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Differential Yield Response of Groundnut, Maize and Sorghum to Water Management

Michel OMOKO[1]* and Luther C. HAMMOND[2]

[1]Department of Soil Science, University of Dschang P.O.Box 294 Dschang, Cameroon
[2]Department of Soil & Water Science, University of Florida, P.O.Box 110290, Gainesville, Florida 32611-0290 USA
*Corresponding Author: Tel: (237) 771-48-36 E-mail: omokomich@yahoo.fr

ABSTRACT

Irrigation scheduling is very critical on groundnut and, at a lesser extent on grain sorghum because of the limited yield response and the risk of yield depression or poor grain quality which can result from over-irrigation. Two experiments were conducted to compare responses of various yield components of groundnut, sorghum and maize to water in order to design optimum field water managements for these crops. The experimental site was a well-drained Millhopper fine sand. Groundnut, sorghum and maize, planted as subplots were subjected to 4 water treatments as main plots in 4 replications: (1) optimum irrigation based on maize water requirements, (2) irrigation allowing 2 days of wilt on sorghum, or (3) on groundnut, and (4) rainfed. Irrigation frequency and seasonal amount decreased from treatment 1 to 4. Yields of groundnut, sorghum and maize increased linearly with seasonal irrigation or ET. Harvest index and ET WUE of the 2 cereals decreased with increasing water stress. These parameters were more fluctuating in groundnut, where the highest harvest index was recorded in treatment 3, followed by 2, 1 and 4, while the ET WUE decreased from treatment 2 to 3, 1 and 4. Irrigation-use efficiency was high for maize (81.7%), but rather low for sorghum (45.2%) and groundnut (29.2%), indicating over-irrigation of these last 2 crops. Treatment 1 was adequate for maize, but resulted in poor grain quality in sorghum and depressed harvestable yield in groundnut. The threshold soil water matric potential at which to irrigate for optimum grain yield was quite high and crop-dependent: -20 kPa for maize (whole crop cycle) and sorghum (from planting to early grain filling period), -50 kPa for sorghum (grain filling and maturing periods) and groundnut (whole crop cycle). These threshold values are greater than those generally found in the literature.

Keywords: Yield, Water use, Groundnut, Maize, Sorghum.

INTRODUCTION

Efficient water management is one of the most challenging environmental issues of the 21st century. Globally, agriculture is the biggest water consumer in the world [1] and irrigation remains an essential farm input in many areas [2]. Improving water use efficiency in irrigated farming is therefore a priority for better environmental and economic sustainability of today's agriculture [3, 4]. Irrigation scheduling has been an important research topic for several decades now and continues to be so today as it can be illustrated by the abundant scientific literature on the matter [5, 6]. Irrigation scheduling strategies and models vary a lot in terms of scope, necessary data input, complexity and applicability in the farm. Deficit irrigation, which is the deliberate and systematic under-irrigation of crops [7] is a common practice in many areas in the world where water supply is limited or when irrigation costs are high [8]. Though resulting in possible yield reductions, this irrigation strategy is usually aimed at maximising water-use efficiency (WUE) and increasing profits through reduced production costs [9]. It is of utmost importance to be able to quantify such yield reductions in order to minimise the risks of crop failure.

Transpirational WUE is necessarily connected to stomatal control of gas exchange rates at the leaf/atmosphere boundary. The light-induced opening of stomates during the day to take in CO_2 necessary for photosynthesis also allows water vapor to escape, in response to the evaporative demand of the atmosphere. Bierhuizen and Slatyer [10] showed that photosynthetic WUE is directly proportional to the CO_2 gradient and indirectly proportional to the vapor pressure deficit gradient between the bulk air and the CO_2 fixation sites inside the leaf. This implies that:

(i) a given crop grown in different climatic zones represented by various vapor pressure deficits may exhibit different WUE;

(ii) all other conditions being equal, C4 plants would be expected to have a greater WUE than C3 because of the differences in their respective photosynthetic pathways.

Nevertheless, the C4 pathway itself may not confer any special tolerance to water stress [11, 12] as evidenced by the lack of tolerance of maize to drought compared to soybean [13]. Even though maize had a higher CO_2 assimilation rate during favorable water conditions, inhibition of photosynthesis due to stomatal closure began at higher leaf water potentials (-3.5 bars) in maize than in soybean (-11 bars). Transpiration WUE has been shown to remain relatively constant for a given crop in a given environment [14]. But it is difficult to measure transpiration under field conditions where crop water use is expressed in terms of actual ET or irrigation amount. Viets [15] pointed out that WUE is a constant only when plants are grown in widely spaced containers having sealed surfaces to prevent evaporation. Yield response to water management in the field is then an extremely dynamic and complex process because of the multiple interactions among the yield-determining plant parameters under limited water conditions. This is particularly true when relating marketable yield to water use [16]. Both linear [17-19] and curvilinear [20-22] relationships between grain yield and seasonal ET or irrigation have been reported.

The farmer is more concerned with minimizing the cost of the water used while improving its economic return by maximizing crop WUE, than with biomass productivity as such. The best water management strategy should be designed to obviate water stress and prevent water from becoming a limiting factor [23]. Stegman *et al.* [24] summarized all these considerations when they stated that water management practices should be designed to: (a) maximize yield per unit of land area, (b) maximize yield per unit of water applied, (c) maximize net profit, and (d) minimize energy cost.

United States Department of Agriculture [25] submitted sorghum and alfalfa to various irrigation strategies and water stress conditions; they reported that the ET WUE was independent of the irrigation treatment in sorghum, but in alfalfa a lower water supply increased WUE as much as 49%. On the other hand, Hillel and Guron [21] reported a reverse situation when they found that ET WUE of corn systematically increased with increased irrigation which maintained continuous high soil water conditions in the root zone. The apparent contradiction between these two sets of results may be due to the differential response of the respective crops to soil water status.

Irrigation scheduling is very critical on groundnut and, at a lesser extent on sorghum because of limited yield response and the risk of yield depression or poor grain quality which can result from over-irrigation. In order to compare yield response of maize, sorghum and groundnut to water management and design better irrigation strategies, two experiments were conducted at the Irrigation Research and Education Park (IREP), University of Florida, Gainesville.

MATERIALS AND METHODS

Three experiments were conducted in two consecutive growing seasons at the Irrigation Research and Education Park (IREP) of the University of Florida, Gainesville. The region has a subtropical climate classified as semi-hot semi-tropical moist monsoon with a minimum of 250 day frost-free growing season running from March to October [26]. The soil of the experimental site is a level, well-drained Millhopper fine sand (loamy, hyperthermic Grossarenic Paleudult) with an underlying argillic horizon starting at 100–190 cm depth.

Crops and Experimental Design

The maize hybrid was the Pioneer 3165, the sorghum crop was the Northrup King Savanna 5 hybrid which is bird-resistant, while groundnut cultivars were Florunner the first year and Southern Runner the second year.

The layout was a randomized block, split-plot design with four water managements as main treatments and four cropping systems as subtreatments, in four replications. Each main plot was 14 m x 14 m in size, divided into four 7 m x 7 m subplots planted to maize, sorghum, groundnut and sorghum-groundnut intercropped. All sole crops were planted in 61 cm rows at a density of 256000 (sorghum), 160000 (groundnut) and 80000 (maize) plants/ha after thinning. Prior to planting, the seedbed preparation involved plowing, incorporation of 0-10-20 (N-P_2O_5-K_2O) fertilizer containing 0.06% B, 0.06% Cu, 0.36% Fe, 0.15% Mn and 0.014% Mo as top dressing at a rate of 830 kg/ha, and of Furadan at a rate of 43 kg/ha, and then disking. Ammonium nitrate was applied in bands along maize and sorghum rows as side dressing in three split applications at 16, 36 and 56 days after sowing (DAS), resulting in a total of 250 kg N /ha; 900 kg/ha of gypsum were broadcast on groundnut crop at 45 DAS as source of calcium to promote pod filling. All crops were properly cared for against weeds, pests and diseases during the growing seasons. Full canopy cover in sorghum was attained around 47, 51, and 58 DAS in treatments 1, 2 and 3, respectively. The corresponding dates were 62, 66, and 69 DAS in maize, and 78, 82 and 90 DAS in groundnut. None of the rainfed plots attained full canopy cover in sorghum or maize, whereas groundnut reached complete ground cover around 100-120 DAS in year 2.

Water Management

The four water treatments were:

(1) optimum water management in which irrigation was applied to prevent any visible stress on anyone of the three crops. Water application was based on maize water requirements and was triggered whenever soil water matric potential at 0.15 and/or 0.30 m depths was less than –20 kPa in maize subplots;

(2) irrigation after two days of visible wilt on sorghum or when soil water matric potential at 0.15 and/or 0.30 m depths was less than –50 kPa in sole sorghum subplots;

(3) irrigation after two days of visible wilt on groundnut or when soil water matric potential at 0.15 and/or 0.30 m depths was less than –50 kPa in sole groundnut subplots; and

(4) rainfed, except when all treatments were irrigated for crop establishment (0-17 DAS in year 1, and 0-32 DAS in year 2).

Seasonal irrigation amounts decreased from treatment 1 to 4. The strategy used in irrigation scheduling was to partly replenish soil profile within the root zone during periods of deficit rainfall (when rainfall was less than crop ET) in order to take advantage of any unexpected precipitation. Irrigation water was applied early in the morning when winds were calm, using a solid-set impact sprinkler system. Quarter circle sprinklers located at each corner of 14 m x 14 m plots gave a full two-sprinkler overlap along the plot edges and a four-sprinkler overlap in the center, resulting in an uneven water distribution. Only the central square of each plot (5.6 m x 5.6 m) in which the rate of irrigation application had a coefficient of uniformity of 97.21% was used for water budget measurements.

One neutron access tube (inserted down to the top of the argillic horizon) and a set of ten tensiometers in 15 cm depth increments, were installed in each subplot, 0.15 m off the 4th crop row from the plot centre. Water content data were collected every other day using a Troxler 1651 neutron probe. Tensiometers were read every day with a Soil Measurement Systems' tensimeter.

Drainage Experiment on Bare Soil

In order to determine the hydraulic characteristics of soil in the experimental site to be used in soil water budget calculations, 2 of the 16 plots were selected, based on their relative position and overall representativeness of the physical characteristics of the whole site, for a drainage experiment. After harvesting the crops in year 2, all plant residues were removed from the soil surface in these 2 plots. Five aluminum neutron access tubes (to a soil depth of 2.4 m) and five sets of 10 tensiometers (in 0.15 m depth increments) were installed in the inner 2.8 by 2.8 m central square in each plot, giving a total of 5 access tubes and 50 tensiometers per plot. The spacing between the access tubes within a given plot was 1.58 m, and the companion set of tensiometers was at least 0.45 m away. Irrigation water was then applied using a solid-set sprinkler system at a rate varying from 18 on the borders to 31 mm/hour on the center of the plots where all the water monitoring devices were located. Water was applied in 4 settings of 120 minutes each, resulting in a total irrigation depth of about 248 mm of water in the central part of the plots. After each irrigation run, tensiometer readings were taken in order to locate the depth of the wetting front. Irrigation was stopped after the wetting front had crossed the 1.50 m depth and the pressure head profiles were relatively uniform within the investigated soil depths. Water contents and hydraulic heads were then measured simultaneously at variable time intervals for 42 days, starting from 4 minutes after the initiation of drainage, using a neutron probe (in 0.15 m depth increments) and a tensimeter. Between 2 rounds of measurements, plots were allowed to drain freely and were entirely covered with a 5-mm polyethylene sheet to prevent any direct soil water evaporation.

The data collected on noncropped plots were then used to determine the *in situ* hydraulic conductivity as a function of water content or matric potential at selected soil depths based on Darcy's equation using the unsteady-flux methods [27]. Water flux in a vertical one-dimensional soil body can be expressed as

$$q = - K\,(dH/dZ) \qquad (1)$$

where q is the soil water flux (L/T), H the hydraulic head (H=h-Z), h the matric potential, Z the vertical distance or depth (positive downward), K the hydraulic conductivity (L/T), dH/dZ the hydraulic gradient (L/L). To describe conditions of unsaturated, unsteady, isothermal, nonhysteretic flow during drainage, Eq. (1) must be combined with the continuity equation (Eq. 2) to yield a nonlinear partial differential equation known as the Richards equation (Eq.3)

$$\partial\theta/\partial t = -\partial q / \partial Z \qquad (2)$$

$$\partial\theta(Z,t)/\partial t = \partial\,[K(\theta)\,\partial H(Z,t) / \partial Z] / \partial Z \qquad (3)$$

where θ is the volume soil water content (L^3/L^3), t time (T), K(θ) the unsaturated hydraulic conductivity of the soil as a function of soil water content (L/T). To solve Eq.(3) we need to set initial and boundary conditions:

At time t = 0, the soil water flux q is assumed to be constant throughout the soil profile for depths $0 \leq Z \leq L$;

For t > 0, q at the soil surface is equal to zero.

Integrating Eq. [3] and solving for K, explicitly, yields

$$\int_0^L \left[\partial\theta(Z,t)/\partial t\right] dZ = K(\theta)\,\partial H(Z,t)/\partial Z\big|_L - K(\theta)\,\partial H(Z,t)/\partial Z\big|_0 \qquad (4)$$

Since the soil surface was covered to prevent any flux across the upper boundary, then the second term of the right hand side of Eq.(4) is zero. Equation (4) can then be simplified to

$$\int_0^L \left[\partial\theta(Z,t)/\partial t\right] dZ = K(\theta)\,\partial H(Z,t)/\partial Z\big|_L \qquad (5)$$

Solving Eq.(5) for $K(\theta)$, explicitly, yields

$$K(\theta) = \frac{\int_0^L \left[\partial\theta(Z,t)/\partial t\right] dZ}{\partial H(Z,t)/\partial Z\big|_L} \qquad (6)$$

A finite difference technique was used to evaluate *K(θ)* at discrete times and depths; θ and ∂H/∂Z were averaged in both space and time at selected depths (in 0.15 m increments) and times during drainage.

Let $\Delta\theta = (\theta_{i+1} - \theta_i)$ and $\Delta t = (t_{i+1} - t_i)$

where i represents a time value, $\Delta\theta$ the change in water content during the time interval Δt. The average hydraulic gradient over that time interval can be evaluated as

$$\left(\overline{\partial H} / \overline{\partial Z}\right)\Big|_L = \frac{1}{2}\left[\left(\frac{\partial H}{\partial Z}\right)_{i+1} + \left(\frac{\partial H}{\partial Z}\right)_i\right]_L \qquad (7)$$

Eq.(6) can then be rewritten as

$$K(\overline{\theta}) = \frac{\int_0^L \left[(\theta_{i+1} - \theta_i)/(t_{i+1} - t_i)\right] dZ}{(1/2)\left[(\partial H/\partial Z)_{i+1} + (\partial H/\partial Z)_i\right]_L} \qquad (8)$$

where $$\overline{\theta} = \frac{1}{2}\left(\theta_{i+1} + \theta_i\right)_L \qquad (9)$$

Eq.(8) was used to determine hydraulic conductivity as a function of soil water content in 0.15 m depth increments in the bare soil.

Soil Water Budget

The K(θ) functions determined during the drainage experiment were then used to compute water percolation below the root zone in the cropped plots during the growing cycle.

The depth of the active root zone increased with time and was based on maize root development rate as described by [19] in a previous experiment on this same site. The maximum rooting depth attained by various maize varieties ranged between 1.40 and 1.68 m during their three years experiment, with an average of 1.54 m at physiologic maturity.

Computations of water budgets were made based on the following assumptions:

(1) Surface runoff and internal horizontal soil-water flow were negligible;

(2) Hysteresis of the K(θ) function was not an important factor;

(3) Water flux below the active root zone obeyed Darcy's law;

Using the water depletion method for measuring evapotranspiration (ET), the soil water balance equation for any time period can be expressed as

$$P+I = ET+R+D+\Delta S+\Delta V \qquad (10)$$

where P is precipitation during the time period, I irrigation amount, ET amount of water lost to the atmosphere by evapotranspiration or root water uptake, R surface runoff (negligible given the level, well-drained sandy nature of the soil), D downward drainage out of (D>0) or upward capillary rise into (D<0) the root zone, ΔS change in soil water storage within the root zone (positive or negative), ΔV the change in plant water storage (negligible). The only unknowns in Eq.(10) are ET and D; the drainage was calculated using the predetermined K(θ) functions at given depths [28]:

$$D(\bar{\theta})|_L = \int_{t1}^{t2} K(\bar{\theta})\overline{\partial H} / \overline{\partial Z}|_L \qquad (11)$$

$D(\bar{\theta})|_L$ is the amount of water drained across the soil depth L below the root zone in mm, between 2 measurement dates t1 and t2; $K(\bar{\theta})$ is the hydraulic conductivity as a function of average water content at depth L, $\overline{\partial H} / \overline{\partial Z}|_L$ is the average gradient measured at depth L.

Daily actual ET was then calculated by difference from Eq.(11) for each soil profile and mean values computed for each water treatment. The upper and lower limits of available soil water in the effective rhizosphere were also determined. The upper limit (UL) was defined as the highest field-measured water content of the soil (θ_u) over the rooting depth after it has been thoroughly wetted and allowed to drain until drainage becomes practically negligible [29, 30]. The lower limit (LL) was taken as the water content at permanent wilting point (θ_{pwp} at -1.5MPa) over the rooting depth:

$$UL = \int_0^L \theta_u dZ \text{ and } LL = \int_0^L \theta_{pwp} dZ \qquad (12) \text{ and } (13)$$

The difference between Eq.(12) and (13) is the apparent available soil water [31, 32].

Harvest procedures

An area of 4.88 m^2 was sampled in each subplot to estimate crop yield at physiological maturity, 102 DAS (treatment 1), 107 DAS (treatment 2), 126 DAS (treatments 3 and 4) for sorghum, 122 DAS for maize, 134 DAS for Florunner and 160 DAS for Southern Runner groundnut. The harvested area consisted of 4 meters of row (0.5-4.5 m from the plot centre) on the 3rd and 4th rows from the centre line in each plot. The above-ground biomass was dried at 65.5°C (corn and sorghum) or 32.2°C (groundnut) until constant weight. Groundnut biomass consisted of both above- and below-ground parts. Kernel yields were then adjusted to 15.5% (corn), 13% (sorghum), and 7% (groundnut) gravimetric water contents.

Crop Yield and Water Use Relationships

Dry matter yield was related to seasonal transpiration according to

$$DMY_a/T_a = m/T_{max} \text{ or } DMY_a = m\, T_a/T_{max} \qquad (14)$$

where DMY_a is total dry matter yield (kg ha^{-1}), T_a, in-season transpiration (cm), T_{max}, mean daily free water evaporation during the growing cycle (cm day^{-1}); m is a constant dependent on crop species (kg ha^{-1} day^{-1}). The model of Stewart *et al.* [17] was used to predict dry matter yield from actual ET as follows:

$$DMY_a/DMY_{max} = 1- \beta_0 ET_D = 1- \beta_0 + \beta_0 ET_a/ET_{max} \qquad (15)$$

where β_0 is the slope of relative dry matter yield vs. ET deficit (ET_D). When $DMY_a/DMY_{max}=0$, soil evaporation can be approximated by the ratio ET_a/ET_{max}. The portion of ET_{max} that is T_{max} is equal to $1/\beta_0$. Thus a β_0 of 1.0 would mean no water loss by direct evaporation from the soil. The value of β_0 must be ≥ 1.0 [33]. Comparing Eq. (1) and (2) reveals that m factor can be computed as

$$m = DMY_{max}\, T_{max}\, \beta_0/ET_{max} \qquad (16)$$

Marketable yields are related to ET according to [34]

$$(1-Y_a/Y_{max}) = ky\,(1-ET_a/ET_{max}) \qquad (17)$$

where Y_a is actual marketable yield attained when evapotranspiration is equal to ET_a, ky is the yield response factor [8].

Statistical Analysis

Analysis of variance, regression and means separation procedures were performed on measured or calculated hydrodynamic data at selected times using the Proc Anova, Proc Reg and LSD in SAS software [35]. The same procedures were used to analyse crop yields.

RESULTS

Yield components and in-season water use of groundnut, maize and sorghum crops are reported on tables 1, 2 and 3 for both seasons. In year 1, groundnut and sorghum dry matter and grain yields were not significantly different (α =0.05) among the 4 water treatments, whereas maize yields were higher in treatments 1 (optimum irrigation) and 2 (stress on sorghum) than in treatment 3 (stress on groundnut) and lastly treatment 4 (rainfed). Treatments 1 and 2 were not significantly different at α =0.05 for maize. In the 2nd year, treatments 1, 2 and 3 were not significantly different (α =0.05) for both groundnut dry matter and grain yields. Only the rainfed treatment had significantly lower yields.

Treatments 1 and 2 were not significantly different for sorghum, whereas grain yields for this crop were lower in treatment 3 and lastly in the rainfed treatment. The situation was quite different for maize with treatment 1 yielding more than all the other treatments, followed by the 2 deficit irrigation treatments, and lastly treatment 4.

Table 1: Yield of Florunner (yr1) & Southern Runner (yr 2) Groundnut subjected to four Water Managements at IREP, Gainesville, Florida

Water Treatment	Seasonal water use (mm) Irrigation	Rainfall	ET	DM Yield kg/ha)	Grain Yield (kg/ha)
Yr 1					
1	309	455	434^{a} (37)	11957^{a} (571)	5040^{a} (362)
2	137	455	428^{a} (39)	11448^{a} (1279)	4678^{a} (488)
3	110	455	426^{a} (35)	12720^{a} (1281)	4782^{a} (495)
4	47	455	405^{a} (33)	12594^{a} (1075)	4735^{a} (293)
LSD (α=0.05)			39	924	632
Yr 2					
1	482	501	536^{a} (41)	13510^{a} (897)	4505^{a} (539)
2	345	501	549^{a} (39)	3900^{a} (1909)	4920^{a} (610)
3	280	501	526^{a} (38)	12420^{a} (1817)	4580^{a} (439)
4	100	501	423^{b} (34)	9865^{b} (922)	2755^{b} (746)
LSD (α=0.05)			41	2259	751

Standard deviation in parentheses

Values followed by the same letter in a given column are not significantly different (LSD test at α=0.05)

Table 2: Yield of Pioneer 3165 Maize subjected to four Water Managements at IREP, Gainesville, Florida

Water Treatment	Seasonal water use (mm) Irrigation	Rainfall	ET	DM Yield (kg/ha)	Grain Yield (kg/ha)
Yr 1					
1	289	425	578^{a} (36)	22581^{a} (1102)	10923^{a} (428)
2	134	425	559^{a} (38)	19952^{a} (1259)	9545^{a} (892)
3	110	425	505^{b} (33)	16874^{b} (3012)	7612^{b} (1847)
4	47	425	398^{c} (41)	11253^{c} (2841)	4325^{c} (822)
LSD (α =0.05)			40	2633	1729
Yr 2					
1	404	420	589^{a} (32)	23430^{a} (1058)	11340^{a} (494)
2	283	420	527^{b} (34)	18615^{b} (1396)	8035^{b} (999)
3	237	420	466^{c} (30)	15710^{b} (3039)	6500^{b} (2021)
4	100	420	348^{d} (34)	8020^{c} (2203)	1020^{c} (746)
LSD (α=0.05)			38	3191	1869

Standard deviation in parentheses

Values followed by the same letter in a given column are not significantly different (LSD test at α=0.05)

Table 3: Yield of Northrup King Savanna 5 Sorghum subjected to four Water Managements at IREP, Gainesville, Florida.

Water Treatment	Seasonal water use (mm) Irrigation	Rainfall	ET	DM Yield (kg/ha)	Grain Yield (kg/ha)
Yr 1					
1	239	379	410^{a} (25)	16777^{a} (702)	6252^{a} (485)
2	117	379	408^{a} (23)	15757^{a} (1667)	6357^{a} (279)
3	100	379	403^{a} (27)	15221^{a} (1774)	6325^{a} (266)
4	47	379	383^{a} (31)	14677^{a} (1722)	6316^{a} (224)
LSD (α =0.05)			38	2140	998
Yr 2					
1	368	286	419^{a} (23)	16900^{a} (639)	8030^{a} (415)
2	241	286	373^{b} (31)	17180^{a} (1590)	7140^{a} (344)
3	195	289	352^{b} (29)	13550^{b} (1956)	4580^{b} (1008)
4	100	289	297^{c} (27)	11720^{b} (1476)	3550^{c} (632)
LSD (α=0.05)			36	2304	1006

Standard deviation in parentheses

Values followed by the same letter in a given column are not significantly different (LSD test at α=0.05)

Irrigation and ET water production functions (WPF) of the 3 crops are summarised in tab. 4. Pooled relative above-ground dry matter yields vs. relative in-season ET for the three crops are depicted in figure 1. All these regression functions are statistically significant at the 5% probability level. The calculated m factor values are 192, 168 and 90 kg ha^{-1}day^{-1} for maize, sorghum and groundnut, respectively.

Yield response factors (YRF), ky, (i. e. slope of relative grain yield reduction vs. relative ET deficit) are represented on figure 2.

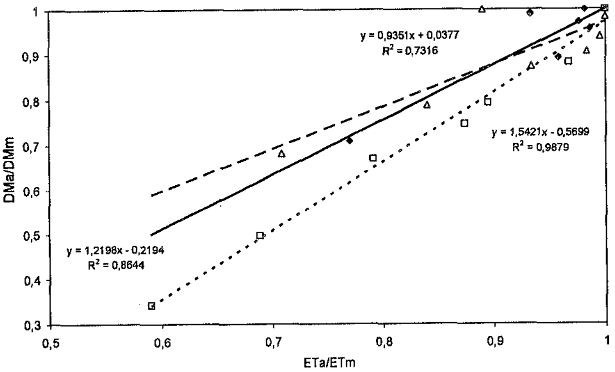

Figure 1: Relative above-ground dry matter yield vs. relative seasonal ET for groundnut (◆ ——), maize (□ ········) & sorghum (Δ– – –) in 2 growing seasons at IREP, Gainesville.

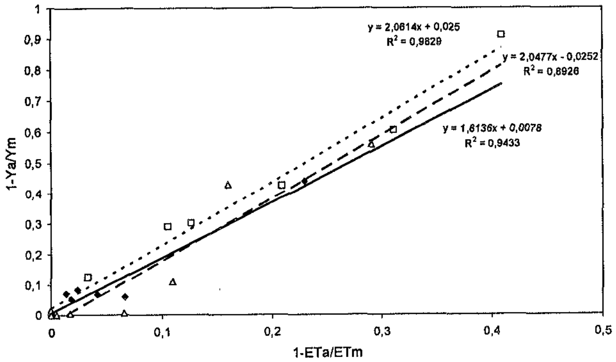

Figure 2: Relative grain yield reduction vs. relative ET deficit for groundnut (◆ ——), maize (□ ·········) & sorghum (Δ– – –) in 2 consecutive seasons at IREP, Gainesville.

DISCUSSION

Rainfall events were fairly well distributed throughout the 1st growing season; this did not allow a good differentiation of water treatments. In the 2nd year, all the three crops responded well to irrigation. The decrease in irrigation frequency from treatment 1 to 4 resulted in increasing crop water stress in the same order. Sorghum grain yield was more affected by water stress than total above-ground biomass as illustrated by the drop in harvest index (HI) values from 0.475 in treatment 1 to 0.415, 0.338 and 0.303 in treatments 2, 3 and 4 respectively. Water stress caused the abortion of many flowers and the enhancement of tillering as the crop recovered later from the droughty periods. Tillering increased total biomass more than it did grain yield. Evapotranspirational WUE was very variable: 40.3, 46.1, 38.5 and 39.5 kg dry matter/ha/mm water for treatments 1, 2, 3 and 4 in that order. The respective values for grain yield decreased more gradually with decreasing irrigation amounts: 19.2, 19.1, 13.0 and 11.9.

Unlike sorghum, maize dry matter and grain yields were depressed in about the same proportions by water stress, resulting in systematic increases in both yields with increasing irrigation. Nevertheless, the drop in harvest index was drastic in the rainfed treatment, 0.127 against 0.484, 0.432, and 0.414 for treatments 1, 2 and 3 respectively. Maize ET WUE decreased systematically with decreasing irrigation: 39.8, 35.3, 33.7 and 23.0 kg DM/ha/mm, and 19.2, 15.2, 13.9, 2.9 kg grain/ha/mm for the respective treatments. The values for treatment 1 compare well with those reported by Stewart *et al.* in California and Colorado [17], or by Howell *et al.* in texas [36].

Groundnut was less sensitive to water stress. Only the yields in the rainfed treatment were significantly less than in the others (Table 1). Harvest index was higher in treatment 3 (0.369), followed by treatments 2 (0.354), 1 (0.333) and 4 (0.279). High soil water status promoted more vegetative growth than grain yield in groundnut. Furthermore, the quantity of grains remaining in the soil at harvest (drops) increased systematically with increasing irrigation: 685, 556, 357 and 217 kg grains/ha in treatments 1, 2, 3 and 4 respectively. Groundnut ET WUE based on dry matter decreased quite regularly with decreasing irrigation (25.2, 25.3, 23.6, 23.3 kg/ha/mm) whereas values for grain yield were more fluctuating (8.4, 9.0, 8.7 and 6.5).

There was about a 2-fold WUE advantage of sorghum and maize over groundnut on the basis of grain yield in irrigated treatments, but that advantage decreased (even disappeared for maize) in the rainfed treatment. Aboveground dry matter and grain yields responded linearly both to irrigation and ET amounts in both years. Usually, curvilinear relationships between yield and irrigation amount are indicative of excessive loss of water by deep percolation or surface runoff due to over-irrigation. On the other hand, curvilinear ET production functions usually result from over-estimation of actual ET by not accounting for the amount of water lost by deep drainage beyond the rhizosphere [37]. Irrigation functions exhibited smaller slopes than ET functions (Table 4). The ratios of the two slopes were used to estimate the irrigation-use efficiency (IUE) as suggested by [20]. The calculated ratios were 0.333, 0.437, 0.816 for dry matter yield, and 0.292, 0.452, 0.817 for grain yield of groundnut, sorghum and maize respectively. This means that only 29.2% of irrigation water was used to improve groundnut grain yield, against 45.2% for sorghum and 81.7% for maize, indicating over-irrigation for the two former crops. The respective yield response factors were 1.813, 2.048 and 2.061. These values indicate that groundnut, sorghum and maize grain yields declined 1.813, 2.048 and 2.061 times as fast as their respective ET reductions. Solving the different equations on figure 2 for Ya = 0 shows that an ET reduction to 52.7% (or an ET deficit of 47.3%) of the observed maximum ET (measured in treatment 1) would result in zero grain yield for maize. The corresponding ET reduction values that would have resulted in $Y_a = 0$ are 49.9% and 45.3% for sorghum and groundnut, respectively.

Table 4: Water production functions of groundnut, maize & sorghum at IREP, Gainesville

Crop	Irrigation Production Functions		ET Production Functions	
	Function	R^2	Function	R^2
Groundnut	DM_1=-2.395 IR+12541	0.21	DM_1=-24.95 ET+22740	0.28
	DM_2=10.273 IR+9324	0.81	DM_2=30.797 ET-3236	0.96
	GY_1=1.252 IR+4620	0.77	GY_1=6.553 ET+2035	0.27
	GY_2=4.890 IR+2714	0.64	GY_2=16.753 ET-4329	0.99
Maize	DM_1=42.252 IR+11538	0.80	DM_1=59.633 ET-12748	0.98
	DM_2=51.144 IR+3351	0.99	DM_2=62.672 ET-13795	0.99
	GY_1=24.542 IR+4542	0.78	GY_1=35.113 ET-9806	0.98
	GY_2=34.072 IR-1999	0.99	GY_2=41.686 ET-13390	0.99
Sorghum	DM_1=10.845 IR+14244	0.97	DM_1=60.148 ET-8511	0.69
	DM_2=20.435 IR+10219	0.74	DM_2=46.708 ET-1989	0.79
	GY_1= -0.3965 IR+6362	0.54	GY_1=-0.592 ET+6550	0.03
	GY_2=17.678 IR+1830	0.87	GY_2=39.110 ET-8264	0.88

DM=Aboveground Dry Matter (kg/ha); GY=Grain Yield (kg/ha); IR=in-season irrigation (mm); ET= in-season ET (mm); subscripts $_1$ & $_2$ stand for year 1 & 2.

CONCLUSION

Yields of the three crops were affected differently by water stress as reflected in their respective HI, WUE, WPF, IUE and YRF. Maize grain yield was the most affected by soil water deficits, followed by grain sorghum and then groundnut. This was probably due to the combined effects of shallower rooting habit and presumed greater physiological sensitivity of maize to drought, as compared to sorghum and groundnut, despite the reputation of water-stress tolerance of Pioneer 3165 hybrid [38]. The leveling off of yield as irrigation increased, observed with sorghum and groundnut but not with maize, suggests that the former crops received more irrigation water (particularly in treatment 1) than needed to achieve maximum ET and yields. This shows that there can be opportunities to improve the ET efficiency of these crops through a better irrigation scheduling.

The soil water matric potential thresholds at which these three crops should be irrigated for optimum water use efficiency must be crop- and soil-dependent. On fine sand textures, maintaining soil matric potential at -20 kPa or higher in the root zone throughout the growing cycle would result in optimum yield for maize, even though such high matric potentials may contribute to significant water loss by deep drainage due to unexpected rainfalls. The same threshold value is recommended for grain sorghum until the end of the flowering stage, after which it should be decreased to -50 kPa until harvest. The threshold for groundnut should be -50 kPa throughout the growth cycle. These values are much higher than those generally recommended in the literature and are due to the loamy sand nature of the Millhopper soil series. In all cases, water should be applied in small amounts at each irrigation event to take full advantage of any unexpected rainfall and reduce water loss by deep drainage.

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