfall for the 3 years was in 1989, 226.5 mm, 1990, 172.0 mm and in 1991 148.3 mm (each year had annual rainfall less than the long-term mean of 282.4 mm); the annual potential evapotranspiration was 2233.2 mm year⁻¹, 2352.4 mm year⁻¹ and 2183.0 mm year⁻¹, respectively. Acacia tortilis and Balanites aegyptiaca maintained live leaves throughout the year (with variations in the leaf area index (Fournier, 1993)), so there is water uptake/ transpiration, outside and inside of the tree crown shade (Acacia tortilis and Balanites aegyptiaca groves) occurred during the rainy and 'deferred' seasons only (periods 1 and 2).

4.1.1. Water content profiles

The soil water profiles (soil water content and potential plotted to soil depth) were determined for the groves and herbaceous zone. All profiles (matric potentials) over the period of 3 years give an account of preferential water uptake zones (the lowest negative matric potential values) and rooting depths. The *Acacia tortilis* grove (Fig. 2(a)) preferentially absorbed from 0 to 1.4 m and close to 2.5-3.0 m (peak of water uptake by roots), the *Balanites aegyptiaca* grove (Fig. 2(b)) preferentially absorbed from 0 to 0.6 m and close to 1.2-1.6 m (peak). The upper layer of the soil profile is rooted by annuals and associated trees while the deeper part is penetrated only by tree roots; according to Cornet (1981) in the thorn scrub, nearly 100% of the herbage root biomass is found in the upper 1.0 m of soil depth. The exploration of soil by absorptive roots reaches 3.5 m and 2.0 m depth for the same species have been reported by Bille (1977). At about 3.5 m depth in the *Acacia tortilis* grove, soil water potentials became more and more negative and the wetting front never penetrated deeper than 4.5 m; at depth in excess of 2 m in the *Balanites*





Fig. 2. Soil water potential profiles (MPa) during the period 9 August 1989 to 2 July 1992 inclusive. (a) *Acacia tortilis* grove; (b) *Balanites aegyptiaca* grove.

aegyptiaca grove's soil the profile remained constantly 'wet' all year. Deeper than 3.5 m, the soil water potentials were identical in both tree groves. Fig. 3 a, presents profiles from the herbaceous zone during the rainy and 'deferred' seasons (the herbaceous growing seasons) and in Fig. 3 b, all profiles from the herbaceous zone during the dry seasons (dead herbs, bare ground area increase) are presented. Water uptake by roots of herbaceous species occured at depth between 0.0 and 1.00 m (Fig. 3(a)). However, below the herbaceous vegetation, water was withdrawn all year from depths between 2.0 and 3.5 m (Fig. 3(a) and (b)). Maximal withdrawn occurred at about 2.5–3.0 m depth, i.e. similar to the depth at which water was removed beneath Acacia tortilis. It seems likely that colonization of the herbaceous zone by roots of Acacia tortilis occurred at this depth (30 m distant from the Acacia tortilis trees). The depth at which maximum water uptake occurred varied with the pluviometric régimes and such variations were synchronous in both the herbaceous zone and Acacia tortilis grove. Thus, during the dry season of 1989-1990, (the relatively 'wet year'), water uptake by Acacia tortilis roots occurred preferentially at 3.0 m depth in the grove's soil and at 2.5-3.0 m depth in the herbaceous zone's soil; during the 'dry year' 1990-1991, preferential uptake was from 2.50 m depth in the grove's soil and 2.0-2.5 m depth in the herbaceous zone's soil.



Fig. 3. The herbaceous zone soil water potential profiles (MPa). a, During the rainy season (mid-June to mid-September), (1) and the 'deferred' season (September to November), (2); b, during the cool dry season (November to February), (3) and the hot dry season (March to May), (4).

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4.1.2. Actual evapotranspiration

The actual evapotranspiration was calculated using Eq. (5) (no drainage). In 1989, 1990, 1991, during the rainy seasons (periods 1) which lasted about 86 days (90, 79 and 90 days, respectively), the mean seasonal actual evapotranspiration of the thorn scrub was 165.1 mm of water with range 120.08–203.31 mm, and mean daily actual evapotranspiration was 1.92 mm day⁻¹. During periods 2, 3 and 4, the thorn scrub's mean daily actual evapotranspiration was 1.62, 0.62 and 0.09 mm day⁻¹. The measured actual evapotranspiration values were compared with those determined by Cornet (1981) who assessed the water balance equation (soil depth of 3.0 m was taken into account). Cornet's plot was also situated on a dune's rise with similar thorn scrub vegetation in the same ecoclimatic zone (Fété Olé, 15°06′W, 16°14′N) during 2 years, 1975 (Pi = 311.2 mm) and 1977 (Pi = 130.3 mm). Cornet reported that seasonal actual evapotranspiration for periods 1 and 2 was 206.4 mm and 126.2 mm (1.4, 1.88 and 1.09, 1.25 mm day⁻¹).

The period from mid-June 1990 to mid-June 1991 was chosen to illustrate the daily maximal actual evapotranspiration of the two groves, herbaceous zone and thorn scrub during the four seasons. The soil depth of 4.75 m was divided into two parts: 0-1.0 m depth and 1.0-4.75 m. According to the soil water potential profiles, herbage roots outside and inside the tree crown are concentrated in the upper 1.0 m of soil (also rooted by trees); the 1.0-4.75 m depth was rooted by trees only.

From 0 to 4.75 m, from period 1 to period 4, for the whole soil profile, all daily maximal actual evapotranspirations decreased in concert with the pluviometric régime (Fig. 4(a)). The daily maximal actual evapotranspiration of the tree groves was higher than that of the herbaceous zone, and maximal daily actual evapotranspiration was higher from the Acacia tortilis grove than from the Balanites aegyptiaca grove. Daily actual evapotranspiration estimates were: 5.04-4.15- 3.98 mm day^{-1} (period 1), $4.28 - 3.76 - 2.89 \text{ mm day}^{-1}$ (period 2), $1.73 - 1.79 - 1.34 \text{ mm day}^{-1}$ (period 3), $0.93 - 0.46 - 0.36 \text{ mm day}^{-1}$ (period 4) for the *Acacia* tortilis grove, Balanites aegyptiaca grove and herbaceous zone, respectively. During the rainy season (period 1, there was no water stress, soil water content was equal to or greater than 60% field capacity), the groves and the herbage preferentially take up water from the upper 0-1.0 m of soil rather than from the layer 1.0-4.75 m depth (Fig. 4(b), a ratio of about 2:1 for Acacia tortilis, and 4:1 for Balanites aegyptiaca and the herbaceous zone), although water was not a limiting factor at depths in excess of 1.0 m. In period 2, the situation inverts, and stays constant for the remainder of the year; i.e. water uptake from the soil layer 1-4.75 m deep contributes more than towards the daily maximal actual evapotranspiration water uptake from the upper 0.0-1.0 m of soil. The herbaceous zone is an individual case; it can be reasonably assumed that water withdrawal from the soil layer 1.0-4.75 m deep is a result of Acacia tortilis water uptake. Two pieces of evidence suggest this: (1) it can be inferred from the matric potential profiles; (2) also from continuous water uptake during periods 1, 2 and 3 (0.73, 0.88 and 0.90 mm day⁻¹) despite the fact that toward the end of period 2 the life-cycle of the herbs is completed and they die.

During the rainy season, the daily maximal actual evapotranspiration derived from the soil layer 0.00-1.00 deep was constant irrespective of vegetation cover (Fig. 4(b),



Fig. 4. Mean daily maximal actual evapotranspiration (mm day⁻¹). (a) From 0.00 to 4.75 m depth (\bigcirc); (b) from 0.00 to 1.00 m depth (\triangle) and from 1.00 to 4.75 m depth (\blacksquare); *Acacia tortilis* grove and herbaceous zone from 1.00 to 4.75 m depth (\blacklozenge).

herbage zone 3.25 mm day^{-1} , Acacia tortilis 3.44 mm day^{-1} , Balanites aegyptiaca 3.29 mm day^{-1}) with 3.31 mm day^{-1} being average for the thorn scrub vegetation complete. Cornet (1981) calculated 3.5 mm day^{-1} for the same soil depth and period. As the seasons progress from wet to dry the daily maximal actual evapotranspiration of the herbaceous zone becames larger than that of the groves. Values

for the herbaceous zone, Acacia tortilis grove and Balanites aegyptiaca grove were 2.01, 1.72 and 1.50 mm day⁻¹ (period 2); 0.44, 0.26 and 0.23 mm day⁻¹ (period 3); 0.21, 0.13 and 0.10 mm day⁻¹ (period 4), respectively. During periods 3 and 4, the herbaceous zones inside and outside the open covered by tree crowns remain more or less denuded of vegetation, (dead herbs and litter remain). Whereas outwith tree crowns only evaporation occurs, in the grove's soil both evaporation and the uptake of water by tree's roots takes place (shade from tree crowns limit evaporation from soil). Assessed from the development of the matric potential profiles in the herbaceous zone during the course of the dry season, there was progressive drying from the soil surface where mulch was absent. Similar drying was also observed in the grove's soil and leads to the conclusion that the water taken up by tree roots (in the first 1.0 m of soil) decreases in relation to soil evaporation during the course of the dry season. For instance, in the Acacia tortilis grove, the depth from which water uptake by tree roots can occur (matric potential equal to or higher than -1.6 MPa), changes from 0.6 m (from 0.4 to 1.0 m) at the beginning of the dry season to 0.1 m (from 0.9 to 1.0 m) at the end of the dry season.

Water uptake at depth from 1.0 to 4.75 m by Acacia tortilis roots which exploited the herbaceous zone was not insignificant, especially during period 3. In total, 25-30% (periods 1 and 2), 40% (period 3) and 15% (period 4) of water taken up by Acacia tortilis comes from the herbaceous zone. At the 1.0-4.75 m depth, Acacia tortilis water uptake was greater than that of Balanites aegyptiaca over the year (excluding period 3 where both water uptakes were similar) and distinctly larger if water uptake in colonized zones was added (Fig. 4(b)). Respectively, Acacia tortilis and Balanites aegyptiaca removed 2.33 and 0.86 mm day⁻¹ (period 1), 3.44 and 2.26 mm day⁻¹ (period 2), 2.37 and 1.56 mm day⁻¹ (period 3), 0.95 and 0.36 mm day⁻¹ (period 4). Acacia tortilis and Balanites aegyptiaca water uptake during period 1 when available water was not a limiting factor was less than that during period 2 (the 'deferred' season). Root growth begins during period 1, so it is reasonable to assume that period 2 is the time of year with the maximum amounts of absorptive roots. Moreover, water uptake by Acacia tortilis and Balanites aegyptiaca during period 3 (Fig. 4(b)) was still significant even though rainfall had stopped at least 5 months previously. Water uptake estimates were similar in periods 1 and 3 for Acacia tortilis and greater in period 3 than in period 1 for Balanites aegyptiaca.

4.1.3. Stemflow, throughfall and net interception

Stemflow was measured on Acacia tortilis only, and was 2.8% of rainfall. It was assumed that (1) stemflow was slight because of the rough bark of Acacia tortilis and because of the pluviometric régime (stemflow was lower than the error in the rainfall measurements, 5%), (2) Balanites aegyptiaca stemflow is lower than that of Acacia tortilis which has sloping branches and an umbrella shaped crown which will have a promotive effect on stemflow. In contrast, Balanites aegyptiaca's crown is ball shaped on top, and has twisted branches with many ramifications. In 1989, 1990 and 1991, years with similar pluviometric régimes ($Pi_{1989} = 226.5 \text{ mm}$, $Pi_{1990} = 172.0 \text{ mm}$ and $Pi_{1991} = 148.3 \text{ mm}$), the throughfall was 88.8% of Pi in the Acacia tortilis grove and 84.8% of Pi in the Balanites aegyptiaca grove, with the percentages

remaining constant from year to year. Throughfall in the Acacia tortilis grove was larger (4.0% of rainfall) than in the Balanites aegyptiaca grove. This difference can be reconciled where stemflow values are similar, by lower net interception in the Acacia tortilis grove (8.4% of Pi, mean for 3 years) than in the Balanites aegyptiaca grove (12.4% of Pi, mean for 3 years). The differing interception losses occur because Acacia tortilis canopy storage capacity (2.9 mm) is lower than that of Balanites aegyptiaca (3.8 mm). Canopy storage capacities were established using a linear regression between cumulative throughfall and cumulative rainfall: $P_{s \ cumulative} = f(Pi_{cumulative})$. The crowns of the two studied species possess very different morphologies: Acacia tortilis crowns (living branches and leaves) are less 'dense' that those of Balanites aegyptiaca crowns which comprise a tangle of dead and living branches and two types of leaf morphology, i.e. either thorn in shape (vast majority) or flat leaves.

4.2. Impact of land clearance on the thorn scrub water balance

Annually, and for soil depth to 4.75 m taken into account in the water balance equation, daily maximal actual evapotranspiration of the *Acacia tortilis* grove was bigger than that of the *Balanites aegyptiaca* grove which in turn was greater than that of the herbaceous zone (Fig. 4(a)). The difference in daily maximal actual evapotranspiration demonstrates the extravagent water use by *Acacia tortilis* which it achieves by its roots colonizing and exploiting the herbaceous zones (Fig. 5). *Acacia tortilis* roots do not colonize all hebaceous zones in the thorn scrub: Instead an intermediate situation prevails between the two situations shown in Fig. 4(a) and



Fig. 5. Mean daily maximal actual evapotranspiration (mm day⁻¹) of an *Acacia tortilis* grove from 0.00 to 4.75 m soil depth with herbaceous zone from 1.00 to 4.75 m depth, of a *Balanites aegyptiaca* grove from 0.00 to 4.75 m depth, and of a herbaceous zone from 0.00 to 1.00 m depth.

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Fig. 5. According to the terms of the water balance, on an annual average, the herbaceous zone water content was larger than that of the Balanites aegyptiaca grove, which was greater than that of the Acacia tortilis grove. If we set the Acacia tortilis grove's water content against that of the Balanites aegyptiaca grove or herbaceous zone, we must conclude that 'surplus water content' exists in the thorn scrub. Balanites aegyptiaca uses less water than Acacia tortilis; consequently Balanites aegyptiaca will have access to available water during rainless years. In the herbaceous zones, we can assume that this 'surplus water content' could be of use to trees if they were present. In this respect, the 'unused water content' is the difference between the water content of the herbaceous zone and that of the Acacia tortilis grove, and the situation in the dry season provides an estimate of 'unused water content' remaining after the vegetative cycle. Thus, the 'unused water content' was 26.7 mm at the end of the dry season of 1990–1991 (18 July 1991; Pi₁₉₉₀: 172.0 mm) and 28.0 mm at the end of the dry season of 1991–1992 (2 July 1992; Pi_{1991} : 148.3 mm). This amounts to 12.1 and 14.0% of the annual rainfall each year, respectively. The depth in the soil where this 'surplus water content' was located has been defined by comparing the moisture profiles of the two groves with the herbaceous zone moisture profile (Fig. 6(a), (b), (c), end of the dry season of 1990–1991). The surplus water was located at: (1) the herbaceous zone at 1.0-2.0 m and close to 2.5-3.0 m depth (Fig. 6(b)); (2) the Balanites aegyptiaca grove at 0.6-1.2 m and at 2.0-3.5 m depth (Fig. 6(c)), these locations of surplus water being unchanged over the 3 years. Fig. 6(a) clearly illustrates: (1) that Balanites aegyptiaca had few if any, absorptive roots located deeper than 2.0 m (the most important depth for water content): (2) that Acacia tortilis roots colonized the herbaceous zones at 2.0 m depth (water content intermediate between the water content of Balanites aegyptiaca groves and Acacia tortilis groves).

The thorn scrub water balance concerned 1989, 1990, 1991, 3 years with annual rainfall less than the long-term mean, and which included a noticeable decline in the numbers of trees in this thorn scrub. The Acacia tortilis population is subjected to heavy cutting and thus the herbaceous and bare soil areas increase. The studied population basal area, representative of the plant community structure in the region in 1989 (date of fencing off of the study plot) was $3.87 \text{ m}^2 \text{ ha}^{-1}$. However, the Acacia tortilis structure analysis demonstrates that the basal area ought to have been larger without woodcutting (missing circumferences of 1.1, 1.2, 1.6, 1.7 m in the pyramid-shaped diagrams representing circumferences of the Acacia tortilis population; deficient numbers of the circumferences 0.7, 0.9 m). From the herbaceous zone 'unused water content' it is possible to calculate the mean 'unused water content' of the whole thorn scrub and evaluate this in terms of the corresponding Acacia tortilis population. The study plot (1 ha) was divided into 100 units, each unit of 10 m² possessing its characteristic tree basal areas. The 'unused water content' of the herbaceous zone was 26.0-28.0 mm with basal area of 0.0 m^2 per 10 m², and the Acacia tortilis grove's 'unused water content' was 0.0 mm with basal area of 0.14789 m^2 per 10 m². The mean 'unused water content' of the thorn scrub was assessed using a linear regression ['unused water content' = f(basal area)] (using the Acacia tortilis population only): 20.82 mm (208.13 m³.ha⁻¹). Knowing the rain-use efficiency of

woody production (woody biomass produced per millimetre of rainfall) in the Sahelian ecoclimatic zone, $0.3 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1} \text{ mm}^{-1}$ (Bailly et al., 1982; Menault, 1983) or 0.66 to 1.00 kg DM ha⁻¹ year⁻¹ mm⁻¹ (Bille, 1977; Poupon, 1980), this thorn scrub ought to have produced $6.25 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ more wood or 14–21 kg DM ha⁻¹ year⁻¹, as well as 7.4% of the mean annual primary production (186–282 kg DM ha^{-1} year⁻¹ with Pi = 282.4 mm, annual mean). On the other hand, knowing that (1) the 3 year mean actual evapotranspiration of the groves was 165.1 mm year⁻¹ and (2) that the actual thorn scrub tree canopy cover (vertical tree's canopy projection onto the 1 ha soil surface) was 3755 m² ha⁻¹ (37.6%) (Akpo, 1992), one can assess the tree canopy cover of Acacia tortilis which would have actual evapotranspiration equal to the 'unused water content' of the thorn scrub ($455 \text{ m}^2\text{ha}^{-1}$). This tree canopy cover can be transformed based on actual evapotranspiration to tree number, with given height and stem circumference according to published Acacia tortilis allometric relationships: (1) aerial woody biomass plotted against stem diameter at soil level (Poupon, 1980); (2) circumference plotted against tree canopy cover (Akpo, 1992). Using the above relationships, the 'unused water content' corresponds to the annual actual evapotranspiration of ten trees in the grove (6.5 m height, 0.84 m stem circumference). In the radiant energy budget, an increase in tree canopy cover decreased thorn scrub albedo (the evergreen crown albedo is smaller than the grassland albedo, which in turn is smaller than that of dry sand) and promotes an increase of the net amount of radiant energy (that is transformed into other forms of energy, basically into sensible and latent heat). In the energy budget of the thorn scrub, the actual evapotranspiration increase promotes a decrease in sensible heat flux and according to General Circulation Models (GCMs), the increase of the actual evapotranspiration of 20.82 mm per year in this Sahel-Sahelian subzone would result in (1) a mean annual air temperature decrease of 1.5°C (Mylne and Rowntree, 1992) (a decrease in sensible heat flux and surface temperature despite the decrease in albedo; evaporation of 20.82 mm, at 30°C, implies 505.75 MJ m⁻² which is equal to 16.04 W m⁻² of sensible heat over the year) and (2) rainfall increase of 0.52 mm day⁻¹ (Sud and Fennessy, 1982, 1984) or 0.91 mm day⁻¹ (Charney et al., 1977)

5. Conclusions and applications

The maximal daily actual evapotranspiration of *Acacia tortilis* groves was twice the maximal daily actual evapotranspiration of herbs with equal climatic conditions and water inputs into soil. This disparity varies with topography, maximal daily actual evapotranspiration can differ by a factor of ten between the crest and hollow of a dune (Cornet, 1981) due basically to runoff. All plant community units and their features ought to be taken into account in evapotranspiration studies, especially those providing comprehensive data to General Circulation Models (GCMs) which, for example, set up linkages between vegetation removal and climate change in the Sahel. Plant adaptation to drought is an additional complication which requires careful planning prior to sampling in evapotranspiration studies of thorn scrub.



Fig. 6. Soil water content profiles ($cm^3 cm^{-3}$), on 18 July 1991. (a) Acacia tortilis grove, Balanites aegyptiaca grove and the herbaceous zone; (b) Acacia tortilis grove and Balanites aegyptiaca grove with 'surplus water content' zones; (c) Acacia tortilis grove and the herbaceous zone with 'surplus water content' zones.



Fig. 6. (continued).

For example, large differences exist between Acacia tortilis and Balanites aegyptiaca in their characteristic drought adaptations (Fournier, 1993). By the end of the dry seasons of 1991 and 1992, the soil moisture differed between the Acacia tortilis grove and the Balanites aegyptiaca grove in favor of Balanites aegyptiaca. In addition, studing the thorn scrub's evapotranspiration poses two technical problems. Firstly, during the dry season, measuring changes in the water content by neutron probe is difficult because the small water content approximates the resolution of the instrument (standard deviation of the water content measurements at a given depth (± 0.01 cm³ cm⁻³), is similar to the measurement itself (Vachaud et al., 1991) also noted this problem). In this situation the neutron probe technique should be combined with micrometeorological techniques, i.e. Bowen ratio. Secondly, the soil's surface in fenced plots differs from that in the grazed rangeland. To simulate the effects of animals, the soil surface should be weeded before the first rainfall otherwise runoff (because of crusting) will occur in the fenced plots, contrary in the open rangeland where infiltration of rainfall will occur.

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References

- Akpo, L.E., 1992. Influence du couvert ligneux sur la structure et le fonctionnement de la strate herbacée en milieu sahelien. Les détérminants écologiques. Thèse de 3ème cycle, Université Cheikh Anta Diop, Dakar, 174 pp.
- Anonymous, 1988. Introduction au projet 'Ecosystèmes pastoraux sahèliens'. GEMS, série SAHEL, PNUE, Editions FAO, Rome, 146 pp.
- Bailly, C., Barbier, J., Clement, J., Goudet, J.P. and Hamel, O., 1982. The problems of satisfying the demand for wood in the dry regions of tropical Africa: knowledge and uncertainties. CTFT, Nogent-sur-Marne, 24 pp.
- Bille, J.C., 1977. Etude de la production primaire nette d'un écosystème sahélien. Travaux et Documents de l'ORSTOM, no. 65, 81 pp.
- Charney, J.G., Quirk, W.J., Chew, S.M. and Kornfield, J., 1977. A comparative study of the effects of albedo change on drought in semi-arid regions. J. Atmos. Sci., 34: 1360-1388.
- Cole, M.M., 1986. The Savannas. Academic Press, New York, 456 pp.
- Cornet, A., 1981. Le bilan hydrique et son rôle dans la production de la strate herbacée de quelques phytocénoses sahéliennes au Sénégal. Thèse de Docteur-Ingènieur, Université des Sciences et Techniques du Languedoc, Montpellier, 354 pp.
- Fournier, Ch., 1993. Fonctionnement hydrique de six espèces ligneuses coexistant dans une savane sahélienne (Region du Ferlo, Nord-Sénégal), Thèse de Doctorat, Université de Paris-Sud, Orsay, 130 pp.
- Lamachère, J.M., 1991. Aptitude au ruissellement et á l'infiltration d'un sol sableux fin après sarclage. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and C. Giraux (Editors), Soil Water Balance in the Sudano-Sahelian Zone. Proc. Niamey Workshop, IAHS Publ. no. 199, pp. 109–119.
- Le Houérou, H.N., 1989. The Grazing Land Ecosystems of the African Sahel. Ecological studies, Vol. 75. Springer, Berlin, 282 pp.
- Mariaux, A., 1975. Essai de dendroclimatologie en climat sahélien sur Acacia raddiana. Bois For. Trop., 163: 27–35.
- Marshall, T.J. and Holmes, J.W., 1988. Soil Physics, 2nd edition. Cambridge University Press, Cambridge, 374 pp.
- Massman, W.J., 1992. A surface energy balance method for partitioning evapotranspiration data into plant and soil components for a surface with partial canopy cover. Water Resour. Res., 28: 1723-1732.
- Menault, J.C., 1983. Structure et production de peuplements de ligneux fourragers. In: B. Toutain et al. (Editors), Espèces ligneuses et herbacées dans l'écosystèmes de Haute-Volta. GERDAT-IEMVT-ENS-CNRS-IRBET, Paris, pp. 17–55.
- Monteith, J.L. 1965. Evaporation and environment. In: G.E. Fogg (Editor), The Stage and Movement of Water in Living Organisms. 19th Symp. Soc. Exp: Biol., The Company of Biologists, Cambridge University Press, Cambridge, pp. 205–234.
- Monteith, J.L., 1981. Evaporation and surface temperature. Q. J. R. Meteorol. Soc., 107: 127.
- Mylne, M.F. and Rowntree, P.R., 1992. Modelling the effects of albedo change associated with tropical deforestation. Climat. Change, 21: 317-343.
- Nizinski, J. and Saugier, B., 1989. A model of transpiration and soil water balance for a mature oak forest. Agric. For. Meteorol., 47: 1–17.
- Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. London, Ser. A, 193: 120–145.
- Poupon, H., 1980. Structure et dynamique de la strate ligneuse d'une steppe sahélienne au nord du Sénégal. Collection Etudes et Thèses, Editions de l'ORSTOM, Paris, 317 pp.
- Shuttleworth, W.J. and Wallace, J.S., 1985. Evaporation from sparse crops. An energy balance combination theory. Q. J. R. Meteorol. Soc., 111: 839–855.
- Sivakumar, M.V.K. and Wallace, J.S., 1991. Soil water balance in the Sudano-Sahelian zone. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and C. Giraux (Editors), Soil water balance in the Sudano-
- Sahelian zone. Proceedings of the Niamey Workshop, IAHS Publ. no. 199, pp. 3–10.

- Sud, Y.C. and Fennessy, M., 1982. A study of the influence of surface albedo on July circulation in semiarid regions using the GAS GCM. J. Climatol., 2: 105-125.
- Sud, Y.C. and Fennessy, M., 1984. A numerical study of the influence of evaporation in semi-arid regions on July circulation. J. Climatol., 4: 383-398.
- Thom, A.S., 1971. Momentum absorption by vegetation. Q. J. R. Meterol. Soc., 97: 414-428.
- Vachaud, G., Vauclin, M. and Cissé, L., 1991. Mesure in situ de la consommation en eau de culture pluviales par humidimétrie neutronique. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and C. Giraux (Editors), Soil Water Balance in the Sudano-Sahelian Zone. Proc. Niamey Workshop, IAHS Publ. no. 199, pp. 275-288.
- Van Bavel, C.H.M., 1966. Potential evaporation: the combination concept and its experimental verification. Water Resour. Res., 2: 455-467.



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