



The influence of tree thinning on the soil water in a semi-arid savanna of southern Africa

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(Received 17 June 1998, accepted 23 July 1999)

The investigation was conducted on an area covered by a dense stand of *Hardwickia mopane* (Leguminosae: Caesalpinioideae). Seven plots (65 × 180 m) were subjected to different intensities of tree thinning, ranging from a totally cleared plot (0%) to plots thinned to the equivalent of 10, 20, 35, 50, and 75% of the leaf biomass of a control plot (100%) with a tree density of 2711 plants ha⁻¹. Thinning was completed during 1989 and the soil water study was conducted during the 1990/91 and 1991/92 seasons with the aid of a neutron water meter. The study area, before thinning, was characterized by the virtual absence of herbaceous plants with severe soil degradation in the form of surface erosion and crust formations. Increased infiltration of rainwater was measured in the thinned plots and this was associated with the establishment of herbaceous plants, mainly grasses. The soil water was predominantly held at a very shallow depth (<450 mm) and only in the totally cleared (0%) plot did the soil water content of the >450–900 mm soil zone show marked increases associated with specific rainfall events. Mean evapotranspiration water losses varied seasonally, but were generally much higher in the 0% plot (grass only plot), which confirmed that grasses use soil water more rapidly than the *H. mopane* trees. Evidence is presented that the roots of the *H. mopane* trees are able to utilize soil water at a matric potential lower than that of grasses ($\psi < -1500$ kPa). This enables the *H. mopane* trees to compete successfully with herbaceous plants and to prevent their establishment at high tree densities.

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Keywords: bush encroachment; competition; evapotranspiration; infiltration; *Hardwickia mopane*; rainwater runoff; water use efficiency

Introduction

Water is the main driving force of semi-arid ecosystems (Snyman *et al.*, 1987; Snyman & Fouché, 1991). In semi-arid savanna ecosystems, it is generally accepted that the suppressive effect of an increase in woody plant density (bush encroachment) on herbaceous plants (mainly grasses) is largely through competition for soil water (Dye & Spear, 1982; Moore *et al.*, 1988). The southern African Mopani veld (Acocks, 1988), dominated by the tree species *Hardwickia mopane* Kirk ex J. Léonard (Kirk ex Benth)

(Leguminosae: Caesalpinioideae), is a water limited ecosystem. It is an important savanna veld type of southern Africa, and the total area in southern Africa under *H. mopane* vegetation types is estimated at 555,000 km² (Mapaure, 1994). Bush encroachment is considered to be a major factor contributing to the low grazing capacity of this veld type (Donaldson, 1980; Gammon, 1984). The selective removal of plants, Mopani trees in this case, would invariably influence the soil water regime. An understanding of the exact nature and magnitude of such influences is an important pre-requisite towards the understanding of the complex biological interactions which exist in these ecosystems.

As part of a comprehensive investigation into the effect of tree thinning on the southern African Mopani veld, the objectives of this study were to determine the influence of intensity of tree thinning on, (1) the redistribution of soil water; (2) incidental and evapotranspiration water losses; (3) the number of potential plant growth days; and (4) the comparative water use efficiency of *H. mopane* and herbaceous plants (grasses).

Material and methods

Study area

The study was conducted in the Northern Province of South Africa on a site located at 29°12'E, 22°19'S, and at 560 m above sea level. The savanna vegetation is described as the so-called Mopani veld (Acocks, 1988). Louw (1970) made a further division of seven plant communities within the South African Mopani veld, and the study area was located in what he named the *Colophospermum-Boscia* community. *Hardwickia mopane* was previously known as *Colophospermum mopane*. This community covers about 60,000 ha of the Mopani veld. Louw (1970) described this community as a virtually pure stand of *H. mopane*, interposed with few individuals of *Boscia foetida* subsp. *rehmanniana* and *Salvadora angustifolia*. Within the study area the most important grass species are *Enneapogon cenchroides*, *Aristida adscensionis*, *Brachiaria deflexa*, *Cenchrus ciliaris*, and *Digitaria eriantha*.

The rainy season usually extends from October to March inclusive, but rainfall is irregularly distributed and unpredictable. Mean long-term seasonal rainfall (July-June) for the period 1966/67 to 1989/90 was 376 mm (S.E. \pm 27.6, range 140–620 mm). The probability of rain is at its greatest during January. The area is largely frost free, and is well known for its high summer temperatures and moderate to warm winter temperatures.

The underlying rock type is mainly sandstone (Louw, 1970). A description of the soil is presented in Table 1.

Trial layout

The study area consisted of seven, 1.17 ha plots (180 \times 65 m), thinned to differing tree densities. The plots were adjacently located on a homogeneous area of 8.2 ha. Treatments were allocated randomly to the plots and not in a numerical order. The control plot was left undisturbed (referred to as the 100% plot), and the others thinned to the approximate equivalents of 75, 50, 35, 20, 10, and 0% (total clearing) of the tree biomass of that of the 100% plot. The control plot yielded a dense stand of *H. mopane* with herbaceous plants almost completely absent. Thinning was completed during the winter of 1989 and the tree densities (trees ha⁻¹) were as follows: 100% (control) plot = 2711; 75% plot = 1978; 50% plot = 1233; 35% plot = 744; 20% plot = 589; 10% plot = 300 and 0% = 0 trees ha⁻¹.

Table 1. Description of the soil of the study area from two representative sites

Soil variable	Profile 1	Profile 2
<i>Soil depth</i> (mm):		
A horizon	0–230	0–200
B1 horizon	230–520	200–400
B2 horizon	520–1200 +	400–1200 +
<i>Sand: silt: clay</i> (%):		
A horizon	81: 7: 12	80: 8: 12
B1 horizon	75: 7: 18	75: 7: 18
B2 horizon	59: 9: 32	65: 8: 27
Colour	Red (2.5YR3/4)	Red (5YR4/6)
Soil form (MacVicar <i>et al.</i> , 1977)	Hutton	Hutton
Soil series (MacVicar <i>et al.</i> , 1977)	Shigalo	Shigalo

Trees were randomly marked for removal during the thinning process. This ensured a fairly even spread of the remaining trees without favouring a particular tree size. The resultant thinned plots resembled the structure of naturally occurring open stands of *H. mopane*. During thinning, trees were sawn off at ground level and removed from the plot. The stumps were sprayed with a 1% concentration of picloram and triclopyr mixed in diesel, thus ensuring that the sawn trees were killed without affecting the remaining plants. The study area was fenced to exclude all grazing or browsing animals.

Soil water study

The soil water study was conducted during the 1990/91 and 1991/92 seasons with the aid of a neutron water meter (CPN model 503 DR). Ten access tubes were assigned to each experimental plot (total of 70 tubes), randomly installed to a depth of 1.0 m within a transect of 5 × 180 m located in the centre of each experimental plot. Soil water measurements were conducted at six different depths (measuring zone in brackets): 75 mm (0–150 mm), 225 mm (>150–300 mm), 375 mm (>300–450 mm), 525 mm (>450–600 mm), 675 mm (>600–750 mm), and 825 mm (>750–900 mm).

Soil water measurements were taken as soon as possible after a precipitation event had occurred. Measurements were normally taken on 3 to 5 successive days after such an event, whereafter the measurements were taken at increasing intervals (Table 2).

Calibration of the neutron water meter was conducted on a representative site next to the study area in accordance with the guidelines given by Karsten & Haasbroek (1973), Karsten & Van der Vyver (1979), Van der Westhuizen *et al.* (1981), and Snyman *et al.* (1987).

Plant measurements

At the end of each growing season, normally April or May, the spatial canopy of all rooted live *H. mopane* trees encountered in fixed transects (5 × 180 m) located in the middle of each of the experimental plots, was measured. The measurements consisted of the following: (1) maximum tree height; (2) height where the maximum canopy diameter occurs; (3) height of first leaves or potential leaf bearing stems; (4) maximum

Table 2. Daily rainfall records (as measured at 7·00 am) for the duration of the soil water study, with indication of the days when measurements were taken (✓) with the neutron water meter (NWM)

Date	Rain (mm)	NWM	Date	Rain (mm)	NWM	Date	Rain (mm)	NWM
23/11/90	1·0	—	27/02/91	—	✓	17/11/91	—	✓
24/11/90	25·0	—	12/03/91	9·5	—	18/11/91	—	✓
26/11/90	—	✓	14/03/91	—	✓	19/11/91	—	✓
27/11/90	—	✓	15/03/91	24·0	—	20/11/91	—	✓
28/11/90	—	✓	16/03/91	3·0	—	21/11/91	—	✓
29/11/90	—	✓	17/03/91	12·0	—	22/11/91	17·8	✓
30/11/90	—	✓	19/03/91	38·1	✓	23/11/91	—	✓
01/12/90	—	✓	20/03/91	—	✓	24/11/91	—	✓
03/12/90	0·3	✓	21/03/91	—	✓	25/11/91	—	✓
04/12/90	7·8	✓	22/03/91	10·1	✓	26/11/91	—	✓
05/12/90	—	✓	23/03/91	—	✓	27/11/91	—	✓
06/12/90	17·4	✓	24/03/91	—	✓	28/11/91	—	✓
07/12/90	18·4	✓	25/03/91	8·0	✓	29/11/91	—	✓
09/12/90	2·6	—	26/03/91	10·0	✓	30/11/91	—	✓
10/12/90	—	✓	25/04/91	—	✓	01/12/91	—	✓
11/12/90	—	✓	07/05/91	37·0	—	02/12/91	—	✓
12/12/90	—	✓	13/05/91	21·0	—	03/12/91	—	✓
13/12/90	—	✓	14/05/91	—	✓	04/12/91	—	✓
14/12/90	—	✓	15/05/91	—	✓	05/12/91	—	✓
17/12/90	—	✓	16/05/91	—	✓	06/12/91	—	✓
18/12/90	9·1	✓	17/05/91	—	✓	08/12/91	7·5	—
19/12/90	2·2	✓	21/05/91	—	✓	10/12/91	—	✓
20/12/90	9·8	✓	22/05/91	—	✓	11/12/91	—	✓
21/12/90	—	✓	23/05/91	—	✓	12/12/91	—	✓
27/12/90	—	✓	24/05/91	—	✓	09/01/92	—	✓
01/01/91	7·0	—	12/06/91	—	✓	17/01/92	16·0	—
08/01/91	—	✓	02/07/91	—	✓	20/01/92	5·0	—
10/01/91	34·0	—	16/07/91	—	✓	23/01/92	2·5	—
12/01/91	—	✓	01/08/91	—	✓	03/02/92	46·0	—
13/01/91	—	✓	15/08/91	—	✓	05/02/92	—	✓
14/01/91	1·7	✓	04/09/91	—	✓	06/02/92	—	✓
15/01/91	2·5	✓	18/09/91	—	✓	07/02/92	—	✓
17/01/91	—	✓	01/10/91	25·9	—	08/02/92	—	✓
20/01/91	33·0	—	02/10/91	—	✓	09/02/92	—	✓
22/01/91	—	✓	03/10/91	—	✓	10/02/92	—	✓
23/01/91	—	✓	04/10/91	—	✓	11/02/92	—	✓
24/01/91	24·1	✓	05/10/91	—	✓	20/02/92	—	✓
25/01/91	—	✓	06/10/91	—	✓	02/03/92	3·5	—
31/01/91	14·1	✓	07/10/91	—	✓	03/03/92	—	✓
01/02/91	—	✓	08/10/91	—	✓	15/03/92	20·0	—
14/02/91	—	✓	17/10/91	—	✓	25/03/92	—	✓
18/02/91	30·9	—	24/10/91	—	✓	14/04/92	—	✓
19/02/91	7·1	✓	07/11/91	—	✓	07/05/92	—	✓
20/02/91	—	✓	14/11/91	20·3	—	20/05/92	—	✓
21/02/91	—	✓	15/11/91	49·5	✓			
22/02/91	—	✓	16/11/91	—	✓			

canopy diameter; and (5) base diameter of the foliage at the height of the first leaves. The spatial canopy volume of each tree was calculated from these measurements (Smit, 1989a, b).

Leaf dry mass and leaf volume estimates were calculated using a modified version of the quantitative description technique of Smit (1989a, b) as described by Smit (1994). This technique provides estimates of the leaf dry mass and leaf volume at peak biomass, based on the relationship between the tree's spatial canopy volume and its leaf dry mass and leaf volume. This technique was compiled into the BECVOL-model (Biomass Estimates from Canopy Volume) (Smit, 1994), and it incorporates regression equations, developed from harvested trees, which relates spatial canopy volume (independent variable) to leaf dry mass (dependant variable): $\ln y = -4.165 + 0.711x$, $r = 0.975$, $p < 0.001$, and leaf volume (dependant variable): $\ln y = -3.196 + 0.728x$, $r = 0.975$, $p < 0.001$. Spatial tree canopy volume (x) was transformed to its normal logarithmic value, while y represents the estimated leaf dry mass (g) and leaf volume (cm^3) respectively. The number of Evapotranspiration Tree Equivalents (ha^{-1}) were subsequently calculated from the leaf volume estimates ($1 \text{ ETTE} = \text{mean leaf volume of a single-stemmed tree with a height of } 1.5 \text{ m} = 500 \text{ cm}^3 \text{ leaf volume}$) (Smit, 1989a).

Above-ground dry matter (DM) yield of herbaceous plants (mainly grasses and a few forbs) within each plot was determined at the end of each growing season, normally April or May. A harvest technique (Grunow *et al.*, 1980; Catchpole & Wheeler, 1992) was employed. Herbaceous plants were randomly harvested in 60 quadrats (0.25 m^2) per plot. Rooted herbaceous plants within each quadrat were clipped with hand clippers to a height of 0.1–3.0 cm, depending on whether the species was tufted or not. The clipped material was dried to a constant mass (70°C) and weighed.

The frequency of bare soil patches was estimated, using the wheel point apparatus (Tidmarsh & Havenga, 1955). Four hundred point-observations per treatment were recorded. A bare soil patch was recorded if no herbaceous plant occurred within a radius of 30 cm of the point. Surveys were done at the end of each growing season, normally April or May. It was shown by Hardy & Walker (1991), using the Richards function (Richards, 1959), that a sample size of 400 point-observations is adequate for detailed scientific studies.

Data analyses and calculations

Since the soil water measurements were fragmented, a complete day to day account of the soil water changes over the trial period was not possible. To quantify the soil water dynamics within each experimental plot, it was necessary to determine basic data values from the succession of water readings recorded. To enable conclusions to be drawn on different aspects of the general hydrology and water use, data was either used from all measurements taken over the experimental period (114 days, 47,880 individual readings), or alternatively only data of specific periods (normally a number of days with continuous soil water measurements).

All the measurements taken over the experimental period (duration of 542 days) were used for the assessment of the redistribution of soil water. The soil water content, expressed as θV , was calculated for each soil depth zone. These values were calculated as the mean of the 10 measuring sites within each plot and plotted over time.

The water content of the soil profile was calculated with the following equation:

$$W = (\theta V_1 + \theta V_2 + \theta V_3 + \theta V_4 + \theta V_5 + \theta V_6)x,$$

where W = total water content of soil profile, θV = volumetric percentage soil water ($1..6$ = values of each of the six soil depth zones), and x = factor for measuring interval (150 mm interval = 1.5) (Moore *et al.*, 1988).

These data were used for the assessment of incidental and evapotranspiration water losses, as well as estimates of the number of potential plant growth days. Incidental water losses were considered losses due to rainfall interception by plant canopies, especially woody plants (Pressland, 1973; Jackson, 1975; Rutter & Morton, 1977; Aston, 1979; Tromble, 1988), as well as rainfall runoff losses. These water losses are generally considered as part of the evapotranspiration process, but are here considered separately since they occur incidentally during specific precipitation events and their consequences are potentially extensive. These assessments were carried out by comparing, by subtraction, the change in soil water content immediately before and after a rain shower (>10 mm) that has occurred in relation to the size of the rain shower, expressed as a percentage of the rain shower.

The determinants of these incidental water losses were evaluated using regression analysis (Statgraphics, 1991). The leaf volume of the *H. mopane* trees (calculated with the BECVOL-model), expressed as Evapotranspiration Tree Equivalents (ETTE ha⁻¹), and percentage bare soil patches were included as possible determinants. Estimates of the daily evapotranspiration was based on an equation which quantifies the soil water balance (Hillel, 1971):

$$\Delta W = I + P \pm R \pm D - (E + T),$$

where ΔW = change in soil water content, I = irrigation, P = precipitation, R = runoff (loss or gain), D = drainage (loss or gain), and $E + T$ = evaporation + transpiration = evapotranspiration (Et).

No irrigation was applied, therefore the variable I doesn't apply to this study. An argument for the inclusion of a separate subtraction variable for rainfall interception by tree canopies could be presented. However, excluding the water channelled down the tree via stem flow, rainwater retained on the tree eventually evaporates. These losses can subsequently be accounted for by variable E . Water losses due to drainage (D) were negligible since the water content of the soil profile never exceeded the field capacity of the soil profile. A shallow water table was absent and water gains due to upward capillary movement did not occur. Due to the virtual absence of herbaceous vegetation in the densely wooded plots, as well as the presence of crust formations on the soil surface, it was expected that water losses due to runoff (R) will be substantial. Crust formations are known to reduce infiltration and cause substantial losses due to runoff (Hillel & Gardner 1970; Agassi *et al.*, 1981; Ralph, 1989; Harmse & Nel, 1990). By definition, the soil of the study area can be considered as having a high runoff potential (Schulze, 1985).

Runoff losses were restricted to rainy days, since water that did not infiltrate disappeared quickly and water retained on tree canopies evaporated. Losses during subsequent days comprised mainly evaporation directly from the soil surface and transpiration by the plants (herbaceous and woody plants). It follows that estimates of Et losses for the study area can be simplified to:

$$(1) Et \text{ on rainy days} = (P \pm R) - \Delta W;$$

$$(2) Et \text{ on non-rainy days} = \Delta W = W_{\text{day } 2} - W_{\text{day } 1} \text{ (mm water).}$$

The comparison of Et losses was restricted to non-rainy days since a comprehensive account of R could not be made.

For the interpretation of the soil water contents in terms of plant growth, the soil water content at any particular time was evaluated in terms of field capacity (FC), wilting point (WP), and plant available water (PAW = FC - WP) (Schulze *et al.*, 1985). Schulze *et al.* (1985) defined the wilting point as the dry limit for water available to plants, a stage at which the hydraulic conductivity is so slow that water cannot move over even short distances to the roots to satisfy the transpirational demand. The matric potential (ψ) at this point is usually accepted to be -1500 kPa (Schulze *et al.*, 1985), but may vary

between species. The specific matric potential for *H. mopane* was not known and the value of -1500 kPa was subsequently used as a point of departure.

From the calibration procedure it was determined that at FC, the soil of the study area had a mean θV of 22.1% (S.E. ± 0.971), calculated from the θV of each soil depth zone at FC: 18.94% (0–150 mm), 20.33% (>150–300 mm), 22.26% (>300–450 mm), 23.72% (>450–600 mm), 25.62% (>600–750 mm), and 21.73% (>750–900 mm). These θV -values, substituted in the given equation, represented a water content (W) of 221.0 mm H_2O m^{-1} for the soil profile at FC. The wilting point (WP) for the soil of the study area was estimated from a soil water retention model proposed by Hutson (1984). This model is based on percentages of clay and silt together with bulk density:

$$O_{\psi} = \beta_1 + \beta_2 Cl + \beta_3 Si + \beta_4 Pb,$$

where O_{ψ} = water retention in mm mm^{-1} for a given matric potential, $\psi = -5$ to -30 kPa at field capacity and -1500 kPa at wilting point, Cl = clay percentage, Si = silt percentage, Pb = bulk density in mg m^{-3} , and β_{1-4} = regression coefficients: (-30 kPa: $\beta_1 = -0.0150$, $\beta_2 = 0.00384$, $\beta_3 = 0.00572$, $\beta_4 = 0.0463$; and -1500 kPa: $\beta_1 = 0.0602$, $\beta_2 = 0.00322$, $\beta_3 = 0.00308$, $\beta_4 = -0.0260$).

The soil water was largely stratified between two soil depth zones (0–450 mm and >450–900 mm) (see results). The former equation was thus applied to each of these zones separately. The mean percentage clay and mean percentage silt for the soil profile were taken from Table 1. The soil of the study area had a mean bulk density of 1.62 mg m^{-3} (S.E. ± 0.02) and the mean bulk density for the two stratified soil zones were calculated as 1.68 mg mm^{-3} (0–450 mm), and 1.60 mg m^{-3} (>450–900 mm) (Smit, 1994).

Substitution of these values in the former equation of Hutson (1984) provided a WP estimate of (1) 0–450 mm: 0.09 mm mm^{-1} (equivalent to 40.5 mm H_2O to a soil depth of 450 mm), and (2) >450–900 mm: 0.15 mm mm^{-1} (equivalent to 67.5 mm H_2O for this 450 mm soil zone). The soil water data were analysed in terms of number of days that the soil water content exceeded the estimated WP, with estimates of PAW, in the different experimental plots. For this analysis data were used only for the days that actual measurements were conducted (114 days) (Table 2).

Since a full account of the Et losses was not possible, the water use efficiency (WUE) was assessed (following Moore *et al.*, 1988) in terms of leaf dry mass production of the *H. mopane* trees, grass dry mass production, and combined leaf and grass dry mass production in the various plots as a function of the total seasonal rainfall.

Determinants of the WUE were assessed using stepwise multiple regression analyses (Statgraphics, 1991). Since correlated variables should not be used in multiple regression analyses, a test for possible co-linearity between the dependant variables was carried out using Principle Component Analysis (PCA) (Statgraphics, 1991).

Results and discussion

Plant measurements

Reduced competition after tree thinning resulted in colonization of bare soil by herbaceous plants, with a subsequent reduction in the percentage of bare soil patches (Table 3), and a corresponding increase in herbaceous (mainly grasses) dry matter production (Table 4). The estimated number of Evapotranspiration Tree Equivalents (ETTE) ha^{-1} of the *H. mopane* trees over the trial period is presented in Table 3 and the leaf dry mass production ha^{-1} is presented in Table 4. The purpose of the vegetation surveys was primarily aimed at obtaining some quantitative data of vegetation change to relate to some aspects of the soil water study. Detailed results and a discussion of the

Table 3. *The estimated number of Evapotranspiration Tree Equivalents (ETTE) ha⁻¹ of the Hardwickia mopane trees and the percentage bare soil patches (areas 60 cm in diameter with no herbaceous plant) over the trial period*

Season	Experimental plot (%)	ETTE ha ⁻¹	Bare soil patches (%)
1990/91	0	0	18.3
„	10	809.9	37.3
„	20	1885.5	38.0
„	35	2136.1	46.3
„	50	3503.3	67.3
„	75	3769.3	69.0
„	100	5962.3	71.7
1991/92	0	0	13.0
„	10	998.4	30.7
„	20	2171.8	43.3
„	35	2540.8	59.0
„	50	3870.8	76.0
„	75	4197.2	83.0
„	100	6733.0	89.3

vegetation changes and dynamics are subsequently reported elsewhere (Smit, 1994; Smit & Rethman, 1998a).

Redistribution of soil water

Results of the redistribution of the soil water at the extreme ends of the tree density gradient are presented graphically in Fig. 1 (0% plot) and Fig. 2 (100% plot). The redistribution patterns within the other five plots followed a linear response between those at the extremes. These figures represent the full duration of the soil water study (542 days), including days when no soil water measurements were taken. It must therefore be noted that the true soil water content of those days not measured will be masked by the straight lines that joined known data values, and that these graphs must serve as a measure of comparison between plots.

Fluctuations in daily soil water content were greatest in the topsoil (0–150 mm), and fluctuations decrease as soil depth increases (Figs. 1 & 2). In general, very little soil water managed to reach the soil layers beyond 450 mm. Only in the 0% plot did the soil water content of the >450–900 mm soil zone show marked increases associated with specific rainfall events (Fig. 1(b), Table 2). In relation to increasing *H. mopane* densities, soil water penetration occurred to shallower depths. Since very little, if any, soil water appeared to be available in deeper soil layers at high tree densities, the shallow, extensive horizontal spread of the *H. mopane* roots (Smit & Rethman, 1998b) proved to be essential for the survival of *H. mopane* under these circumstances.

The water content of the soil of the 100% plot (Fig. 2) suggests high rainwater losses (runoff plus interception), as expected for plots with a high tree density and poor grass cover, compared to plots with a low tree density and some grass cover. In addition, it presents evidence suggesting that soil water extraction within the 0–300 mm soil zone by the roots of the *H. mopane* trees occurred at a rate fast enough to prevent soil water from reaching deeper soil layers. In the grass only plot (0% plot), some water did manage to reach deeper soil layers, but the considerable difference between the water content of the >300–450 mm and the >450–600 mm soil zones (Fig. 1) indicates that grasses predominantly utilize water within the top 450 mm.

Table 4. Water use efficiency (WUE) (based on total seasonal rainfall and not actual evapotranspiration) expressed in terms of leaf dry mass production of the *Hardwickia mopane* trees, grass dry mass production and combined leaf and grass dry mass production in the various experimental plots for the 1990/91 and 1991/92 seasons

Season (rainfall)	Exp. plot (%)	Dry mass production (kg ha ⁻¹)			WUE (kg ha ⁻¹ mm ⁻¹)		
		Leaves	Grass	Combined	Leaves	Grass	Combined
1990/91	0	0	1106	1106	0	2.51	2.51
(440 mm)	10	209	842	1051	0.48	1.91	2.39
„	20	486	849	1335	1.10	1.93	3.03
„	35	551	442	993	1.25	1.00	2.26
„	50	903	410	1313	2.05	0.93	2.98
„	75	972	176	1148	2.21	0.40	2.61
„	100	1537	125	1662	3.49	0.28	3.78
1991/92	0	0	1055	1055	0	4.73	4.73
(223 mm)	10	257	459	716	1.15	2.06	3.21
„	20	560	355	915	2.51	1.59	4.10
„	35	655	230	885	2.94	1.03	3.97
„	50	998	81	1079	4.48	0.36	4.84
„	75	1082	38	1120	4.85	0.17	5.02
„	100	1736	50	1786	7.78	0.22	8.01

In view of the theory proposed by Walker *et al.* (1981) that stratification of soil water between the topsoil and subsoil may lower competition between woody plants and grasses (since woody plants presumably have exclusive use of subsoil water), it is significant to note that no such spatial separation of soil water existed in the study area.

This would invariably mean that the *H. mopane* trees and grasses are in direct competition for soil water, and that the *H. mopane* trees at high densities utilize the available soil water to such an extent as to prevent the establishment or survival of grasses.

Incidental and evapotranspiration water losses

Some indication of the magnitude of incidental rainwater losses (predominantly surface runoff, but also interception by tree canopies), can be assessed from the results presented in Fig. 3. Unfortunately, data that met the set criteria for these estimates come down to only five rain showers (>10 mm). These incidental water losses were responsible for a lowering of the effective rainfall, and establish themselves as important determinants of the soil water content of this vegetation and soil type.

Subjective observation has shown that the 0 and 20% plots, due to the nature of their location, may have received additional water from surface runoff from neighbouring plots. This was, however, confined to large rain showers of high intensity. A higher grass cover, in turn, lowered runoff water losses. Evapotranspiration Tree Equivalents (ETTE ha⁻¹) (as a measure of tree density) explained only 44.13% of the incidental water losses, and this relation was statistically non-significant ($p = 0.103$). The percentage bare soil patches (Table 3) accounted for 64.95% of the incidental water losses, and this relation was statistically significant ($p = 0.029$). This relation was best described by the linear regression equation: $y = 14.3486 + 0.8205x$ ($p < 0.05$), where y = incidental water losses in mm, and x = the percentage of bare soil patches. This regression equation predicted a mean incidental water loss of 0.82% for

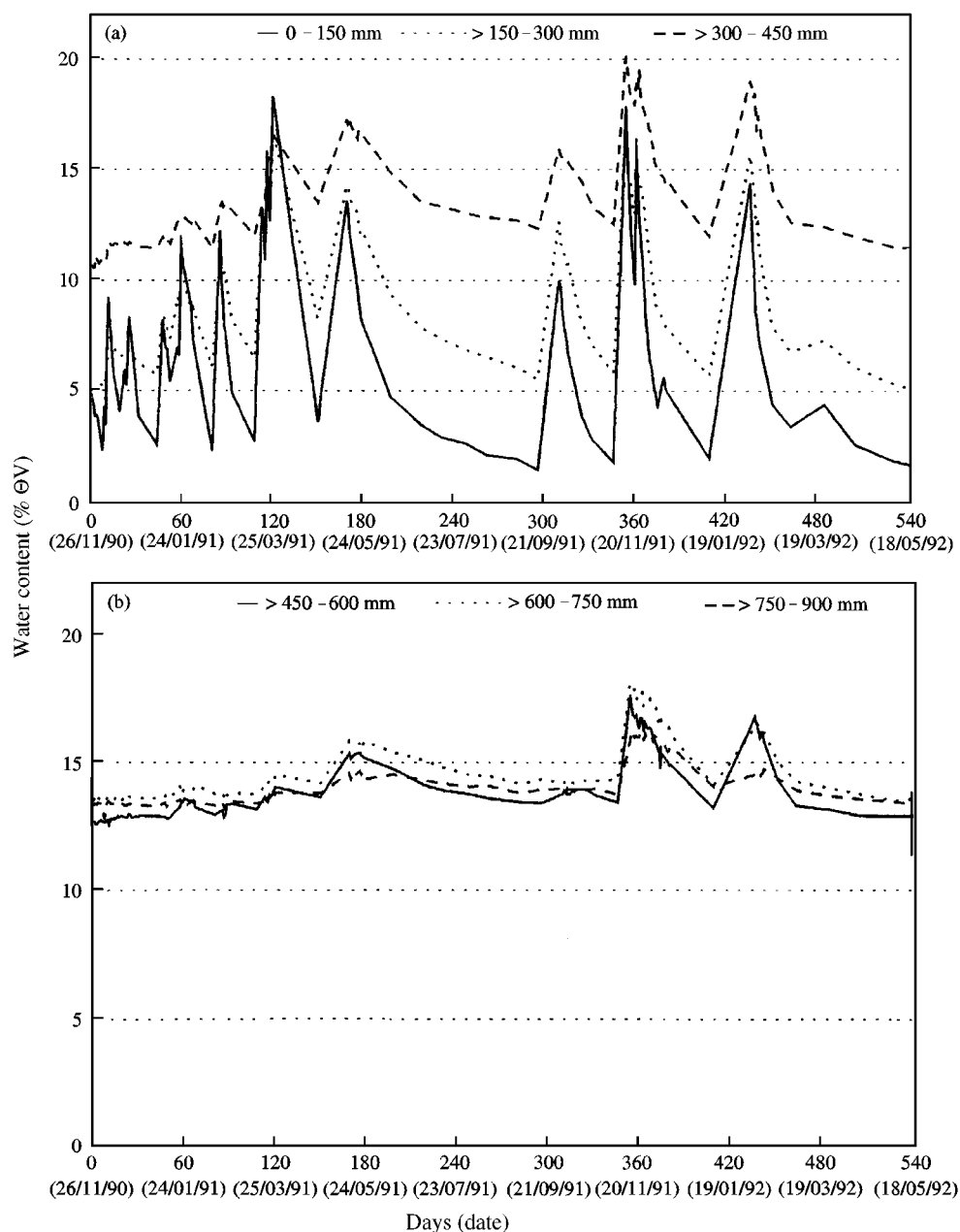


Figure 1. Soil water redistribution in the soil profile of the 0% plot: (a) soil depth zones 0–450 mm, and (b) soil depth zones >450–900 mm. The redistribution patterns within the other plots followed a linear response between the 0% and 100% plot.

every 1% reduction in herbaceous ground cover, to a mean minimum of 14.35% at zero bare soil. These results are in accordance with the report by Snyman & Van Rensburg (1986) who concluded that grass basal cover had the greatest influence on runoff water losses.

The mean evapotranspiration (Et) water losses from the soil profiles of the various experimental plots during specific periods of the trial period are presented in Fig. 4.

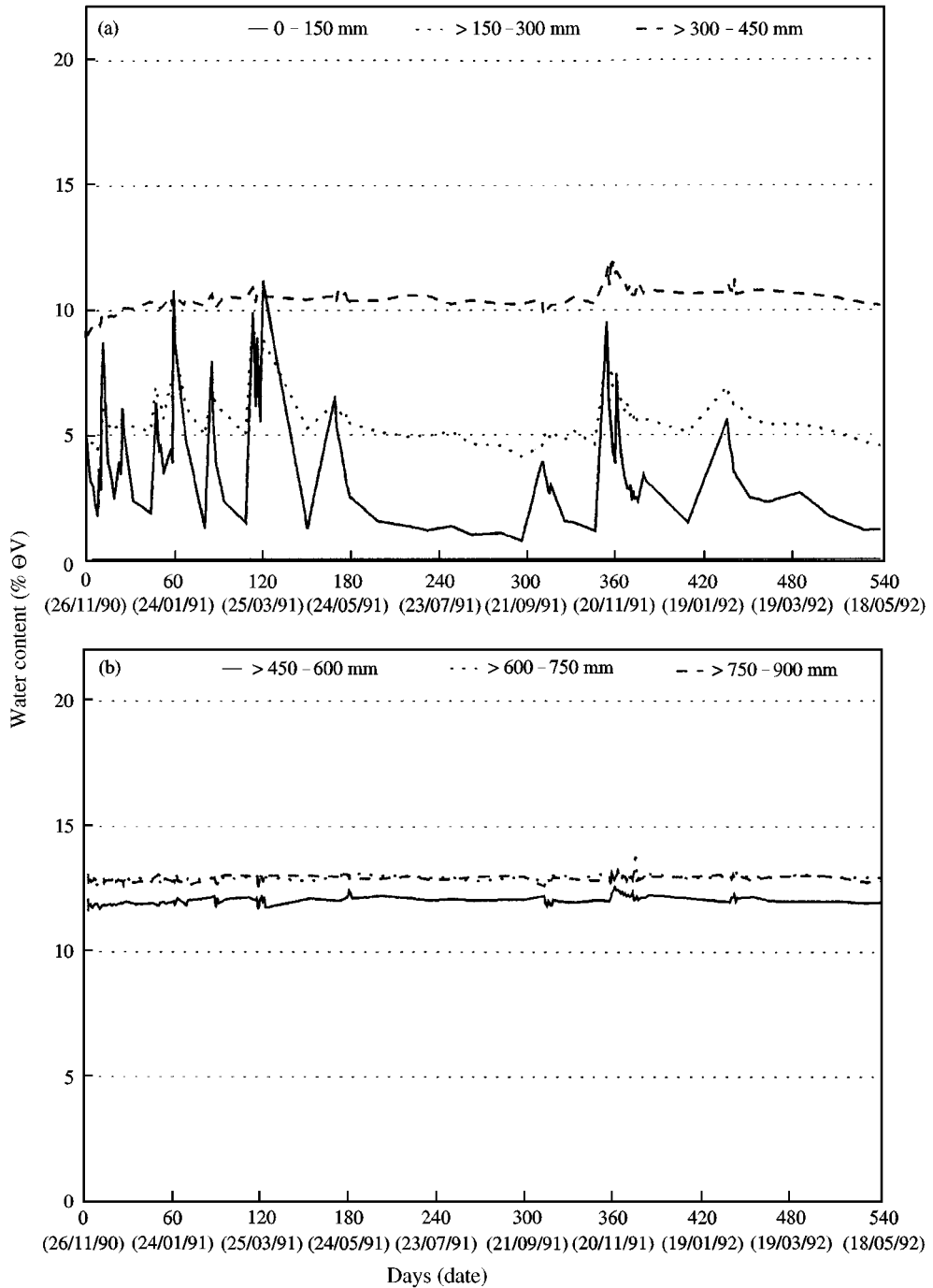


Figure 2. Soil water redistribution in the soil profile of the 100% plot: (a) soil depth zones 0–450 mm, and (b) soil depth zones >450–900 mm. The redistribution patterns within the other plots followed a linear response between the 0% and 100% plot.

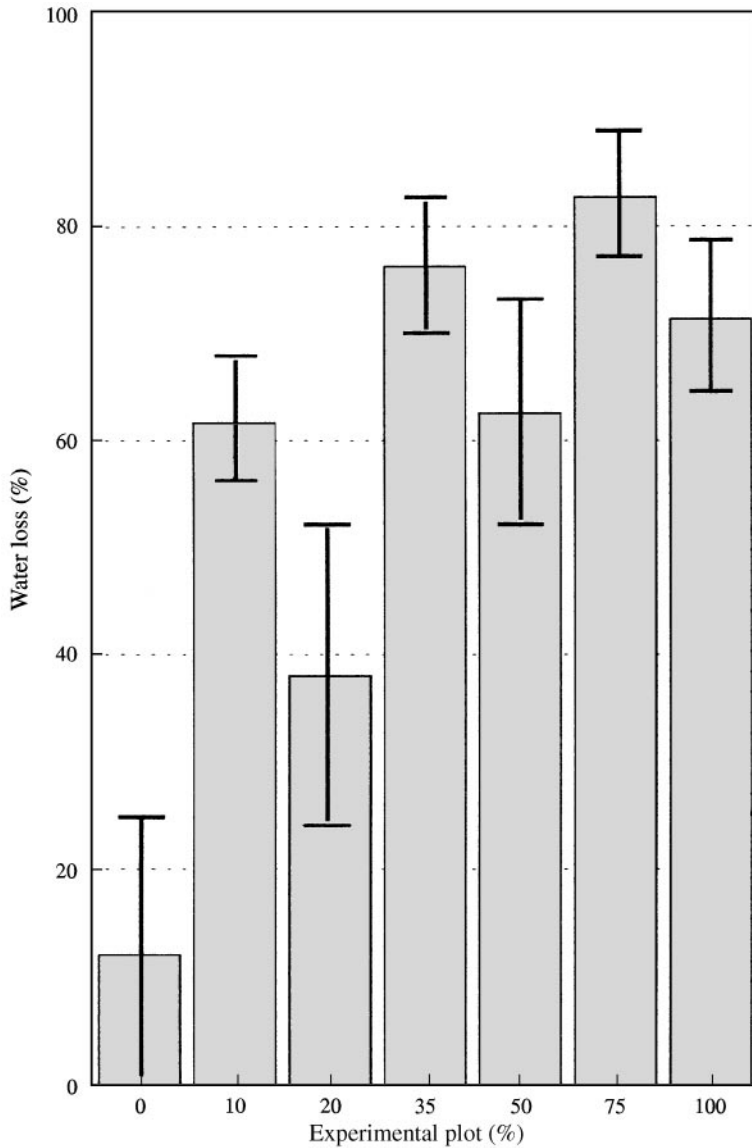


Figure 3. Estimates of the mean percentage incidental water losses (interception and runoff) of five rain showers >10.0 mm in the various experimental plots during the 1990/91 and 1991/92 seasons, with indication of the standard errors (S.E.) of the mean.

From these results some seasonal variation in the pattern of Et losses is discernible, as well as some variation between experimental plots. In the majority of cases the Et losses were higher within the grass only plot (0% plot) than in any of the other plots. However, a lack of a more linear response between the extremes of the thinning treatments, as well as the low number of observations, limit the absolute validity of the data. Nonetheless, the results correspond with a similar finding by Moore *et al.* (1988) that grasses use soil water more rapidly than the drought resistant shrub *Rhigozum trichotomum*. They reported Et values of 3.23 mm day^{-1} for a grass community and 1.41 mm day^{-1} for a *R. trichotomum* community.

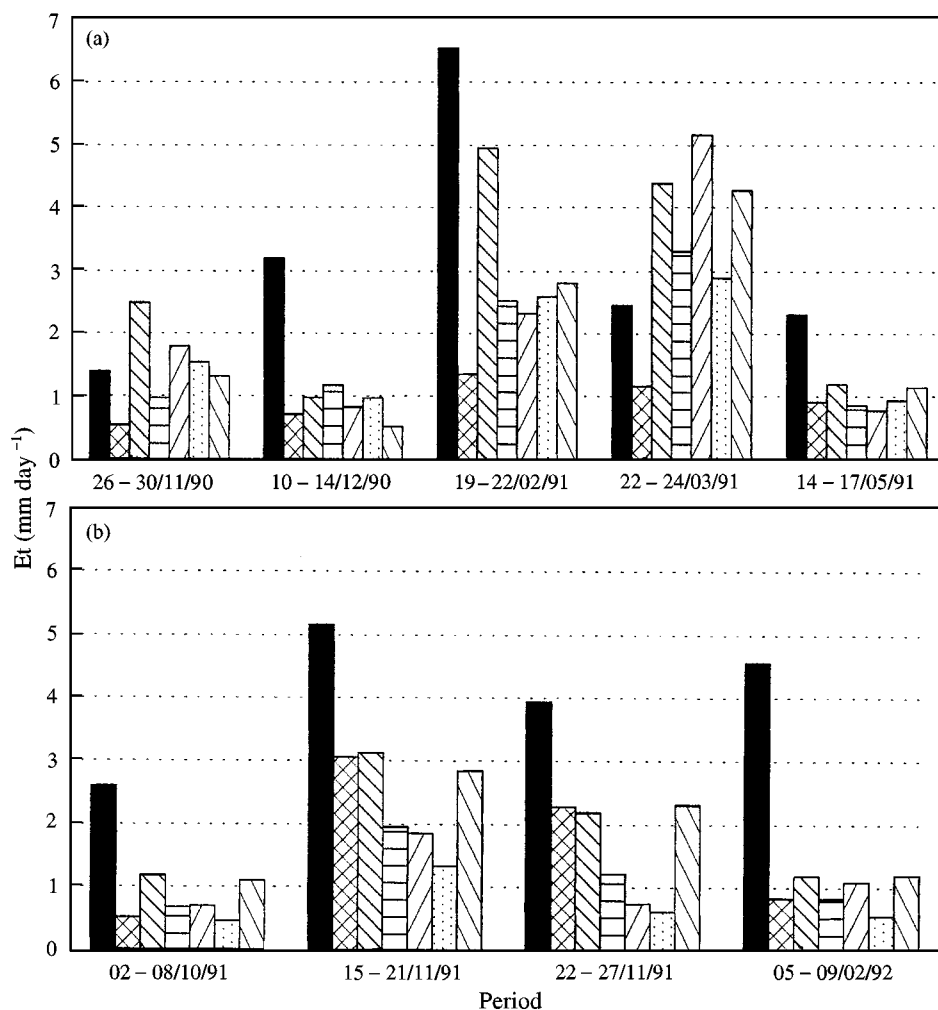


Figure 4. Mean evapotranspiration (E_t) water losses from the soil profiles of the various experimental plots during specific periods of (a) the 1990/91 season, and (b) the 1991/92 season: ■, 0% plot; ▨, 10% plot; ▩, 20% plot; ▤, 35% plot; ▥, 50% plot; ▦, 75% plot; □, 100% plot.

Number of potential plant growth days

The number of days (of a total of 114 days during which soil water measurements were taken) that the soil water content of the 0–450 mm soil zone exceeded the estimated wilting point ($WP = 0.09 \text{ mm H}_2\text{O mm}^{-1}$) are presented in Fig. 5.

Marked differences occurred between experimental plots in the number of days that the soil water exceeded WP in the 0–450 mm soil zone (Fig. 5), with the number and percentage exceptionally low in the high tree density plots (75% and 100% plots). The percentage days that the soil water exceeded WP was negatively correlated with $ETTE \text{ ha}^{-1}$ ($r^2 = 0.514$, $r = -0.719$, $n = 14$), but this relation was only significant at $p = 0.068$.

Comparison of the amount of PAW, based on a wilting point at a matric potential of -1500 kPa , revealed dramatic differences between experimental plots (Figs. 6 & 7). As can be seen from Fig. 6 (1990/91 season), the 0% plot had a markedly higher amount

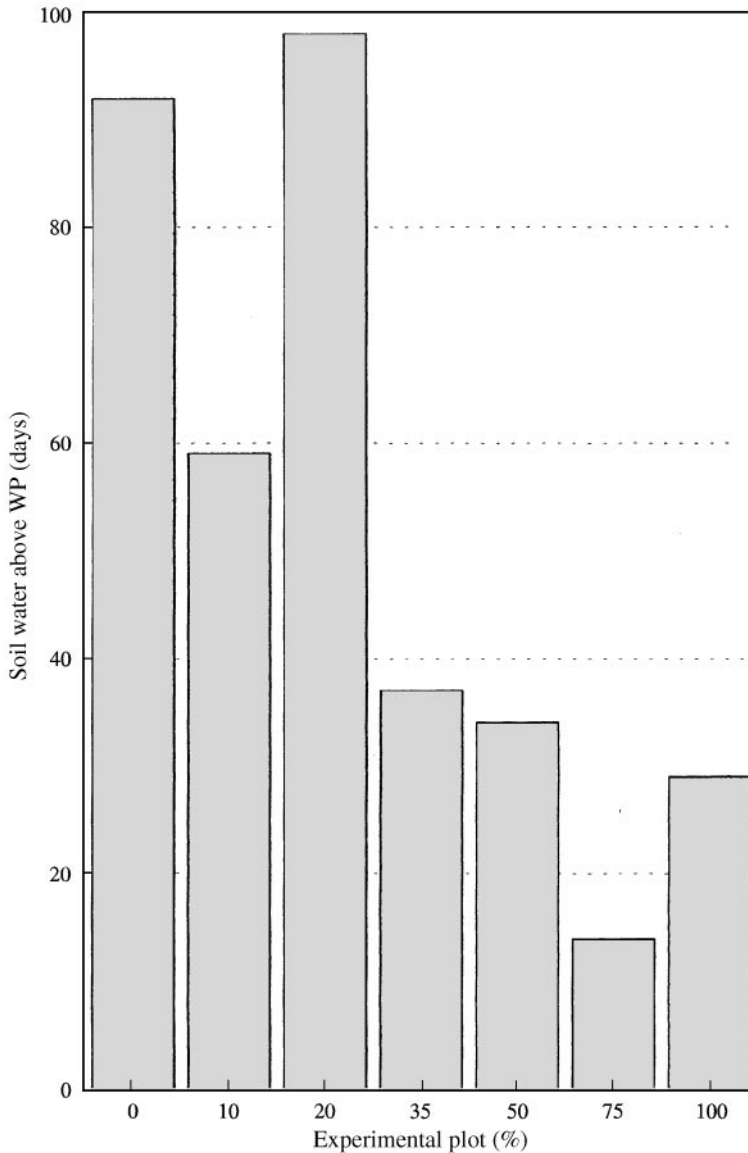


Figure 5. Number of days (of a total of 114 days during which soil water measurements were taken) that the soil water content of the 0–450 mm soil zone exceeded the estimated wilting point ($WP = 0.09 \text{ mm H}_2\text{O mm}^{-1}$).

of PAW than any other plot, and this difference was more pronounced during the 1991/92 season (Fig. 7). While the low amount of PAW in the densely wooded plots corresponds with the virtual absence of grasses in these plots, the ability of the *H. mopane* trees to survive and produce considerable amounts of leaf material under such soil water regimes clearly shows that the *H. mopane* trees are able to utilize soil water at a matric potential much lower than that of grasses ($\psi < -1500 \text{ kPa}$).

It was not possible to determine the exact wilting point of *H. mopane* from this study, but it is clear that the *H. mopane* trees are physiologically well adapted to arid conditions. Combined with an extensive, shallow root system (Smit & Rethman, 1998b), *H. mopane* trees are at a considerable advantage regarding their ability to compete with grasses for

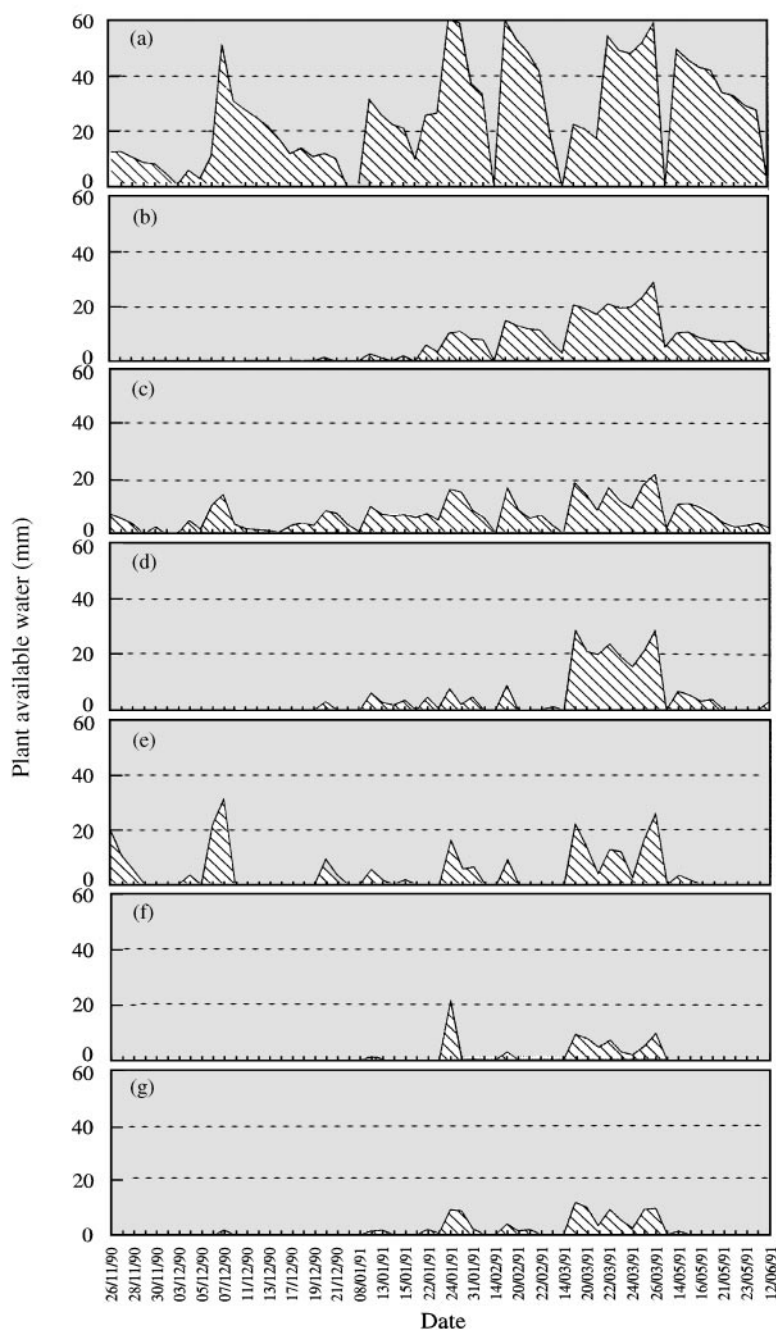


Figure 6. Comparative estimates of the amount of plant available water ($WP = 0.09 \text{ mm H}_2\text{O mm}^{-1}$) within the 0–450 mm soil zone during the 1990/91 season (59 non-continues days): (a) 0% plot, (b) 10% plot, (c) 20% plot, (d) 35% plot, (e) 50% plot, (f) 75% plot, and (g) 100% plot.

soil water, even though the grass species of the study area are likely to be better adapted to drought conditions than those from more temperate regions. From the mean Et losses (Fig. 4), it can be concluded that grasses are able to utilize soil water at a fast rate during those periods when the soil water exceeded the estimated WP (demonstrated

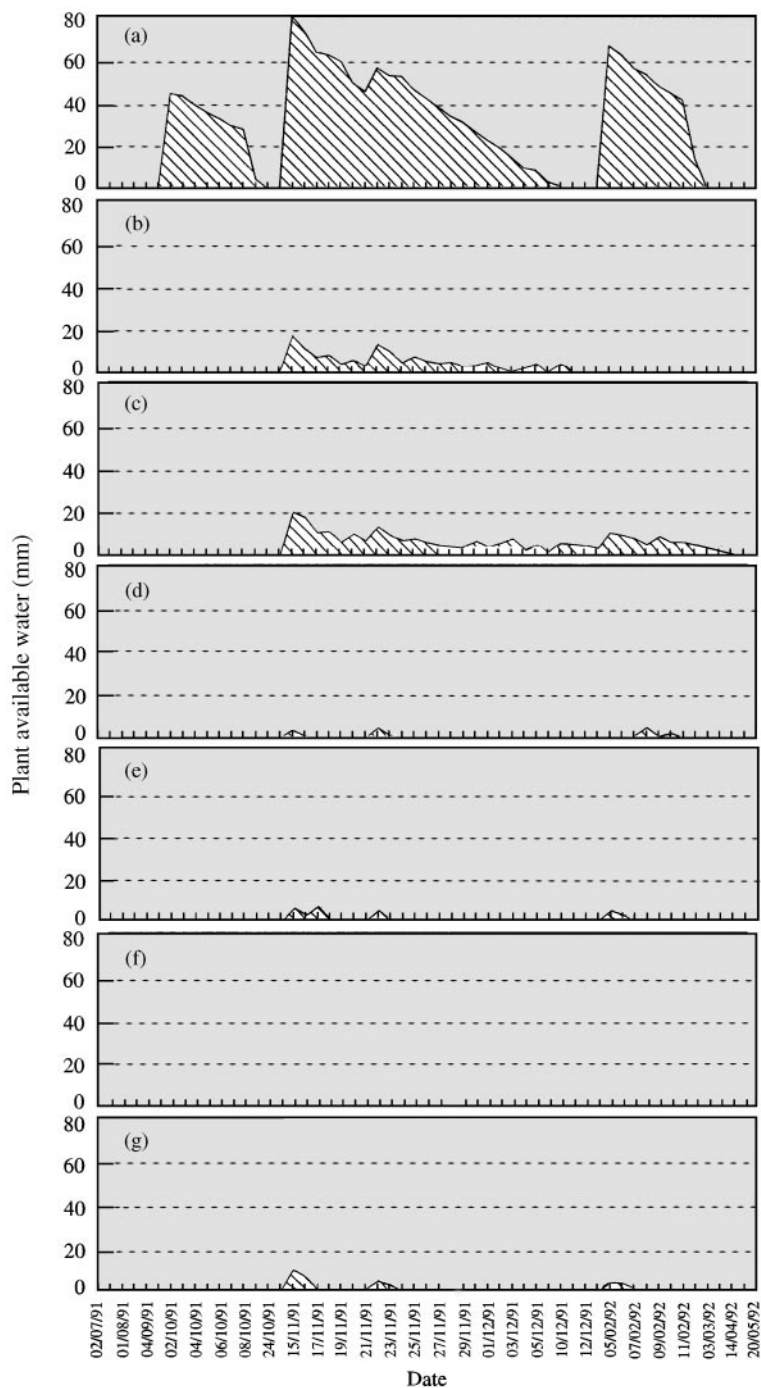


Figure 7. Comparative estimates of the amount of plant available water ($WP = 0.09 \text{ mm H}_2\text{O mm}^{-1}$) within the 0–450 mm soil zone during the 1991/92 season (55 non-continues days): (a) 0% plot, (b) 10% plot, (c) 20% plot, (d) 35% plot, (e) 50% plot, (f) 75% plot, and (g) 100% plot.

in Figs. 6 and 7), whereafter the *H. mopane* trees can continue utilizing soil water to a lower, unknown, WP (WP_{Hm}).

This means that the soil is being dried out to below the WP of grasses (WP_g), and this deficit must first be replenished during a subsequent rain shower before any soil water becomes available again to grasses. If this deficit is not replenished to a level above WP_g , no water will be available to grasses while the *H. mopane* trees will have some soil water exclusively available to them ($PAW_{Hm} = WP_g - WP_{Hm}$). Through this process, the number of days that the soil water exceeded WP can be higher for the *H. mopane* trees than for the grasses. In the low tree density plots (10 and 20% plots), the quantity of PAW_{Hm} would thus be considerably higher than in the high tree density plots, since fewer trees have access to this exclusive source of soil water. This would explain why the *H. mopane* trees in the low tree density plots showed increased growth rates notwithstanding the substantial presence of grasses (Smit, 1994), while the opposite was demonstrated to happen with *R. trichotomum* in the presence of grasses (Moore *et al.*, 1988).

Water use efficiency

The water use efficiency (WUE), expressed in terms of the leaf DM yield of the *H. mopane* trees, grass DM yield, and combined leaf and grass DM yield in the various plots as a function of the total seasonal rainfall, is presented in Table 4.

From Table 4 it can be concluded that the WUE of grasses decreased with increasing tree density, while that of the *H. mopane* leaves increased with increasing tree density. Since the WUE efficiency was calculated on an area basis, plant abundance had obviously influenced the WUE to a large extent. It was thus not surprising that the multiple regression analyses have shown that $ETTE\ ha^{-1}$ explained the most variation in the WUE of grasses ($r^2 = 0.67$, $r = 0.819$, $n = 14$, $p < 0.01$), while rainfall had little effect. Inclusion of rainfall as an independent variable, however, increased r^2 to 0.70. The WUE of grasses on an area basis was best described by the regression equation $y = 3.2928 - 0.000506x_1 - 0.001605x_2$, where $y = WUE\ (kg\ ha^{-1}\ mm^{-1})$, $x_1 = ETTE\ ha^{-1}$, and $x_2 = \text{total seasonal rainfall (mm)}$. In the case of the *H. mopane* leaves, $ETTE\ ha^{-1}$ also explained the most variation in their WUE ($r^2 = 0.79$, $r = 0.889$, $n = 14$, $p < 0.01$), but in combination with rainfall, more of the variation was explained ($r^2 = 0.93$, $r = 0.964$, $n = 14$, $p < 0.01$). The WUE of *H. mopane* leaves was best described by the regression equation $y = 2.35038 + 0.000901x_1 - 0.00719x_2$, where $y = WUE\ (kg\ ha^{-1}\ mm^{-1})$, $x_1 = ETTE\ ha^{-1}$, and $x_2 = \text{total seasonal rainfall (mm)}$.

Variation in total seasonal rainfall, on average, did not appear to affect the leaf production of *H. mopane* at peak biomass (Table 4). In contrast to the grasses (predominantly annuals) where new plants establish in response to a higher rainfall, the number of trees remains constant, and though individual trees showed differing growth rates in response to decreasing inter-tree competition (Smit, 1994), the predominant limitation on leaf yields at peak biomass is tree numbers. By combining grass and leaf DM yields, the WUE of the 100% plot is consistently higher than any of the other plots. The ability of *H. mopane* to yield more dry material (leaves) than grasses with the same amount of rainfall, combined with a potentially high water loss to runoff in the densely wooded plots, emphasizes how well adapted *H. mopane* is to drought conditions.

Conclusion

Results of this study have given clear evidence of the complex inter-relationships between the plants, soil, and soil water of this vegetation type, and that tree thinning has a significant effect on the soil water status. The absence of herbaceous plants at high tree densities reflects the low soil water status that exists under such conditions, and that

tree thinning will be essential in ensuring conditions which will favour the establishment of herbaceous plants.

It would be difficult to recommend a specific intensity of tree thinning since the objectives of tree thinning as a management tool can differ. The low WUE of grasses and high WUE of *H. mopane*, respectively, at the opposite extremes of the tree density gradient could lead to the conclusion that the high tree density plots are the most productive, and that tree thinning resulted in reduced productivity. This assumption, however, will have to be evaluated in terms of other considerations such as variations in food and habitat preferences of different herbivore species (Grunow, 1980; Dekker *et al.*, 1996) and aspects of soil loss under a high rainwater runoff regime (Snyman *et al.*, 1985).

The authors wish to thank the South African Department of Agriculture, Northern Province, for funding the project. We gratefully acknowledge the field assistance of A. le Roux and J.S. Swart. Mr A.C. Roux is thanked for making available the study area on his farm, and Mrs M.F. Smith for her help with the statistical analysis.

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