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The Hydrothermal Soil Regime under Gum Arabic Trees [*Acacia senegal* (L.) Willd.] in Al-Rawashda Forest, Al-Gedarif State, Sudan*

Kamal El Din Mohamed Osman and Mukhtar Ahmed Mustafa

Faculty of Agriculture, University of Khartoum, Shambat, Sudan

Abstract: The study was undertaken to generate broad-base data on the hydrothermal regimes in a Vertisol under *Acacia senegal* in Al Rawashda forest, 35 km northeast Al-Gedarif town. The indicators measured for describing the moisture regime were rainfall, infiltration and evaporation rates from U.S. Class A pan, soil moisture storage and actual evapotranspiration. In 1997, the total rainfall was 403 mm, 48% was received in August and 82% was received in July, August and September. The soil was fully recharged with moisture during June-September, depleted and desiccated during October-March and started to rewet in April-May. The daily evaporation ranged from 2.9 to 5.6 mm in autumn, 7.5 to 13.6 mm in winter and 12.8 to 16.0 mm in summer. The soil moisture storage was lowest in 14th May and highest in 5th September, 1997. Although rainfall reduced the vapour pressure gradient, it increased the availability of water to the evaporating site and consequently increased evaporation. Thus, mean monthly evaporation (Em, mm) increased significantly (P = 0.05) with increase of mean monthly rainfall (Rm, mm) as shown by the following power relationship: $Em = 1738\ Rm^{0.5402}$ ($r^2 = 0.790$). The pooled infiltration rate (IR) as a function of time for the two sites in three successive months' best fitted the following

Key words: Soil temperature variation; evaporation; infiltration rate

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highly significant mean power relationship: IR= 0.344 $t^{-0.527}$ (r^2 = 0.985). This equation is recommended for predicting infiltration rate. The steady state-infiltration rate was 12 mm/hr. Cumulative evaporation (Ec) versus time (days) relationships were significantly linear in all studied months. From cumulative rainfall (Rc) and pan evaporation data, a crop coefficient was calculated. Hourly, diurnal, monthly and seasonal air and soil temperatures were measured as indicators of the thermal regime in two successive seasons. In 1997, the mean air temperature was 32.1°C in summer, 29.1°C in autumn and 23.7°C in winter. The mean soil surface temperature was 38.0°C in summer, 33.4°C in autumn and 25.2°C in winter. The daily fluctuations of soil temperature decreased with soil depth reaching a value of 0.15°C or less at depths ≥ 20 cm. The maximum, minimum and mean soil temperature versus soil depth data for all studied seasons yielded highly significant quadratic relationships.

INTRODUCTION

Comprehensive review on soil temperature, interpretation and prediction was provided by Jackson and Kirkham (1958) and Kirkham and Powers (1972) among others. *Acacia senegal* (L.) Willd. is a typical leguminous tree species of the Sahel spreading from Senegal to the Red Sea. It is a gum Arabic tree known as "Hashab", and in Sudan, it occurs in the gum Arabic belt between latitudes 10º and 15º N. In western Sudan, it grows on stabilized sand (Entisols) under annual rainfall ranging between 280 and 450 mm. In eastern and central Sudan, it grows on Vertisols where the annual rainfall is 500 or more. In the latter area, it is not found as pure stand as in western Sudan, but is usually mixed with *Acacia mellifera* and *Acacia seyal* (El Huri 1986, Badi *et al.* 1989).

In the Sudan, *Acacia senegal* is grown on both Vertisols and Entisols under rain-fed conditions. Its production may be constrained by soil, climate, topography, pest and diseases. Research is essential for elucidating these constraints and generating methods for alleviating their adverse effects. Soil temperature is an essential determinant of plant growth and gum Arabic productivity. It affects directly the life processes of seeds, plant roots and microbes, especially rihzobium. Furthermore, it controls the availability of water, nutrients, enzyme activities and decomposition of organic matter.

The soil moisture regime is governed by the field water cycle, which begins with infiltration of water in the soil and it continues with its storage in the soil and ends with its partial removal by surface runoff, deep percolation, uptake by plant roots and evapotranspiration. Under rain-fed conditions, the nature and extent of these processes depend upon rainfall, soil physicochemical properties and management.

The soil thermal regime is determined by environmental and soil factors. The main environmental factor is the short wave radiation, which is actually received by the soil surface as affected by latitude, slope, aspect, insulation by air, dust, clouds, water vapour, and plants or mulch. The main soil factors include long-wave radiation, soil thermal diffusivity and biological activity. The soil thermal diffusivity reflects the rate of change of temperature with time. It is the ratio of the soil thermal conductivity to its thermal capacity. The soil thermal regime varies continuously due to variation in global radiation and soil surface conditions. In general, temperature variation is great on the soil surface and decreases markedly with soil depth. The soil thermal regime is managed by irrigation, drainage, shelterbelts, mulching and ridging (Kohnke 1968; Baver *et al.* 1972; Hillel 1980).

To our knowledge, no research work was conducted in the Sudan to characterize the soil thermal regime under *Acacia senegal* or any other crop. Thus, this study was undertaken to characterize the hydrothermal regime under *Acacia senegal* in Al-Rawashda forest.

MATERIALS AND METHODS

The study was conducted in Al- Rawashda forest, which is located about 35 km north-east of the Gedarif town (Lat. 12º45`–14º30`N and Long. 34º–36º30`E). The selected *Acacia senegal* stand was about 13 years old and had a stocking density of 350 trees/feddan (1 fed = 0.42 ha). Two sites were selected within the stand. The soil was classified as very fine, smectitic, isohyperthermic Chromustert (Table 1).

Table 1. Some physical and chemical properties of a soil profile in Al-Rawashda forest under *Acacia senegal*

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	pH	ECe (dS/m)	SAR $(mmole+/l)^{½}$
0 - 30	26	26	48	Clay	7.7	0.60	4.6
30 - 45	24	28	48	Clay	7.6	0.32	2.6
45 - 90	16	24	60	Clay	7.9	0.38	3.0
90 - 110	22	22	56	Clay	7.6	0.38	2.8
110 - 150	18	16	66	Clay	8.0	2.20	8.7
150 - 200	16	20	64	Clay	7.6	1.30	6.0

Determination of the soil moisture regime

At site A, rainfall was measured by a rain gauge during 28th April and 10th October, 1997. Daily pan evaporation measurements were made at 8 a.m. during a specific period for each season using a standard U.S. Class A pan. A soil profile was dug and soil clods were collected from the following successive soil layers: 0-5, 5-10, 10-20, 20-40, 40-60, 60-90, 60-110 and 110-130 cm. Soil bulk density was then determined by the paraffin wax method applying Archimedes principle. Soil moisture profiles were determined for site A. On 19 February 1997, 14 May 1997, 9 February 1998 and during the rainy season, the soil moisture content was determined for samples collected by an auger from the following depths: 0-5, 5-10, 10-20, 20-40, 40-60, 60-90, and 90-110 cm. During the rainy season, thirteen soil moisture profiles were determined during the period 17 July-9 October. In most cases, soil samples were collected after a rainfall event. From each soil moisture profile data, the amount of water stored (Ms, cm) was calculated by he following equation:

$$Ms = \Sigma^{n}_{i=1} (Mi/100) \times BDi \times Di$$

where Mi is the gravimetric moisture content in the ith layer, BDi is the bulk density of the ith layer (g/cm^3), Di is the soil depth of the ith layer (cm) and n is the number of layers down to 110 cm depth.

The infiltration rate was measured in both sites in winter, summer and autumn of 1997 using a fabricated double ring infiltrometer with a float and side manometer (Elbassir 1989; Osman 1999). Daily evaporation measurements were made during specific periods in winter, summer and autumn in 1997 and winter in 1998.

Determination of the soil thermal regime

At each site, soil thermometers were placed in the soil profile at the following depths: 0, 2.5, 5, 10, 20 and 30 cm. Air temperature was also measured with an ordinary thermometer at 1.5 m above ground level. Temperature measurements were taken daily at 8 a.m. and 2 p.m. for a period of one month in the three successive seasons of 1997 and in winter of 1998. The actual measurement periods in 1997 were 3 February - 8 March (winter), 20 April – 23 May (summer) and 1st July – 11th October (autumn). Temperature measurements were also made during winter, 1998. For monitoring the diurnal variation of temperature in each site, hourly measurements were made for one day in each of the studied seasons. For site A, the measurements were made on 14 to 15 February, 3 to 4 May, and 16 to 17 August 1997 and on 14 to 15 February, 1998. For site B, the measurements were made one or two days after the measurements made on site A.

RESULTS AND DISCUSION

The soil moisture regime

The comprehensive data of the measured indicators of the moisture regime are presented in Osman (1999). Summary statistics are provided in this section.

Rainfall 1997

The distribution of monthly rainfall during 1997 season is shown in Fig 1. The rains started in April and increased gradually with time reaching its peak in August and declined sharply in September. The total rainfall in that season was 403 mm; about 18% was received during April – June and about 82% during July – September. The distribution pattern was uneven since about 48% was received in August. Thus, the soil was fully recharged with moisture during June-September, depleted and desiccated during October-March and started to rewet in April-May. Nearly similar delineations of soil moisture regimes were identified by Khan (1989) in Al-Hawata area. The following successive moisture regimes: recharge (2.5 months), utilization (1 month), restricted moisture (2.5 months) and deficiency water regimes (6 months) were observed.

Infiltration rate

The measured infiltration rate (IR) data for the two sites in the three successive months are presented elsewhere (Osman 1999). The data showed that for each measurement, IR decreased gradually from a relatively high initial value to a nearly constant steady-state rate (IRs). The initial infiltration rate varied with site and season, whereas the IRs was independent of the two variables. Table 2 shows that the data for each site and month best fitted a highly significant power relationships (at^b). These relationships accounted for more than 94% of the variability of IR. Previous studies showed that the steady-state infiltration rate is reached after five hours. Thus, the infiltration rate at 300 min was considered equal to IRs. It is evident that IRs is nearly independent of site and month; it is a characteristic of soil. Although 'b' is nearly constant, 'a' varies with site and month. Thus, it is possible to use the following average equation for predicting IR at relatively high t values:

$$IR = 0.344\ t^{-0.527}$$

Table 2. The parameters of best-fit power relationships ($IR = at^b$) of the infiltration rate (IR, cm/min) as a function of time (t, min) (13-17 pairs of data) for the two sites at different months

Month	Site	a	b	r^2	IRs
January	A	0.269	- 0.506	0.994	0.015
	B	0.282	- 0.492	0.988	0.017
May	A	0.386	- 0.537	0.995	0.018
	B	0.381	- 0.536	0.997	0.018
August	A	0.340	- 0.532	0.940	0.016
	B	0.404	- 0.561	0.993	0.016
Mean		0.344	- 0.527	0.985	0.017
C.V. (%)		16.6	4.7	2.2	7.3

$r_{0.001}$ = 0.801; IRs = the steady state infiltration rate calculated from the power relationships at 300 min.

Evaporation

In February (winter), the evaporation rate (E) ranged from 7.5 to 13.6 mm/day with a mean of 11 mm/day and a coefficient of variation (C.V.) of 13.2%. The monthly total was 309 mm. Evaporation was highest in May (summer) ranging from 12.8 mm/day to 16.0 mm/day with a mean of 14.2 mm/day, a C.V. of 5.2% and a monthly total of 439 mm. In July, E decreased markedly with significant increase in rainfall, ranging from 3.8 mm/day to 7.4 mm/day with a mean of 4.9 mm/day, a C.V. of 18.4% and a monthly total of 153 mm. In August, when 48% of the annual rainfall occurred, E was further reduced, ranging from 2.9 mm/day to 5.2 mm/day with a mean of 3.9 mm/day, a C.V. of 15.1% and a monthly total of 121 mm. In September, E increased due to decrease in rainfall, ranging from 3.4 mm/day to 8.6 mm/day with a mean of 4.9 mm/day and a monthly total of 146 mm. The monthly evaporation (Em) was plotted along with monthly rainfall in Fig. 1.

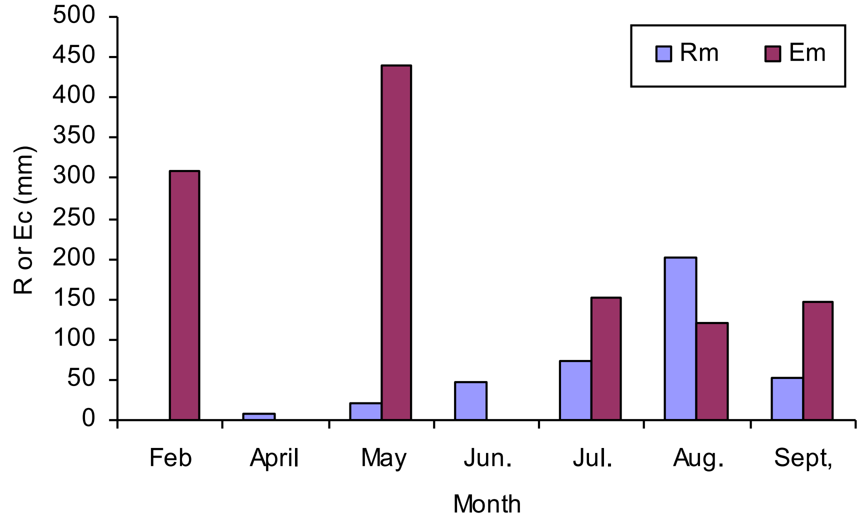

Fig. 1. Distribution of monthly rainfall (Rm) and evaporation (Em) at Al-Rawashda forest in 1997

Two factors affect E; namely, the vapour pressure gradient as influenced by soil temperature and rainfall. Rainfall increases the relative humidity of the air, reduces the vapour pressure gradient between the soil surface and the air above it and thus reduces evaporation rate. However, rainfall increases the availability of water to the evaporating soil surface. The latter factor seemed to be predominant, resulting in increase in evaporation with increase in rainfall. The following significant (5% level) power relationship between monthly total evaporation (Em) and monthly total rainfall (Rm) was found:

$$Em = 1738\ Rm^{0.5402}$$

Table 3 shows highly significant linear relationship between daily E and average temperature (Ta). Ta was calculated as the mean daily air temperature at 8.00 hours and 14.00 hours. Thus, increase in E was attributed to increase in rainfall and temperature. Temperature is responsible for providing the latent heat requirement for the evaporation process.

Table 4 shows that cumulative evaporation (Ec) versus time (days) relationships were significantly linear in all studied months. The relationships were almost perfect with an average correlation coefficient of 0.999. This pattern, unlike the model of hourly evaporation of a saturated soil column under constant climatic conditions, does not depict the three characteristic stages; namely, constant-, falling- and slow-evaporation rates (Hillel 1980). Unlike in the field, the conditions in the laboratory were well controlled.

Table 3. Summary statistics of temperature and the variables of best-fit linear regression line (Ec = a + b Ta) of daily evaporation (E, mm) versus average daily temperature (Ta, ºC) in Al-Rawashda forest at different months

Month	Range of Ta	Average Ta (ºC)	C.V. (%)	a	b	r^2
February	22.0 – 31.9	28.1	8.6	- 2.148	0.469	0.613
May	32.0 – 36.4	34.0	3.6	- 3.874	0.531	0.739
July	29.5 – 36.5	32.6	5.1	- 9.473	0.441	0.635
August	25.5 – 33.0	30.3	6.5	- 0.281	0.138	0.213
September	29.5 – 35.9	32.7	5.1	-13.566	0.564	0.614

$r_{0.01}$ (n = 29) = 0.4563; $r_{0.001}$ (n = 29) = 0.5628

Table 4. Total monthly cumulative evaporation and the data of best-fit linear regression line (Ec = a + b t) of cumulative evaporation (Ec, mm) as a function of time (t, day) in Al-Rawashda forest at different months

Month	Total Ec (mm)	a	b	r^2
February	309	- 1.118	11.270	0.999
May	439	0.462	14.153	1.000
July	153	3.901	4.721	0.999
August	121	2.268	3.837	0.999
September	146	- 7.318	4.947	0.990

$r_{0.01}$ (n = 29) = 0.4563; $r_{0.001}$ (n = 29) = 0.5628

Soil moisture storage

The soil moisture profile was driest in May (summer) and wettest in August, the peak of autumn. In May and February, the moisture content was lowest at the surface and increased with depth reaching a nearly constant value at 30 cm depth. In July, August and September, the moisture content was highest at the surface and decreased with depth reaching a nearly constant value at 30 cm. Table 5 shows a summary of the soil moisture regime at Al-Rawashda forest in the studied period.

Table 5 shows the seasonal variation of soil moisture regime. The increase in cumulative rainfall (Rc) from May to mid-July was very high resulting in substantial increase in the amount of water stored. The water stored (Ms) in the soil profile varied with month and date within each month depending on total rainfall received and evaporation. As the rainy season progressed, both Rc and pan evaporation (Ep) increased; and during the period 25 July to 5 September the water stored (Ms) fluctuated around a relatively high value. From 5 September onwards, evaporation increased steeply while rainfall remained nearly constant resulting in lowering of Ms.

By 1st October, Rc was 403.1 mm and Ep was 420.8 mm resulting in a net Ms value of 236.0 mm. From 17 July to 1st October, Rc was 329.1 mm, out of this a net of 50.8 mm was stored in the soil profile and 278.3 mm was actually lost from the soil profile by evaporation. A 'crop' coefficient for the pan data may thus be calculated as follows:

ETa / Ep = 278.3/420.8 = 0.66.

Table 5. Soil moisture regime under Al-Rawashda forest during the study period in 1997

Month	Date	Ms	ΔMs	R	Rc	Ep
February	19/2	120.4	0.0	0.0	0.0	216.6
April				7.5	7.5	
May	14/5	102.4	18.0	13.2	20.7	
	19/5			6.5	27.2	311.7
June				46.8	74.0	
July	17/7	185.2	82.8	60.0	134.0	84.2
	21/7	191.0	5.8	9.5	143.5	101.0
	25/7	258.7	67.7	0.0	143.5	121.7
August	6/8	276.6	17.9	35.0	178.5	179.1
	9/8	266.0	- 10.6	28.0	206.5	191.6
	12/8	248.8	- 17.2	0.0	206.5	202.6
	18/8	274.3	25.5	60.0	206.5	266.3
	27/8	274.3		72.0	266.5	259.7
September	5/9	281.8	7.5	43.3	338.5	295.2
	13/9	232.4	- 49.4	10.0	381.8	328.2
	21/9	251.9	19.5	0.0	391.8	369.6
October	1/10	236.0	- 15.9	11.3	391.8	420.8

Ms = water stored; R = rainfall; ΔMs = the difference in the amount of water stored in the soil profile; Ep = pan evaporation; from July to October, the Ep is the cumulative evaporation.

The thermal regime

The comprehensive hourly and daily air and soil temperature data collected for both sites and the studied seasons of 1997 and 1998 as well as some pertinent statistical parameters are reported elsewhere (Osman 1999).

Winter season

Table 6 shows that the mean temperature did not vary greatly between sites and seasons. The C.V. was highest at the surface (5.1%) and lowest at 30 cm. (0.3%). The C.V.s of the maximum soil temperatures were low, ranging from 0 at 30 cm. to 4.1 at 10 cm. However, the C.V.s for the minimum soil temperatures were higher, ranging from 2.2 at 20 cm to 12.2 at 10.0 cm. The mean and minimum air temperatures were lower than the corresponding soil temperatures at all depths. However, the maximum air temperature was lower than the soil temperature at 0, 2.5, 5.0 and 10 cm, but higher than those at 20 and 30 cm. The overall average maximum soil temperature increased from 35.4 °C at the surface, reaching a maximum value (38.3°C) at 10 cm depth, dropped to 28.8 °C at 20 cm and then levelled at lower depths. The trend line depicted the following highly significant ($P = <0.001$) quadratic relationship between soil temperature and depth:

$$Ts = - 0.0087 Z^2 – 0.0533 Z + 36.888 \quad (r^2 = 0.7228)$$

where Ts is the soil temperature in °C and Z is the soil depth in cm.

The overall mean soil temperature increased steadily from 26°C at the surface reaching 30.3°C at 10 cm depth, decreased to 28.3°C at 20 cm and levelled off at lower depths. The trend line depicted the following significant ($P = 0.05$) Ts versus Z relationship:

$$Ts = - 0.0111 Z^2 + 0.3627 Z + 26.901 \quad (r^2 = 0.5652)$$

The overall mean minimum soil temperature increased steadily with depth from 17.2°C at the surface to 27.8°C at 20 cm and then levelled off. The trend line depicted the following highly significant ($P< 0.001$) quadratic Ts versus Z relationship:

$$Ts = - 0.0129 Z^2 + 0.7085 Z + 17.976 \qquad (r^2 = 0.9476)$$

Table 6. Summary statistics of mean daily temperatures in °C, average (Avg.), maximum (Max.), and minimum (Min.) of sites A and B in the winter seasons of 1997 and 1998

Statistic	Year/Site		Air	Soil depth (cm) 0	2.5	5	10	20	30
Mean	1997	A	23.4	24.7	27.0	28.7	29.6	28.3	30.0
		B	24.5	27.0	28.7	30.1	31.8	28.4	28.4
	1998	A	23.5	24.9	27.2	28.4	29.0	28.2	28.2
		B	24.6	27.2	28.8	29.4	30.6	28.3	28.3
Avg.			24.0	26.0	27.9	29.2	30.3	28.3	28.3
S.D.			0.6	1.3	1.0	0.8	1.2	0.1	0.1
C.V. (%)			2.7	5.1	3.4	2.6	4.1	0.3	0.3
Max.	1997	A	32.9	34.7	35.9	37.6	36.9	28.7	28.7
		B	33.0	36.0	36.7	38.0	39.6	28.8	28.7
	1998	A	32.9	34.7	35.9	37.6	36.9	28.7	28.7
		B	33.0	36.0	36.7	38.0	39.6	28.8	28.7
Avg.			33.0	35.4	36.3	37.8	38.3	28.8	28.7
S.D.			0.1	0.8	0.5	0.2	1.6	0.1	0.0
C.V. (%)			0.2	2.1	1.3	0.6	4.1	0.2	0.0
Min.	1997	A	15.8	16.2	21.0	23.6	25.1	28.0	28.1
		B	15.0	16.1	20.0	23.0	24.0	28.1	28.2
	1998	A	15.8	16.2	21.0	21.8	21.4	26.9	26.8
		B	15	18.1	20.0	20.0	19.0	27.1	26.9
Avg.			15.4	17.2	20.5	22.1	22.4	27.5	27.5
S.D.			0.5	1.1	0.6	1.6	2.7	0.6	0.8
C.V. (%)			3.0	6.4	2.8	7.2	12.2	2.2	2.7
Amplitude*	1997	A	9.5	10.0	8.9	8.9	7.3	0.4	0.3
		B	8.5	9.0	8.0	7.9	7.8	0.4	0.3
	1998	A	9.4	9.8	8.7	9.2	7.9	0.5	0.5
		B	8.4	8.8	7.9	8.6	9.0	0.5	0.4
Avg.			9.0	9.4	8.4	8.7	8.0	0.5	0.4
S.D.			0.5	0.5	0.4	0.5	0.6	0.1	0.1
C.V. (%)			5.6	5.4	5.2	5.6	7.8	11.1	22.1

* Amplitude = It is the amplitude of the temperature wave = Max. – Avg.

Fig. 2 depicts the average sinusoidal air and temperature profiles of the two sites in the two winter seasons measured in February. The air temperature was 22.2 at 1 a.m. and then decreased with increase of time reaching a minimum value of 15.4°C at 6 a.m.; afterwards; it increased steadily with increase of time reaching 24.9°C at 11 a.m. and a maximum value of 33°C at 15.00 hrs. It progressively decreased with time reaching 23.3°C at 24.00 hrs.

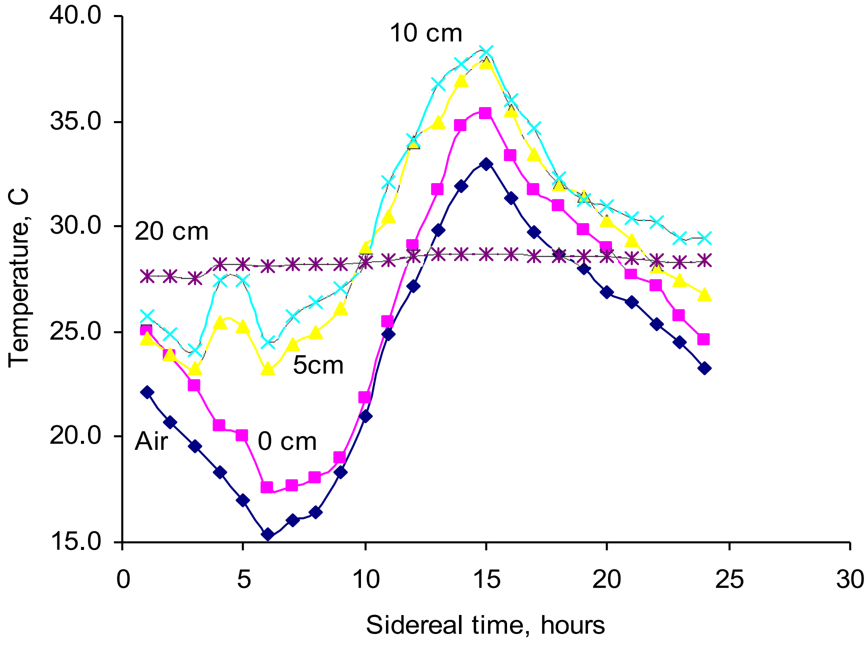

Fig.2. Average diurnal variation of air and soil temperature profile under Al-Rawashda forest of the two sites and the two winter seasons

At the surface, the soil temperature was 25.1°C at 1 a.m., decreased with increase of time reaching a minimum value of 17.6°C at 6 a.m. At 11 a.m., it reached 25.5°C, nearly equal to that of air, and it continued to increase reaching a maximum value of 35.4°C at 15.00 hrs. Afterwards, it decreased with time reaching 24.6°C at 24.00 hrs.

At 1 a.m., the soil temperature was 25.8°C at 10 cm. It decreased with increase of time reaching a minimum value of 24.6°C at 6 a.m. At 7 a.m., it reached 25.8°C, which was higher than that at the surface, and it continued to increase reaching a maximum value of 38.3°C at 15.00 hrs. Afterwards, it decreased with time reaching 29.5°C at 24.00 hrs.

At 20 and 30 cm, the soil temperature profiles were similar. The soil temperature at both depths ranged from 27.6°C to 28.8°C with a mean of 28.3°C and CV of 1.2%.

The amplitude of the air and soil surface temperature was greater than those at 2.5, 5 and 10 cm depth. They were very low at deeper depths.

Summer season 1997

The means of the daily temperature measurements for both sites in May 1997 and August 1997 are presented in Tables 7 and 8, respectively. It is evident that the mean temperature did not vary greatly between sites and seasons. The C.V. was highest at a depth of 5 cm (6.0%) and lowest at 30 cm. (0.8%). The C.V.s of maximum soil temperatures were relatively higher, ranging from 1.4 at 30 cm. to 10.0 at the soil surface. However, CVs for the minimum soil temperature were relatively lower ranging from 0.4 at 20 cm to 8.8 at 5.0 cm. In general, the average and minimum air temperatures were lower than the soil temperature at all depths, whereas the maximum air temperature was lower than the soil temperatures at 0, 2.5 and 5 cm depths but higher than the soil temperatures at 10, 20 and 30 cm. The overall maximum soil temperature decreased steadily from 53.1°C at the surface to 34.7°C at 20 cm and levelled off thereafter. The trend line depicted the following highly significant ($P = <0.001$) quadratic Ts versus Z relationship:

$$Ts = 0.0389\ Z^2 - 1.768\ Z + 53.119 \qquad (r^2 = 0.9816)$$

Table 7. Summary statistics of mean daily temperatures in °C, average (Avg.), maximum (Max.), and minimum (Min.) of sites A and B in May 1997 (Summer)

			Soil depth (cm)					
Statistic	Site	Air	0	2.5	5	10	20	30
Mean	A	32.7	36.5	36.8	36.0	33.7	34.2	34.2
	B	33.1	39.7	39.4	39.2	35.2	34.6	34.6
Avg.		32.9	38.1	38.1	37.6	34.5	34.4	34.4
STD		0.3	2.3	1.8	2.3	1.1	0.3	0.3
C.V. (%)		0.9	5.9	4.8	6.0	3.1	0.8	0.8
Max.	A	41	49.3	48.0	43.6	37.0	34.3	34.3
	B	44	56.8	50.6	48.0	38.0	35.0	35.0
Avg.		42.5	53.1	49.3	45.8	37.5	34.7	34.7
STD		2.1	5.3	1.8	3.1	0.7	0.5	0.5
C.V. (%)		5.0	10.0	3.7	6.8	1.9	1.4	1.4
Min.	A	24.4	24	26	26.5	31.4	34	34
	B	24.2	26	27.8	30.0	32.3	34.2	34.2
Avg.		24.3	25	26.9	28.3	31.9	34.1	34.1
STD		0.1	1.4	1.3	2.5	0.6	0.1	0.1
C.V. (%)		0.6	5.7	4.7	8.8	2.0	0.4	0.4
Amplitude	A	8.3	12.8	11.2	7.6	3.3	0.1	0.1
	B	10.9	17.0	11.2	8.8	2.8	0.4	0.4
Avg.		9.6	15	11.2	8.2	3.1	0.2	0.2
STD		1.8	3.0	0	0.8	0.4	0.2	0.2
C.V. (%)		19.2	20.3	0	10.3	11.6	84.9	84.9

* Amplitude = It is the amplitude of the temperature wave = Max. – Avg.

Table 8. Summary statistics of mean daily temperatures in °C, average (Avg.), maximum (Max.), and minimum (Min.) of sites A and B in August 1997 (Autumn)

			Soil depth (cm)					
Statistic	Site	Air	0	2.5	5	10	20	30
Mean	A	29.2	33.6	30.2	30.3	30.6	30.0	30.1
	B	29.5	32.3	30.5	30.0	29.4	30.3	30.3
Avg.		29.4	33.0	30.4	30.2	30.0	30.2	30.2
STD		0.2	0.9	0.2	0.2	0.8	0.2	0.1
C.V. (%)		0.7	2.8	0.7	0.7	2.8	0.7	0.5
Max.	A	35.0	48.7	38.0	36.4	32.7	30.3	30.7
	B	36.9	45.0	39.1	33.9	31.3	30.5	30.4
Avg.		36.0	46.9	38.6	35.2	32.0	30.4	30.6
STD		1.3	2.6	0.8	1.8	1.0	0.1	0.2
C.V. (%)		3.7	5.6	2.0	5.0	3.1	0.5	0.7
Min.	A	22.1	22.6	23.1	23.7	27.0	29.8	30.0
	B	23.0	22.4	21.9	24.8	26.8	30.1	30.2
Avg.		22.6	22.5	22.5	24.3	26.9	30.0	30.1
STD		0.6	0.1	0.8	0.8	0.1	0.2	0.1
C.V. (%)		2.8	0.6	3.8	3.2	0.5	0.7	0.5
Amplitude	A	5.8	15.1	7.8	6.1	2.1	0.3	0.6
	B	7.4	12.7	8.6	3.9	1.9	0.2	0.1
Avg.		6.6	13.9	8.2	5.0	2.0	0.3	0.4
STD		1.1	1.7	0.6	1.6	0.1	0.1	0.4
C.V. (%)		17.1	12.2	6.9	31.1	7.1	28.3	101.0

* Amplitude = It is the amplitude of the temperature wave = Max. – Avg.

The overall mean soil temperature decreased steadily from 38.1°C at the surface reaching 34.4°C at 20 cm depth and levelled off thereafter. The trend line depicted the following significant ($P< 0.05$) quadratic Ts versus Z relationship:

$$Ts = 0.0089 Z^2 - 0.4041 Z + 38.618 \qquad (r^2 = 0.8866)$$

The overall minimum soil temperature increased steadily with depth from 25°C at the surface to 34.1°C at 20 cm and then levelled off. The trend line depicted the following highly significant (P< 0.001) quadratic Ts versus Z equation:

$$Ts = -0.0162\,Z^2 + 0.7458\,Z + 26.219 \qquad (r^2 = 0.9898)$$

Fig. 3 shows the average sinusoidal air and temperature profiles of the two sites in May, 1997. The air temperature was 28.7 at 1 a.m. and it decreased with increase of time reaching a minimum value of 24.6 °C at 5 a.m.; afterwards, it increased steadily with increase of time reaching 30.0°C at 9 a.m. and a maximum value of 42.5°C at 14 hrs. It progressively decreased with time reaching 29.8°C at 24.00 hrs.

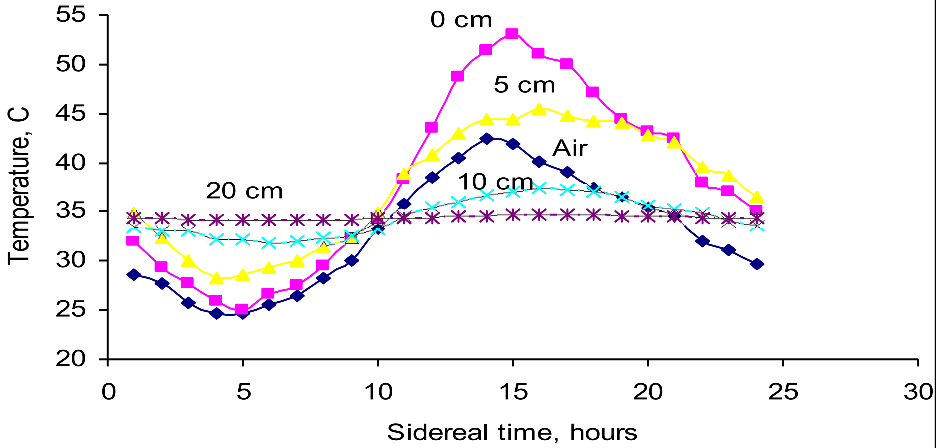

Fig. 3. Average diurnal variation of mean soil temperature of the two sites under Al Rawashda forest in May 1997 (Summer)

At the soil surface, the temperature was 32.0°C at 1 a.m., decreased with increase of time reaching a minimum value of 25.0 °C at 5 a.m. At 9 a.m., it reached 32.2°C, higher than that of air, and it continued to increase reaching a maximum value of 53.1 °C at 15.00 hrs. Afterwards, it decreased with time reaching 35.0°C at 24.00 hrs.

At 1 a.m., the soil temperature was 33.4 °C at 10 cm. It decreased with increase of time reaching a minimum value of 31.9 °C at 6 a.m. At 11 a.m., it reached 34.5 °C, which was nearly equal to that of air and the soil at 20 cm and 30 cm, and it continued to increase reaching a maximum value of 37.5 °C at 16.00 hrs. Afterwards, it decreased with time reaching 33.7 °C at 24.00 hrs.

At 20 and 30 cm, the soil temperature profiles were similar. The soil temperature at both depths ranged from 34.2°C to 34.7 with a mean of 34.4°C and an average CV of 0.45%.

The amplitude of the soil temperature wave decreased with increase of soil depth ranging from 15 at the soil surface to 0.2 at 20 and 30 cm depth.

Autumn 1997

The means of the daily temperature measurements for both sites in August 1997 are presented in Table 8. It is evident that the mean temperature did not vary greatly between the two sites. The C.V. ranged between 2.8, at the soil surface and at 10 cm, and 0.5 at 30 cm. The CVs of maximum soil temperatures were higher, ranging from 5.6 at the soil surface and 0.5 at 20 cm. The C.V.s for the minimum soil temperatures were also lower than those of the mean values and they ranged from 3.8 at 2.5 cm to 0.5 at 30 cm.

In general, the average air temperature was lower than that of the mean soil temperature at all depths. The average minimum air temperature was similar to the soil temperature at the surface and 2.5 but lower than the soil temperature at other soil depths. The average maximum air temperature was lower than the soil temperatures at 0, 2.5 depths but higher than the soil temperatures at other soil depths. cm. The overall maximum soil temperature decreased steadily from 46.9°C at the surface to 30.4°C at 20 cm and levelled off thereafter. The trend line depicted the following highly significant (P = <. 0.01) quadratic Ts versus Z relationship:

$$Ts = 0.0376\ Z^2 - 1.547\ Z + 44.048 \qquad (r^2 = 0.893)$$

The overall mean soil temperature showed a slight decrease from 33.0 at the surface to 30.4°C at 2.5 cm and nearly levelled off at lower depths. The trend line depicted the following quadratic Ts versus Z relationship:

$$Ts = 0.0072\ Z^2 - 0.2626\ Z + 31.913 \qquad (r^2 = 0.5672)$$

The overall minimum soil temperature increased steadily with depth from 22.5°C at the surface to 30.0°C at 20 cm and then levelled off. The trend line depicted the following highly significant ($P< 0.001$) quadratic Ts versus Z relationship:

$$Ts = -\ 0.0112\ Z^2 + 0.6176\ Z + 21.763 \qquad (r^2 = 0.9785)$$

Fig. 4 shows the average sinusoidal air and temperature profiles of the two sites in August,1997. The air temperature was 26.1 at 1 a.m. and it decreased with increase of time reaching a minimum value of 22.6 °C at 5 a.m.; afterwards, it increased steadily with increase of time reaching 30.0 °C at 11 a.m. and a maximum value of 36.0 °C at 15 hrs. It progressively decreased with time reaching 27.6 °C at 24.00 hrs.

At the soil surface, the temperature was 27.0 °C at 1 a.m., decreased with increase of time reaching a minimum value of 23.7 °C at 4 a.m. At 8 a.m., it reached 27.0 °C, equal to that at the surface, and it continued to increase reaching a maximum value of 46.9 °C at 15 hrs. Afterwards, it decreased with time reaching 27.7 °C at 24.00 hrs.

At 1 a.m., the soil temperature was 30.2°C at 10 cm. It decreased with increase of time reaching a minimum value of 27.7°C at 6 a.m. At 12 a.m., it reached 30.3°C, and it continued to increase reaching a maximum value of 31.8°C at 15 hrs and 31.9 at 16 hrs. Afterwards, it decreased with time reaching 30.2 °C at 24.00 hrs.

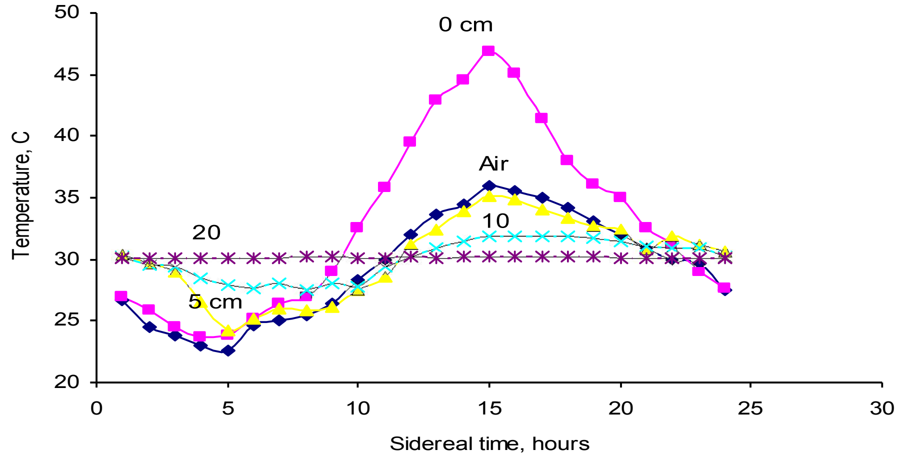

Fig 4. Average diurnal variation of soil temperature of the two sites at different soil deths under Al-Rawashda forest in August 1997 (Autumn)

At 20 and 30 cm, the soil temperature profiles were similar. The soil temperature at both depths ranged from 30.5°C to 30.1 with a mean of 30.1°C and an average C.V. of 0.25 %.

The amplitude of the soil temperature waves decreased with increase of soil depth ranging from 13.9 at the soil surface to 0.3 at 20 and 0.4 at 30 cm depth (Table 3).

Diurnal variation of soil temperature

In general, the C.V. of the soil surface was slightly lower than that of the air in winter, but higher than that of the air in summer and autumn. The C.V. of the soil temperature showed highly significant ($P < 0.001$) quadratic decrease with increase of soil depth. For example for the month of May (summer), the C.V. value at any depth may be predicted from the following equations:

$$C.V. = 0.0458\, Z^2 - 2.1712\, Z + 24.607 \qquad (r^2 = 0.9866)$$

It is fortunate that in all seasons, the fluctuation of soil temperature at lower depths, where the maximum root density occurs, is very small. Thus, the crop at the germination stage may be subjected to relatively higher soil temperature fluctuation. However, at a later stage when the root system reaches ≥ 20 cm, the soil temperature remains almost constant. This fact is an essential consideration when breeding crops for temperature tolerance.

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ظروف رطوبة وحرارة تربة تحت أشجار الصمغ العربى (*Acacia senegal* L.) فى غابة الرواشدة بالقضارف

كمال الدين محمد عثمان ومختار احمد مصطفى

كلية الزراعة، جامعة الخرطوم، شمبات، السودان

موجز البحث: أجريت الدراسة لجمع قاعدة بيانات واسعة لظروف رطوبة وحرارة تربة "فيرتيسولز" تحت اشجا ر الهشاب فى غابة الرواشدة، على بعد 35 كم شمال شرق مدينة القضارف . تم قياس مؤشرات ظروف الرطوبة التالية: معدلات الامطار والتسرب والتبخر من وعاء الولايات المتحدة صنف أ، والمخزون المائي والبخرنتح الحقيقى . فى عام 1997 كان المعدل السنوى للأمطار 403.1 مم، 48% منها هطلت فى شهر أغسطس، و82% فى يوليو وأغسطس وسبتمبر. لقد امتلأت التربة بالماء فى هذه الثلاثة شهور واستنفدت رطوبتها وجفت أثناء فترة أكتوبر – مارس وبدأت تبتل بهطول الامطار فى ابريل - مايو. ولقد تراوح معدل التبخر بين 2.9 و 5.6 مم/اليوم فى الخريف و بين 7.5 و 13.6 مم/اليوم فى الشتاء و بين 12.8 و 16.0 فى الصيف. كان المخزون المائى فى أدنى مستواه فى 14 مايو و أعلى مستواه فى 5 سبتمبر 1997. وبالرغم من أن الأمطار خفضت ميل ضغط البخار، إلا إنها زادت كمية الماء الميسر فى سطح التربة ومن ثم زادت معدل التبخر. لذلك فإن متوسط معدل التبخر (Em) بالمليمتر زاد معنويا (مستوى 5%) بزيادة متوسط معدل الأمطار الشهرى (Rm) بالمليمتر وفق المعادلة الأسية التالية: $Em = 1738\ Rm^{0.5402}$ (ر^2 = 0.790). إن مجموع بيانات معدل التسرب (IR)

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*جزء من أطروحة قدمها المؤلف الأول لجامعة ألخرطوم كجزء من مطلوبات درجة الماجستير فى الزراعة

كدالة للزمن (t) التى جمعت فى ثلاثة شهور اعطت المعادلة الأسية التالية: $IR = 0.344\ t^{-0.527}$ (ر^2 = 0.985)، وعليه يوصى باستخدامها للتنبؤ بمعدل التسرب. كانت علاقات التبخر التراكمى كدالة للزمن خطية فى كل شهور القياس. و تم حساب معامل المحصول من بيانات معدل الامطار التراكمى وتبخر الوعاء . تم قياس حرارة الهواء والتربة اليومية والشهرية والموسمية وفى كل ساعة خلال بعض الايام كمؤشرات لظروف التربة الحرارية. فى عام 1997 كان متوسط حرارة الهواء 32.1 مئوية فى الصيف و29.1 مئوية فى الخريف و 23.7 مئوية فى الشتاء. وكان متوسط حرارة سطح التربة 38.0 مئوية فى ألصيف و 33.4 مئوية فى الخريف و 25.2 مئوية فى الشتاء. وانخفضت ذبذبة حرارة التربة بازدياد عمق التربة ووصلت 0.15 أو أقل عند أعماق ≤ 20 سم . لقد أعطت بيانات الحرارة القصوى والدنيا والمتوسطة، كدالة لعمق التربة، علاقات أسية معنوية فى كل المواسم.