**Available online at http://ajol.info/index.php/ijbcs**

Int. J. Biol. Chem. Sci. 4(3): 587-600, June 2010

International Journal of Biological and Chemical Sciences

ISSN 1991-8631

*Original Paper*

http://indexmedicus.afro.who.int

# Comparison of soil water capture rates of irrigated sole versus intercropped *Sorghum bicolor* and *Arachis hypogaea*

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## ABSTRACT

A fundamental understanding of how intercrop systems capture and use water resources is crucial in providing the scientific basis of the advantage of mixed crops over sole cropping. The objective of this paper was to investigate how water management affects the temporal and spatial water capture ability of each crop in an intercrop system. Field experiments were conducted in 2 contrasting growing seasons on a level, well-drained loamy, Grossarenic Paleudult. Sorghum and groundnut, sown as sole crops and intercrops were subjected to 4 water treatments in 4 replications. The 4 treatments were: (1) Optimum irrigation, (2) deficit irrigation allowing 2 days of stress on sorghum, or (3) on groundnut, (4) rain fed. Sole crops were seeded in 30 or 60 cm rows at densities of 256000 (sorghum), 160000 (groundnut) plants/ha. In the intercrop, 2 rows of sorghum 30 cm apart, were alternated with 2 rows of groundnut 45 cm apart, resulting in densities of 157000 p/ha for sorghum and 102000 p/ha for groundnut. Daily and seasonal crop water use rates ($ET_C$) of both crops in the mixture were slightly higher than in the corresponding sole crops in all but the rain fed treatments during the growth cycle in the drier year, with a seasonal increase in the intercrop $ET_C$ of 8.90, 8.21 and 8.78% relative to sole cropping in treatments 1, 2 and 3. The contrary was observed in the wetter year with a slight decrease in the mixture $ET_C$ of 2.47, 2.47 and 0.38% in treatments 2, 3, and 4. Likewise, intercropping increased the seasonal water capture efficiency by 8.47, 6.94 and 8.51% respectively in treatments 1, 2, and 3 relative to sole cropping during the dry year. The improved water uptake rate and efficiency of the intercrop system was attributable to the spatial and temporal complementarities and reduced competition between the component crops.

**Keywords**: Water capture, sole crop, intercrop, spatial and temporal complementarities.

## INTRODUCTION

The concept of resource capture defined as the uptake per unit area (Morris & Garrity, 1993a), has been used to assess resource use efficiencies of various farming systems. This concept has been applied to light interception or capture to investigate the mechanisms responsible for over yielding in intercropping systems and to the understanding of temporal and spatial complementarities in intercropping systems (Black & Ong, 2000). Under intercropping systems, natural resources (i.e., land, soil nutrients, water, heat and radiation) may be used more effectively both in time and in space as compared to sole cropping (Rodrigo et al., 2001; Gao et al., 2009). Many studies have shown that higher efficiencies can be achieved with intercropping in the utilization of radiation (Awal et al., 2006), nutrients (Rowe et al., 2005), land (Dhima et al., 2007; Zhang et al., 2007), and water (Morris & Garrity, 1993b; Mandal et al., 1996; Walker & Ogindo, 2003).

The resource capture principle can be applied to water by breaking its utilization down into capture and conversion efficiency components. Solar energy drives both $CO_2$ assimilation and water transpiration, and because of the functional link between these two processes, the quantity of dry matter produced is highly correlated to the quantity of water captured and the efficiency with which that water is used to produce dry matter (Passioura, 2006). Actively growing well-watered vegetation generally transpires at rates determined by the prevailing evaporative demand of the atmosphere. But the relationship between transpiration and absorption rates depends on both aboveground (canopy architecture and conductance, canopy physiological attributes, aerodynamic conductance, atmospheric saturation deficit, air temperature, solar radiation, wind speed) and belowground (soil properties, soil water content and potential, roots characteristics) factors (van Duivenbooden et al., 2000; de Barros et al. 2007; Jahansooz et al., 2007).

These relationships are even more complex in intercrop systems because of their extensive horizontal and vertical variations in canopy and root architectures that are constantly changing. Partitioning of water capture or use between the component crops of intercropping systems is very problematic (Black & Ong, 2000). Three general approaches may be used: (i) Evapotranspiration (ET) by each component crop is measured separately; (ii) Total community water use and ET by one of the components are measured, and ET by the other component is calculated as the difference; (iii) ET may be estimated using ET models based on solar radiation intercepted by each crop.

Each of the three approaches has its advantages and inconveniences. The first method is more reliable (Black & Ong, 2000), but is too demanding, labour-intensive and costly (Zhang et al., 2009). To overcome these limitations, mathematical modelling of ET has been attempted by many authors (Katerji & Rana, 2006; Ortega-Farias et al., 2007; Zhang et al., 2008). The FAO-Penman-Monteith model (Allen et al., 1998; Campbell, 2000; Mdemu et al., 2009) has been widely adopted to estimate ET from open water surfaces and uniform full-cover canopies in a range of agricultural and natural vegetations. However, the model is less accurate when applied to mixed or discontinuous vegetation due to the difficulty of obtaining suitable values for aerodynamic and canopy resistances (Lovelli et al., 2008; Mdemu et al., 2009). In the second approach, the estimates for each component crop are not statistically independent and the values derived by difference are influenced by two sets of errors. Despite these drawbacks, this approach has been the most widely used (Corlett et al., 1992; Ong et al., 1996; Wallace, 1996; McIntyre et al., 1997).

There is substantial agronomic evidence concerning yield advantage of intercropping over sole cropping (Ogindo & Walker, 2005). A fundamental understanding of how the intercropping systems capture and use resources, especially a mobile resource like water would provide the scientific basis for explaining how these yield advantages come about (Walker & Ogindo, 2003). Yield advantage of crops in mixtures often stems from the capacity of the component species to increase capture and use of available resources as compared to sole cropping (Jahansooz et al., 2007). Poor capture and use of water and radiation are usually associated with low leaf area during the establishment and senescence phases of single crops (Caviglia et al., 2004; Jahansooz et al., 2007). Agronomic practices that shorten these “lost time to growth” phases can increase capture and efficiency in the use of resources (Caviglia et al., 2004). This is achievable by mixing crop species of widely different phenology and/or morphology to maximize capture of, and minimize competition for, solar radiation and soil-water (van Duivenbooden et al., 2000; Jahansooz et al., 2007).

The seasonal soil-water balance of a cropped land can be expressed as follows:

$$\Delta S = P + I \pm D \pm R - E - T \quad \ldots\ldots\ldots\ldots [1]$$

Where $\Delta S$ = change in the water content in the root zone; P= precipitation; I= irrigation; D= downward drainage out of the root zone (-) or upward capillary flow into the root zone (+); R= runoff (-) or run on (+); E= evaporation from the soil surface; and T= transpiration. E and T can be merged as evapotranspiration. This equation can be rearranged as follows:

$$T = P + I \pm \Delta S \pm D \pm R - E \quad \ldots\ldots\ldots\ldots\ldots [2]$$

To allow for the maximum amount of water to be available for crop transpiration (T), and thereby leading to maximum crop growth and yield, the parameters on the right hand side of Eq.[2] should be optimized (van Duivenbooden et al., 2000; Jahansooz et al., 2007). Furthermore, water productivity (i.e., biomass or yield per unit water input, WP) can be analysed as the product of capture and efficiency factors (Caviglia et al., 2004; Steduto et al., 2007):

$$WP = C_{WATER} \times WUE \quad \ldots\ldots\ldots\ldots\ldots [3]$$

Where $C_{WATER}$ is water capture efficiency calculated as the ratio between seasonal crop evapotranspiration (ET) and available water, and WUE is water use efficiency calculated as above-ground biomass (or yield) per unit ET. Though biomass water productivity is shown to be conservative, water use efficiency can be improved through the increase in $C_{WATER}$ (Kassam et al., 2007).

The objective of this paper is to investigate how water management affects the temporal and spatial water capture ability of component crops in a sorghum/groundnut intercrop system by (i) monitoring soil water status in the root zone;
(ii) measuring ET rates for each crop using the water balance approach; and
(iii) comparing water capture efficiency of the two cropping systems.

## MATERIALS AND METHODS

The field work was conducted during two consecutive growing seasons on a level, well-drained fine sand, classified as a loamy, hyperthermic Grossarenic Paleudult (US soil Taxonomy) with an underlying argillic horizon starting at 120-190 cm depth.

### Experimental layout

The layout was a randomized block, split-plot design with four water managements as main treatments and four cropping systems as sub treatments, in four replications. Each main plot was 14 m x 14 m in size, split into four 7 m x 7 m subplots planted to sorghum, groundnut, sorghum/groundnut intercropped, and maize. Sole crops were planted in rows 30 cm (60 cm in year 2) apart at a density of 256000 (sorghum, after thinning), 180000 (160000 in season 2) (groundnut) plants/ha. In season 1 intercropping planting followed an additive scheme with each crop seeded in 30 cm alternate rows at 100% of the sole crop density. In season 2, intercropped sorghum/groundnut were seeded in two paired rows of sorghum 30 cm apart, alternating with two paired rows of groundnut 45 cm apart. The distance between sorghum and groundnut rows was 60 cm, resulting in a density of 157000 p/ha for sorghum (61.3% of sole sorghum density occupying 46% of land area) and 102000 p/ha for groundnut (63.8% of sole groundnut density sown on 54% of land area). The groundnut cultivars were Florunner (season 1) and Southern Runner (season 2), whereas Northrup King Savanna 5 sorghum hybrid was used in both seasons. The seedbed was fertilized according to the common practice in the region and all the crops were properly cared for against weeds, pests and diseases during the two growing seasons.

### Water management

The four water treatments were:

(1) Optimum water management in which irrigation was applied to prevent any visible stress on crops. Water application was triggered whenever soil water pressure (matric potential) at 15 and/or 30 cm depths was less than –20 kPa.

(2) Irrigation after two days of visible wilt on sorghum, or when soil water pressure at 15 and/or 30 cm depths was less than –50 kPa in sole sorghum subplots.

(3) Irrigation after two days of visible wilt on groundnut or when soil water pressure at 15 and/or 30 cm depths

was less than –50 kPa in sole groundnut subplots.

(4) Rain fed, except when all treatments were irrigated early in the season for seed germination and crop establishment.

Treatments 2 and 3 were identical during the 1st growing season, because of fairly well distributed rainfall. Seasonal irrigation amounts decreased from treatment 1 to 4. Irrigation was applied using a solid-set impact sprinkler system. Quarter circle sprinklers located at each corner of 14 x 14 m plots gave a full two-sprinkler overlap along the plot edges and a four-sprinkler overlap in the centre, resulting in an uneven water distribution. Only the central part of each plot (5.6 x 5.6 m) in which the rate of irrigation application had a coefficient of uniformity of 97.21% was used to monitor soil water balance. A set of 1 neutron access tube and 10 tensiometers (at 15, 30, 45, 60, 75, 90, 105, 120, 135, 150 cm depths) was installed in each sole crop subplot, 15 cm off the 4th crop row from the plot centre. Two sets of same devices were installed in each intercrop subplot in between sorghum and groundnut rows, respectively. Soil water content and potential were measured daily using a neutron probe and a tensimeter, respectively. Daily water budgets were then calculated for each soil profile using the soil water balance method and mean values computed for each water treatment.

The soil water balance equation for any time period can be expressed as

$$P + I = ET \pm R \pm D \pm \Delta S + \Delta V \quad \ldots\ldots\ldots\ldots [4]$$

Where $\Delta V$ is the change in plant water storage (negligible); the other terms are defined as in Eq [1]. R was negligible given the level, well-drained sandy nature of the soil. The only unknowns in Eq. [4] are ET and D; the drainage was calculated using the pre-determined $K(\theta)$ functions at given depths as proposed by Omoko & Hammond (2007):

$$D(\bar{\theta})\,|_L = \int_{t_1}^{t_2} K(\bar{\theta})\,\overline{\partial H / \partial Z}\,|_L \quad \ldots\ldots [5]$$

$D(\bar{\theta})\,|_L$ is the amount of water drained across the soil depth L below the root zone in mm, between 2 measurement dates $t_1$ and $t_2$; $K(\bar{\theta})$ is the hydraulic conductivity as a function of average volume water content at depth L, $\overline{\partial H} / \overline{\partial Z}\,|_L$ is the average hydraulic gradient measured at the progressive maximum depth of the crop root zone, L, that varied from 5 cm at plant emergence to 150 cm at harvest (Hammond & Bennett, 1988). Daily actual ET was then calculated by difference from Eq.[4] for each soil profile and mean values computed for each water treatment.

Using Morris and Garrity (1993b) approach, we calculated changes in crop evapotranspiration ($ET_C$) and in water capture efficiency ($C_{WATER}$) of intercrops relative to sole crops as:

$$\Delta V = 100 \times [(V_{IS} + V_{IG}) / (V_{SS}+V_{GG}) - 1] \quad \ldots\ldots [6]$$

Where $\Delta V$ is the change in variable $V=ET_C$ or $V=C_{WATER}$, and subscripts $_{IS}$, $_{IG}$, $_{SS}$ and $_{GG}$ indicate intercrop sorghum, intercrop groundnut, sole sorghum and sole groundnut, respectively.

### Statistical analysis

Analysis of variance, orthogonal contrast test and paired-difference t-test procedures were performed on measured or calculated hydrodynamic data at selected soil depths and times using the SAS software (SAS Institute, 1999). The null hypothesis was rejected each time the p-value was $\leq 0.05$; p-value is the smallest probability of being wrong when rejecting the null hypothesis Ho (or concluding the alternative hypothesis Ha).

## RESULTS

### Soil water potential

Daily matric potentials in selected water treatments and crop root zone depths during the second growing season in one replicate are represented on Figures 1 to 3. Matric potential values were quite systematically lower in intercrop sorghum root zone in almost all treatments and depths, followed by sole sorghum, intercrop groundnut and lastly sole groundnut during the vegetative and early flowering growth periods of both crops (40- 80 DAS). These trends changed around the mid- and late-season development stages of sorghum (80-110 DAS) where intercrop groundnut exhibited the lowest matric potentials, thus the driest water status as compared to intercrop sorghum, sole groundnut and sole sorghum. This trend continued after the harvest of sorghum, 102 (treatment 1), 107 (treatment 2) and 126 (treatments 3 and 4) days after sowing (DAS), with intercrop groundnut systematically experiencing drier soil conditions than sole groundnut. The 3 other replications showed similar trends in matric potential variations.

The seasonal comparison of the daily matric potentials between sole crops and intercrops using the paired difference t-test is summarized on Table 1. The reported values are the seasonal mean differences in matric potential of sole minus intercrop at the selected depths of 15, 30 and 90 cm for the 4 replicates in each water treatment. A positive matric potential difference means that the sole crop had a higher matric potential, thus wetter soil conditions than intercrop. A negative difference implies the reverse. Sole sorghum root zone had higher water potential values at 120 data points at 15 cm, 128 data points at 30 cm, and 112 data points at 90 cm soil depths in treatment 2, as against 28, 12 and 24 data points for intercrop sorghum at the respective depths. The corresponding comparison between sole and intercrop groundnut gives 208, 200, and 184 data points with higher water potentials for sole groundnut as against 16, 20 and 48 for intercrop groundnut, respectively. All the other water treatments showed similar trends, except the rain fed treatment. The overall seasonal mean differences in matric potential values between sole crops and intercrops were quite systematically positive, indicating lower water potentials, thus drier soil conditions for intercrops as compared to sole crops.

## Soil water balance

Periodic soil water budgets in the root zone of the various crops are represented on Tables 2 to 7. As with the matric potentials, intercrop sorghum showed significantly higher water uptake rates than sole sorghum in treatments 2 (deficit irrigation allowing stress on sorghum) and 3 (deficit irrigation allowing stress on groundnut) all over the cropping cycle, except at 70-81 and 102-105 DAS for treatment 2, 102-105 DAS for treatment 3. The same trend was observed with intercrop groundnut having higher evapotranspiration rates than sole groundnut in all treatments (Tables 5 to 7). Consequently, intercropping was more efficient in capturing soil water than sole cropping in almost all the treatments and times. It also suffered more from water deficit and stress as illustrated by the rain fed treatment. The severity of water deficit in this treatment seriously hampered the development of the sorghum crop, with sole sorghum being less affected. This explains why sole sorghum showed higher ET rates than intercrop sorghum throughout the growing cycle in that treatment.
Table 8 summarizes the effects of water management and cropping system on seasonal water uptake of the various crops for the two growing seasons. The input represents seasonal rainfall + irrigation, $ET_C$ is apparent seasonal crop evapotranspiration and $E_0$ is computed reference evapotranspiration according to FAO-Penman-Monteith (Allen et al., 1998). Based on $ET_C$ the difference between the two cropping systems was highly significant in both seasons and all treatments (contrast test at $p \leq 0.05$), and there was a significant interaction between the cropping systems and the water treatments. The seasonal water extraction efficiencies ($C_{WATER}=ET_C/Input$) were very variable, ranging from 64.07 to 90.12% for sole sorghum, 66.05 to 93.41% for intercrop sorghum, 54.53 to 80.84% for sole groundnut, and 54.78 to 77.45% for intercrop groundnut. The relative seasonal evapotranspiration (ratio of crop ET over reference ET, $ET_C/ET_0$) also varied a lot.

The seasonal water uptake amounts and efficiencies of the intercropping system relative to sole cropping are reported in Table 9. The results are somewhat contrasting between season 1 (wet year) and 2 (dry year). Intercropping increased crop ET by 8.90, 8.21 and 8.78% relative to sole cropping in treatments 1, 2 and 3, respectively during the dry year. Likewise, water capture efficiency was increased by 8.47, 6.94 and 8.51% in these same treatments. A reverse situation was observed during the wet year with a decrease both in intercrop $ET_C$ and $C_{WATER}$ in treatments 2, 3 and 4 relative to sole cropping

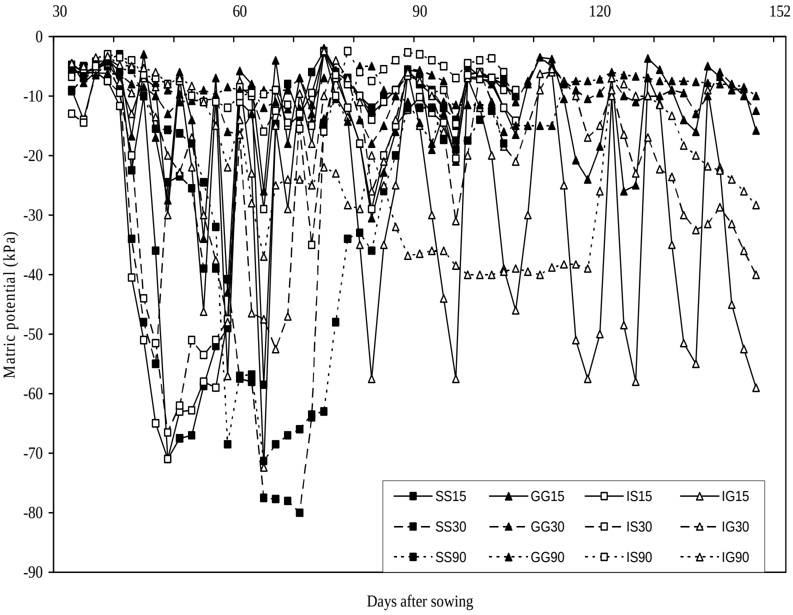

**Figure 1:** Daily matric potential at 15, 30 and 90 cm in the rhizosphere of sole sorghum (SS), sole groundnut (GG), intercrop sorghum (IS) and intercrop groundnut (IG) in rep 1, treatment 2 during the growing season 2.

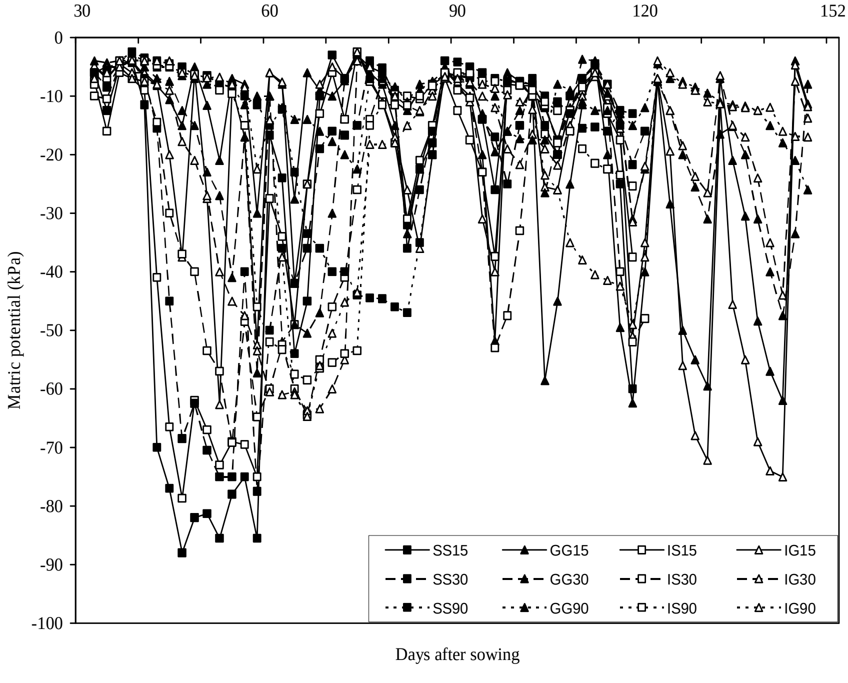

**Figure 2:** Daily matric potential at 15, 30 and 90 cm in the rhizosphere of sole sorghum (SS), sole groundnut (GG), intercrop sorghum (IS) and intercrop groundnut (IG) in rep 1, treatment 3 during the growing season 2.

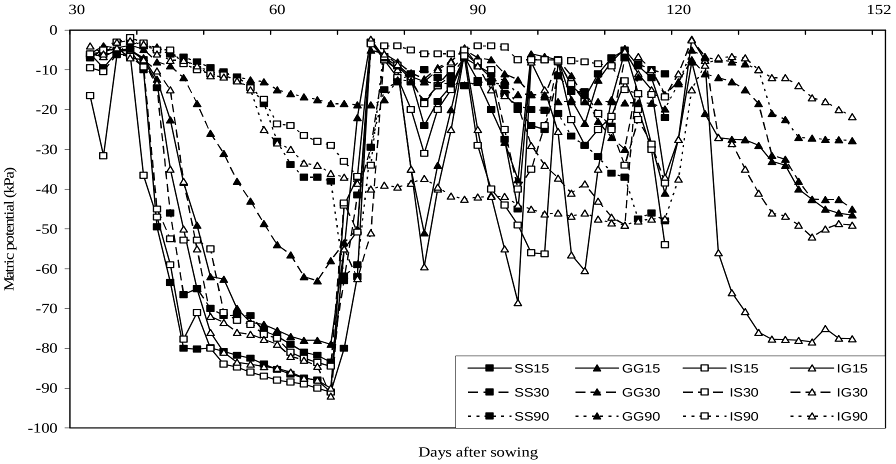

**Figure 3:** Daily matric potential at 15, 30 and 90 cm in the rhizosphere of sole sorghum (SS), sole groundnut (GG), intercrop sorghum (IS) and intercrop groundnut (IG) in rep 1, treatment 4 during the growing season 2.

**Table 1:** Comparison of daily matric potentials for selected treatments and depths in the root zone of sole vs. intercrop (Paired difference t-test using all 4 replicates in each treatment).

| Trt(Sea.) | Depth (cm) | Sole–Intercrop | No. of obs. | Mean difference (kPa) | Prob >\|T\| |
|---|---|---|---|---|---|
| 2(2) | 15 | SS-IS | 152 | 4.19±1.67 | 0.0169 |
| 2(2) | 15 | GG-IG | 236 | 13.92±1.89 | 0.0001 |
| 2(2) | 30 | SS-IS | 152 | 8.15±2.43 | 0.0019 |
| 2(2) | 30 | GG-IG | 236 | 10.78±1.51 | 0.0001 |
| 2(2) | 90 | SS-IS | 152 | 7.84±2.02 | 0.0004 |
| 2(2) | 90 | GG-IG | 236 | 13.26±1.42 | 0.0001 |
| 3(2) | 15 | SS-IS | 176 | -1.72±1.39 | 0.22 NS |
| 3(2) | 15 | GG-IG | 236 | 3.01±1.68 | 0.07 NS |
| 3(2) | 30 | SS-IS | 176 | 4.71±2.46 | 0.06 NS |
| 3(2) | 30 | GG-IG | 236 | 3.63±1.57 | 0.0247 |
| 3(2) | 90 | SS-IS | 176 | 3.01±2.54 | 0.24 NS |
| 3(2) | 90 | GG-IG | 236 | 8.35±1.90 | 0.0001 |
| 4(2) | 15 | SS-IS | 176 | 6.72±2.22 | 0.0042 |
| 4(2) | 15 | GG-IG | 236 | 14.07±2.09 | 0.0001 |
| 4(2) | 30 | SS-IS | 176 | 2.33±1.65 | 0.16 NS |
| 4(2) | 30 | GG-IG | 236 | 13.31±1.81 | 0.0001 |
| 4(2) | 90 | SS-IS | 176 | -9.66±1.52 | 0.0001 |
| 4(2) | 90 | GG-IG | 236 | 12.80±1.89 | 0.0001 |

Trt(Sea.) = Treatment(Season); SS = Sole Sorghum; IS = Intercrop Sorghum; GG = Sole Groundnut; IG=Intercrop Groundnut; Tabulated values are Mean differences ± SEM; NS = Not significant (p> 0.05).

**Table 2:** Periodic soil water balance in the rhizosphere of sorghum, treatment 2 (season 2).

| DAS | INPUT | Sole Sorghum | | Intercrop Sorghum | | p-value |
|---|---|---|---|---|---|---|
| | | D | $ET_C$ | D | $ET_C$ | |
| 0 – 32 | 135.4 | 30.1 | 89.7±0.3b | 28.3 | 93.3±1.0a | 0.008 |
| 32 - 38 | 79.8 | 21.5 | 32.9±1.2b | 20.2 | 35.7±1.3a | 0.0001 |
| 38 – 46 | 17.5 | 19.4 | 47.8±1.8b | 18.6 | 50.9±1.3a | 0.009 |
| 46 – 52 | 23.9 | 1.3 | 35.4±2.4a | 1.2 | 36.5±0.5a | 0.34 NS |
| 52 – 59 | 42.0 | 0.1 | 37.8±2.9a | 0.1 | 36. 8±1.9a | 0.10 NS |
| 59 – 70 | 43.4 | 0.1 | 45.1±3.7b | 0.1 | 45.4±2.7a | 0.03 |
| 70 – 81 | 54.0 | 3.3 | 39.8±5.7a | 4.5 | 36.3±2.4b | 0.002 |
| 81 – 88 | 59.3 | 13.2 | 21.7±5.1a | 1 3.1 | 22.3±1.6a | 0.2 NS |
| 88 – 95 | 7.6 | 11.5 | 23.3±4.6a | 11.5 | 23.5±0.9a | 0.2 NS |
| 95 – 102 | 64.2 | 19.4 | 24.2±4.6a | 19.5 | 23.7±0.6a | 0.2 NS |
| 102-105 | 5.8 | 1.6 | 8.9±5.6a | 2.1 | 6.2±0.9b | 0.0001 |
| TOTAL | 532.9 | 121.5 | 406.6±3.4b | 119.2 | 410.6±1.4a | 0.003 |

$ET_C$ Mean ± SEM are based on 4 observations. Values followed by the same letter in a given row are not significantly (NS) different (contrast test at p≤0.05); DAS= Days After Sowing; Input= rain +Irrigation; D= drainage; $ET_C$= crop evapotranspiration. INPUT, D and $ET_C$ are all in mm.

**Table 3:** Periodic soil water balance in the rhizosphere of sorghum, treatment 3 (season 2).

| **DAS** | **INPUT** | **Sole Sorghum** | | **Intercrop Sorghum** | | **p-value** |
|---|---|---|---|---|---|---|
| | | **D** | **$ET_C$** | **D** | **$ET_C$** | |
| 0 – 32 | 135.4 | 30.4 | 89.3±0.9a | 28.5 | 91.5±1.6a | 0.2 NS |
| 32 - 38 | 79.8 | 24.5 | 31.2±1.3b | 24.2 | 32.4±1.9a | 0.032 |
| 38 – 46 | 2.5 | 14.5 | 43.2±1.9b | 14.3 | 44.7±2.6a | 0.0003 |
| 46 – 52 | 18.8 | 1.0 | 22.1±1.7b | 0.9 | 24.7±2.6a | 0.0003 |
| 52 – 59 | 36.0 | 0.1 | 29.0±2.8b | 0.1 | 31.2±3.4a | 0.0001 |
| 59 – 70 | 44.8 | 0.0 | 37.1±4.1b | 0.0 | 40.2±2.9a | 0.0001 |
| 70 – 81 | 54.0 | 1.5 | 39.3±2.3a | 1.7 | 35.6±2.6a | 0.2 NS |
| 81 – 88 | 59.3 | 4.7 | 26.4±3.7b | 4.2 | 31.4±5.4a | 0.024 |
| 88 – 95 | 7.6 | 10.6 | 26.2±4.8b | 9.9 | 32.8±5.2a | 0.0002 |
| 95 – 102 | 43.2 | 1.2 | 32.8±4.2b | 1.1 | 36.6±3.6a | 0.0001 |
| 102-105 | 5.8 | 0.3 | 11.0±2.4a | 0.4 | 9.7±0.9b | 0.014 |
| 105-115 | 50.0 | 2.2 | 41.3±2.9b | 2.0 | 46.7±5.7a | 0.05 |
| 115-122 | 120.1 | 47.7 | 33.6±0.8b | 44.1 | 39.8±5.1a | 0.006 |
| 122-126 | 2.8 | 19.4 | 19.8±1.2b | 19.0 | 25.2±1.2a | 0.03 |
| TOTAL | 660.1 | 158.1 | 482.3±2.5b | 150.4 | 522.5±3.2a | 0.001 |

$ET_C$ Mean±SE are based on 4 observations. Values followed by the same letter in a given row are not significantly (NS) different (contrast test at $p \leq 0.05$); DAS= Days After Sowing; Input= rain +Irrigation; D= drainage; $ET_C$= crop evapotranspiration. INPUT, D and $ET_C$ are all in mm.

**Table 4:** Periodic soil water balance in the rhizosphere of sorghum, treatment 4 (season 2).

| **DAS** | **INPUT** | **Sole Sorghum** | | **Intercrop Sorghum** | | **p-value** |
|---|---|---|---|---|---|---|
| | | **D** | **$ET_C$** | **D** | **$ET_C$** | |
| 0 – 32 | 135.4 | 29.0 | 89.9±1.7a | 28.4 | 93.1±2.2a | 0.17 NS |
| 32 - 38 | 79.8 | 26.7 | 30.5±1.6a | 27.1 | 27.9±2.2b | 0.046 |
| 38 – 46 | 2.5 | 19.5 | 34.7±3.0a | 19.6 | 32.5±1.5b | 0.007 |
| 38 – 46 | 2.5 | 19.5 | 34.7±3.0a | 19.6 | 32.5±1.5b | 0.007 |
| 46 – 52 | 2.8 | 0.3 | 9.22±2.9a | 0.3 | 8.6±1.4b | 0.002 |
| 52 – 59 | 0.0 | 0.1 | 9.0±3.1a | 0.1 | 8.1±1.7b | 0.003 |
| 59 – 70 | 22.4 | 0.0 | 16.1±2.8a | 0.3 | 14.0±2.3b | 0.035 |
| 70 – 81 | 54.0 | 2.1 | 38.0±3.5a | 4.2 | 34.4±2.7b | 0.02 |
| 81 – 88 | 38.4 | 1.2 | 26.8±1.6a | 2.3 | 22.2±3.1b | 0.023 |
| 88 – 95 | 7.6 | 0.5 | 22.3±1. 4a | 0.7 | 19.8±3.0b | 0.002 |
| 95 – 102 | 43.2 | 0.1 | 37.8±1.7a | 1.3 | 33.2±1.4b | 0.001 |
| 102-105 | 5.8 | 0.2 | 13.2±3.1a | 0.9 | 12.0±1.0b | 0.004 |
| 105-115 | 29.0 | 0.0 | 30.5±5.4a | 0.2 | 28.3±1.8a | 0.058 |
| 115-122 | 99.1 | 25.7 | 28.2±4.7a | 26.1 | 26.4±1.7b | 0.02 |
| 122-126 | 2.8 | 10.9 | 10.0±2.2a | 11.1 | 9.1±0.9a | 0.09 NS |
| TOTAL | 522.8 | 116.3 | 396.2±2.8a | 122.6 | 369.6±1.9b | 0.001 |

$ET_C$ Mean±SE are based on 4 observations. Values followed by the same letter in a given row are not significantly (NS) different (contrast test at $p \leq 0.05$); DAS= Days After Sowing; Input= rain +Irrigation; D= drainage; $ET_C$= crop evapotranspiration. INPUT, D and $ET_C$ are all in mm.

**Table 5:** Periodic soil water balance in the rhizosphere of groundnut, treatment 2 (season 2).

| DAS | INPUT | Sole Groundnut | | Intercrop Groundnut | | p-value |
|---|---|---|---|---|---|---|
| | | D | $ET_C$ | D | $ET_C$ | |
| 0 – 32 | 135.4 | 51.8 | 73.6±0.7a | 52.3 | 70.2±0.7b | 0.009 |
| 32 - 38 | 79.8 | 46.4 | 16.0±1.4a | 46.8 | 14.5±1.1b | 0.006 |
| 38 – 46 | 17.5 | 21.3 | 29.8±1.8a | 21.6 | 28.6±1.7b | 0.0009 |
| 46 – 52 | 23.9 | 4.0 | 23.8±1.5a | 2.3 | 25.2±1.4a | 0.34 NS |
| 52 – 59 | 42.0 | 1.4 | 37.0±1.7a | 1.1 | 38.7±1.6a | 0.09 NS |
| 59 – 70 | 43.4 | 0.3 | 50.2±1.9b | 0.2 | 55.3±2.0a | 0.001 |
| 70 – 81 | 54.0 | 0.8 | 49.5±5.7b | 0.1 | 55.1±2.8a | 0.0001 |
| 81 – 88 | 59.3 | 4.0 | 26.0±9.5b | 1.3 | 35.8±3.8a | 0.0002 |
| 88 – 95 | 7.6 | 1.6 | 36.8±9.0b | 0.7 | 42.3±5.1a | 0.0002 |
| 95 – 102 | 64.2 | 12.6 | 36.4±9.3b | 5.2 | 43.5±4.9a | 0.0023 |
| 102-105 | 5.8 | 1.5 | 12.9±5.4b | 0.8 | 16.6±2.2a | 0.0001 |
| 105-115 | 50.0 | 8.0 | 36.8±2.7b | 4.7 | 46.2±1.8a | 0.0001 |
| 115-122 | 120.1 | 55.6 | 25.2±1.4b | 26.2 | 29.6±1.9a | 0.0001 |
| 122-130 | 2.8 | 7.8 | 34.9±1.5b | 3.6 | 39.1±1.7a | 0.0001 |
| 130-139 | 42.0 | 4.7 | 31.1±5.0b | 3.2 | 39.8±2.1a | 0.0073 |
| 139-146 | 4.2 | 0.9 | 19.5±8.0b | 0.3 | 28.0±1.9a | 0.02 |
| 146-156 | 60.0 | 10.8 | 27.1±4.7b | 8.4 | 34.6±2.1a | 0.03 |
| 156-160 | 34.5 | 17.4 | 12.0±0.3b | 12.2 | 13.2±1.8a | 0.027 |
| TOTAL | 846.5 | 250.9 | 578.6±4.0b | 191.0 | 656.3±2.2a | 0.001 |

$ET_C$ Mean±SE are based on 4 observations. Values followed by the same letter in a given row are not significantly (NS) different (contrast test at p≤0.05); DAS= Days After Sowing; Input= rain +Irrigation; D= drainage; $ET_C$= crop evapotranspiration. INPUT, D and $ET_C$ are all in mm.

**Table 6:** Periodic soil water balance in the rhizosphere of groundnut, treatment 3 (season 2).

| DAS | INPUT | Sole Groundnut | | Intercrop Groundnut | | p-value |
|---|---|---|---|---|---|---|
| | | D | $ET_C$ | D | $ET_C$ | |
| 0 – 32 | 135.4 | 51.0 | 73.8±1.8a | 52.1 | 71.3±2.0a | 0.4 NS |
| 32 - 38 | 79.8 | 47.2 | 16.5±2.3a | 47.4 | 16.2±2.3a | 0.23 NS |
| 38 – 46 | 2.5 | 20.7 | 20.9±2.6b | 20.1 | 22.9±2.6a | 0.047 |
| 46 – 52 | 18.8 | 3.6 | 17.4±1.7b | 2.0 | 24.5±2.9a | 0.0003 |
| 52 – 59 | 36.0 | 2.8 | 28.1±2.7b | 0.9 | 39.2±3.9a | 0.0001 |
| 59 – 70 | 44.8 | -0.9 | 42.0±3.9b | -5.6 | 50.4±4.4a | 0.0001 |
| 70 – 81 | 54.0 | 2.9 | 48.1±8.2b | -1.1 | 55.1±5.8a | 0.02 |
| 81 – 88 | 59.3 | 4.4 | 24.5±8.8b | 1.2 | 38.1±7.8a | 0.0245 |
| 88 – 95 | 7.6 | 5.4 | 33.9±8.2b | 0.7 | 48.2±6.9a | 0.0002 |
| 95 –102 | 43.2 | 0.6 | 33.3±6.5b | 0.4 | 46.8±7.6a | 0.0001 |
| 102-105 | 5.8 | 0.3 | 13.5±2.9b | 0.1 | 19.0±4.5a | 0.0138 |
| 105-115 | 50.0 | 6.1 | 39.0±1.1a | 7.2 | 31.9±5.9a | 0.055 NS |
| 115-122 | 120.1 | 52.6 | 25.2±1.5a | 36.2 | 17.1±3.7b | 0.0065 |
| 122-130 | 2.8 | 13.0 | 28.8±1.9a | 14.2 | 25.3±1.4b | 0.0006 |
| 130-139 | 21.0 | 0.4 | 30.6±1.5a | 1.2 | 25.5±1.5b | 0.0272 |
| 139-146 | 25.2 | -0.1 | 21.1±1.2a | 0.8 | 17.5±2.8b | 0.0001 |
| 146-156 | 39.0 | 0.1 | 22.7±5.5a | 1.6 | 19.8±1.0a | 0.077 NS |
| 156-160 | 34.5 | 5.1 | 11.4±3.3a | 6.2 | 9.7±1.2b | 0.0032 |
| TOTAL | 779.8 | 215.2 | 530.8±3.6b | 185.6 | 578.5±3.8a | 0.002 |

$ET_C$ Mean±SE are based on 4 observations. Values followed by the same letter in a given row are not significantly (NS) different (contrast test at p≤0.05); DAS= Days After Sowing ; Input= rain +Irrigation; D= drainage; $ET_C$= crop evapotranspiration. INPUT, D and $ET_C$ are all in mm.

**Table 7:** Periodic soil water balance in the rhizosphere of groundnut, treatment 4 (season 2).

| **DAS** | **INPUT** | **Sole Groundnut** | | **Intercrop Groundnut** | | **p-value** |
|---|---|---|---|---|---|---|
| | | **D** | **$ET_C$** | **D** | **$ET_C$** | |
| 0 – 32 | 135.4 | 50.7 | 72.1±1.2a | 51.5 | 71.8±0.9a | 0.17 NS |
| 32 - 38 | 79.8 | 45.7 | 17.2±2.9a | 45.9 | 15.2±1.8b | 0.0466 |
| 38 – 46 | 2.5 | 18.3 | 27.4±2.7b | 17.1 | 30.4±1.6a | 0.007 |
| 46 – 52 | 2.9 | 2.5 | 11.3±2.2b | 2.0 | 14.9±1.6a | 0.003 |
| 52 – 59 | 0.0 | -7.7 | 15.1±1.5b | -7.9 | 17.4±1.5a | 0.003 |
| 59 – 70 | 22.4 | -1.0 | 17.5±1.4a | -1.3 | 17.2±1.4a | 0.09 NS |
| 70 – 81 | 54.0 | 0.6 | 45.4±1.7a | 1.1 | 38.3±6.0b | 0.029 |
| 81 – 88 | 38.4 | 0.5 | 23.0±1.2a | 0.9 | 21.1±5.8a | 0.82 NS |
| 88 – 95 | 7.6 | 0.1 | 30.7±1.3a | 0.3 | 26.7±7.6a | 0.275 NS |
| 95 – 102 | 43.2 | 0.0 | 38.5±0.9a | 0.0 | 39.6±7.6a | 0.468 NS |
| 102-105 | 5.8 | 0.0 | 7.5±3.7b | 0.0 | 14.1±1.6a | 0.0046 |
| 105-115 | 29.0 | 0.0 | 33.5±8.1a | 0.0 | 38.9±5.0a | 0.20 NS |
| 115-122 | 99.1 | 26.1 | 23.6±4.7a | 27.2 | 21.2±6.3a | 0.14 NS |
| 122-130 | 2.8 | 8.8 | 18.6±1.8a | 9.0 | 14.2±4.7a | 0.12 NS |
| 130-139 | 0.0 | -0.9 | 17.3±3.4a | -1.1 | 20.9±0.8a | 0.28 NS |
| 139-146 | 4.2 | -0.3 | 7.4±2.6a | -0.2 | 5.1±1.5b | 0.04 |
| 146-156 | 39.0 | 0.0 | 21.1±6.5a | 0.0 | 21.1±2.0a | 0.6 NS |
| 156-160 | 34.5 | 2.3 | 10.7±8.6a | 2.3 | 13.7±1.4a | 0.64 NS |
| TOTAL | 600.6 | 145.7 | 437.9±3.1a | 146.8 | 441.8±3.3a | 0.08 NS |

$ET_C$ Mean±SE are based on 4 observations. Values followed by the same letter in a given row are not significantly (NS) different (contrast test at $p \leq 0.05$); DAS= Days After Sowing ; Input= rain +Irrigation; D= drainage; $ET_C$= crop evapotranspiration. INPUT, D and $ET_C$ are all in mm.

**Table 8:** Effect of water management and cropping system on seasonal consumptive water use.

| **Season** | **Trt** | **Crop** | **Input** | **Irrigation** | **$ET_C$** | **$ET_C$/Input ($C_{WATER}$)** | **$ET_C/E_0$** |
|---|---|---|---|---|---|---|---|
| 1 | 1 | SS | 617 | 239 | 410±4.0d | 0.66±0.006 | 0.77 |
| 1 | 1 | IS | 617 | 239 | 426±4.2b | 0.69±0.006 | 0.80 |
| 1 | 1 | GG | 763 | 309 | 434±4.7a | 0.57±0.005 | 0.70 |
| 1 | 1 | IG | 763 | 309 | 418±3.8c | 0.55±0.005 | 0.67 |
| 1 | 2/3 | SS | 495 | 117 | 420±3.9b | 0.85±0.008 | 0.79 |
| 1 | 2/3 | IS | 495 | 117 | 422±4.1b | 0.85±0.008 | 0.80 |
| 1 | 2/3 | GG | 591 | 137 | 428±5.1a | 0.72±0.009 | 0.69 |
| 1 | 2/3 | IG | 591 | 137 | 405±3.2c | 0.68±0.005 | 0.65 |
| 1 | 4 | SS | 425 | 47 | 383±3.0c | 0.90±0.007 | 0.72 |
| 1 | 4 | IS | 425 | 47 | 397±2.7b | 0.93±0.006 | 0.75 |
| 1 | 4 | GG | 501 | 47 | 405±3.5a | 0.81±0.006 | 0.65 |
| 1 | 4 | IG | 501 | 47 | 388±3.4c | 0.77±0.007 | 0.62 |
| 2 | 1 | SS | 654 | 368 | 419±3.8d | 0.64±0.006 | 0.76 |
| 2 | 1 | IS | 654 | 368 | 432±2.7c | 0.66±0.004 | 0.78 |
| 2 | 1 | GG | 983 | 481 | 536±3.9b | 0.54±0.004 | 0.64 |
| 2 | 1 | IG | 983 | 481 | 608±3.1a | 0.62±0.003 | 0.73 |
| 2 | 2 | SS | 533 | 241 | 407±3.4d | 0.76±0.006 | 0.71 |
| 2 | 2 | IS | 533 | 241 | 411±1.4c | 0.77±0.002 | 0.72 |
| 2 | 2 | GG | 847 | 345 | 579±4.0b | 0.68±0.005 | 0.69 |
| 2 | 2 | IG | 847 | 345 | 656±2.2a | 0.77±0.002 | 0.79 |
| 2 | 3 | SS | 660 | 237 | 482±2.5d | 0.73±0.004 | 0.71 |
| 2 | 3 | IS | 660 | 237 | 523±3.2c | 0.79±0.005 | 0.77 |
| 2 | 3 | GG | 780 | 280 | 531±3.6b | 0.68±0.004 | 0.64 |
| 2 | 3 | IG | 780 | 280 | 579±3.8a | 0.74±0.005 | 0.69 |
| 2 | 4 | SS | 523 | 10 | 396±2.8b | 0.76±0.005 | 0.59 |
| 2 | 4 | IS | 523 | 10 | 370±1.9c | 0.71±0.003 | 0.55 |
| 2 | 4 | GG | 601 | 10 | 438±3.1a | 0.73±0.005 | 0.52 |
| 2 | 4 | IG | 601 | 10 | 442±3.3a | 0.74±0.005 | 0.53 |

$ET_C$ and $C_{WATER}$ Mean±SE are based on 4 observations. Values followed by the same letter within a given treatment/season are not significantly (NS) different (contrast test at $p \leq 0.05$); ETc=crop evapotranspiration; $C_{WATER}$=water capture efficiency; $ET_0$=Reference ET (FAO-Penman-Monteith). Input, Irrigation and $ET_C$ are all in mm.

**Table 9:** Change in water capture efficiency of intercropping in relation to sole cropping.

| **Treatment** | **$\Delta ET_C$ (%)** | | **$\Delta C_{WATER}$ (%)** | |
|---|---|---|---|---|
| | **Season 1** | **Season 2** | **Season 1** | **Season 2** |
| 1 | 0 | 8.90 | 0.81 | 8.47 |
| 2 | -2.47 | 8.21 | -2.80 | 6.94 |
| 3 | -2.47 | 8.78 | -2.80 | 8.51 |
| 4 | -0.38 | -2.64 | -0.58 | -2.68 |

$\Delta ET_C$ and $\Delta C_{WATER}$ are calculated according to Eq. 6.

## DISCUSSION

Daily and seasonal water use by intercrops was little different when compared to sole crops in almost all treatments and seasons. Nevertheless, the difference, though little was statistically significant ($p \leq 0.05$) in most cases, providing a competitive water capture advantage of the sorghum/groundnut intercropping over sole cropping during the dry year. These results are similar to those reported by several researchers (Morris & Garrity, 1993b; Walker & Ogindo, 2003; Ogindo & Walker, 2005). Natarajan & Willey (1980) found no difference in water use rate between sole crops and intercrops of sorghum and pigeonpea up to the point when the shorter duration sorghum was harvested. However, the longer duration pigeonpea extracted a further 170 mm of water before its harvest 10 weeks later, utilizing residual soil water and late-season rainfalls that would have otherwise been lost. Morris & Garrity (1993b), when reviewing several field experiments involving various crop mixtures in which seasonal rainfall varied between 84 and 575 mm concluded that water use by intercrops was generally within ±7% of equivalent sole crops, although larger benefits were occasionally observed. In the present study the seasonal water use by intercrop sorghum ranged from -6.5% to +8.5% as compared to sole sorghum. The corresponding percentages for groundnut varied from -4.2% to +13.4%. Using pooled ET values, intercropping had a higher water capture amounts and efficiencies during the dry year, except for the rain fed treatment. Its lower efficiency in the wet year may be due to the seeding density that was too high, thus increasing competition for light.

A critical factor influencing both soil surface evaporation and transpiration is crop cover represented by leaf area index. Wallace et al. (1999), Ogindo & Walker (2005) showed that water use by various intercrop systems exceeded that of the sole crops, primarily because a larger leaf area index was attained and maintained for longer. Poor water (and radiation) capture efficiency is usually due to low leaf area during the establishment and senescence phases of single crops. Agronomic practices such as intercropping that shorten these periods can increase capture and efficiency in the use of these resources (Caviglia et al., 2004). This was the case in the present study where intercropping had narrower row spacing than sole cropping and the sorghum component in the mixture, a C4 cereal, resulted in more rapid canopy development. Another possible improvement in water use by the sorghum/groundnut intercropping stems from the complementary root distribution of the component crops. The deep and fast growing sorghum root system must have extracted substantial quantities of water from below the rooting zone of groundnut during the early and mid-season as illustrated by the contrasting trends in matric potential values between the component crops in the mixture. Jena & Misra (1988) reported a similar situation in a rice/pigeonpea system. Water capture efficiency of intercropping seems to increase with water stress up to a certain limit. This was observed in both years and was in agreement with the results reported by Caviglia et al. (2004) on a soybean/wheat intercropping. As water stress increases, so does the competition for water by the co-existing species in the mixture, thus reducing significantly the growth of the less competitive component. This may account for the reduced intercrop $ET_C$ and $C_{WATER}$ values found in the rain fed treatment. Such results were reported by Ogindo & Walker (2005). Furthermore, the larger the difference in growing cycles between the component crops in a mixture, the smaller the intercrop capture efficiency tend to be. The Fluronner groundnut had a growth cycle of 134 days as against 160 days for the Southern Runner. After the harvest of sorghum (102 days), the remaining groundnut crop could no longer optimize water use in the intercropping plots, thus contributing to the reduction of its efficiency.

## Conclusion

This study compared water uptake rate of sorghum and groundnut grown in a mixture or as sole crops using various water management strategies ranging from full irrigation to rainfed agriculture. Daily and seasonal water use of both crops in the mixture was slightly higher than in the sole crops during the dry year. The improved water uptake rate of the sorghum/groundnut intercrop system was attributable to the spatial and temporal complementarities in the water absorption patterns of the component crops. Intercropping advantage over sole cropping may have occurred when the management of crops and water enhanced complementarity while reducing competition between the component crops. The adverse results in the wetter year may be due to increased competition for light rather than to water abundance.

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