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Soil water balance of annual crop–native shrub systems in Senegal's Peanut Basin: The missing link

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ABSTRACT

Shrubs in the Senegal Peanut basin co-exist with annual food crops in the landscape but are vulnerable to destruction by farmers in a bid to increase agricultural acreage and meet fuel demands. This study determined the impact of two native semi-arid shrub species (*Guiera senegalensis* and *Piliostigma reticulatum*) on field water balance components. Soil water fluxes in crop–shrub intercrops and in sole crops were quantified from soil moisture, soil micro-lysimetery and atmospheric measurements. Up to a depth of 1.10 m, shrubs did not compete with crops for water but preferentially extracted water from the lower portion of the profile below 1.10 m and even beyond the maximum measured depth of 3.5 m. This served as a significant component of the field water balance and was more pronounced at the *G. senegalensis* site. Shrubs also captured drainage losses beyond the effective root depth of annuals and revealed 25–50% lower deep drainage losses than in sole crop plots. Both shrub species conferred a positive impact on the field moisture regime when intercropped with annuals through enhancing profile recharge in the rainy season. Shrub-mediated effects resulted in 20% higher soil water storage in the upper 1.10 m of the profile in crop–shrub intercrops compared to sole crop control plots. Findings from this study revealed a missing link that deserves special mention. Future work on quantification of water balance in semi-arid regions with crop–shrub associations needs to account for shrub contribution to field moisture fluxes through ground water uptake (G_{wup}), a parameter often ignored, yet serves as a vital component in semi-arid ecosystems.

1. Introduction

The Sahel climate is generally characterized by one distinct dry season (October–June) followed by a precipitation season (July–September) within which rainfall is erratic and poorly distributed (Wang et al., 2004) resulting in limited plant-available water within the crop rooting zone (Hillel, 1998). This limited water availability combined with the fragile, inherently low-fertility soils (Boffa, 1999), leads to low crop yields (Noy-Meir, 1973). Effective management of soil and scarce water resources in semi-arid settings is critical for improving crop productivity (Gregory, 1989; Le Houérou, 1992). In order to

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fully develop and maintain crop productivity in these regions, quantitative accounting of water balance components is vital. Although this has been done for some crops in some parts of the Sahel, there are still relatively few comprehensive water balance studies available for this region (Desconnets et al., 1997).

In the Senegalese Peanut Basin, annual food crops (Millet: *Pennisetum glaucum* (L.) R. Br. and Groundnut: *Arachis hypogaea* L.) are grown in association with two widely occurring shrub species; *Guiera senegalensis* and *Piliostigma reticulatum*. These shrubs are being studied for their potential to facilitate crop production as suggested by Kizito et al. (2006). However, the impact of these woody perennials on the overall water balance and hydrology of these agro-ecosystems remains an issue of scientific inquiry (House et al., 2003; Seyfried et al., 2004).

Previous work by Knoop and Walker (1985) as well as Droppelmann et al. (2000) reported facilitative interactions of woody and herbaceous vegetation in a southern Africa savanna. Additionally, in his work on fallow areas in the north of Senegal, Louppe (1991) documented higher soil evaporation trends at bare soil areas compared to areas populated by *G. senegalensis*. Gaze et al. (1998) investigated dry-season water use patterns of *G. senegalensis* in Niger and stated that shrub clearance could result in increased deep drainage through reduced dry-season water use by these deeply rooted shrubs. Conversely, Cuenca et al. (1996) reported an infiltration front penetration to more than 3 m below tiger bush vegetation in Niger, in sharp contrast with what was observed in bare soil areas with the front extending only 0.50 m.

In an earlier study, Kizito et al. (2006) reported that shrubs improved Pearl millet performance with higher soil moisture levels sustained around shrub micro-sites. It seems likely that the presence of these shrubs could positively impact regional agrarian productivity by increasing near surface soil moisture redistribution. However, the impact of these shrubs on ecosystem hydrology remains to be determined.

Based on our current knowledge, quantitative water balance studies of annual crop–shrub systems in Senegal have not been done. Therefore, the objectives of this study were to determine: (1) the impact of shrubs on profile soil moisture variability; (2) the field-scale water balance of shrubs in association with annual food crops.

2. Materials and methods

2.1. Field site characteristics

The study was conducted in two different agro-ecological zones of Senegal with different vegetation composition. The first site, Keur Matar Arame (KMA) is located at Thies (14°46′N, 16°51′W), with a mean annual temperature of 30 °C in a lower rainfall region with approximately 470 mm per annum. It has a sandy, ferruginous Oxisol (FAO, 1998) with a water table depth at 15 m below the soil surface. This site has mound-forming *Guierra senegalensis* shrubs as the dominant vegetation.

The second site is located at Nioro (13°45′N, 15°47′W), predominantly occupied by *Piliostigma reticulatum* shrubs on a sandy, lateritic area classified as an Oxisol (FAO, 1998). The area has unimodal rainfall, 700 mm per annum and a mean annual temperature of 32 °C. The water table lies at approximately 18 m.

2.2. Experimental design and trial layout

The experimental area at both sites was 65 m × 46 m. Each site had six plots with dimensions of 4 m × 6 m. The experiment had a randomized block design with two treatments within three blocks replicated three times. Treatment 1 served as the control: the peanut or millet crop was grown alone with no shrub influence. Treatment 2 was comprised of an intercrop: peanut or millet with shrub.

Before the rainy season in April 2003, fields were prepared with hand hoes to remove weeds prior to sowing of Pearl millet (*P. glaucum* (L.) R. Br.) for both treatments. The millet was planted both as a sole crop and as an intercrop with shrubs at a seed rate of 6–10 kg/ha with seeds drilled in rows 90 cm apart. Plants were then thinned to three plants per planting hole with a plant population of about 6000 plants/ha but millet density in shrub treatments was slightly lower (5500 plants/ha). In June 2004, Peanut (*A. hypogea* L. variety: Fleur 11) was sown for both sole-crop control plots and shrub plots as a rotation to mimick farmer-managed systems in Senegal. For the sole-crop control plots, peanut was planted at a spacing of 50 cm between rows by 15 cm within rows yielding a planting density of approximately 130,000 plants/ha (sown as one seed per hole). For the peanut–shrub intercrop, the peanut density was slightly reduced (125,000 plants/ha) owing to shrub presence however, similar spacing as the control plots was maintained. The *G. senegalensis* site had a shrub stand density of 240 shrubs/ha while the *Piliostigma reticulatum* site had a shrub density of 185 shrubs/ha (Kizito et al., 2006). Peanut seeds were dressed with Granox which served as both a contact fungicide (against *Aspergillus niger*) and a systemic insecticide.

2.3. Experimental approach to quantify water balance components

The effect of shrub presence on the water balance over the study period was determined by quantifying incoming and outgoing water fluxes (Fig. 1) into the crop–shrub root zone compared to sole crop (no shrub) treatments following the principle of mass conservation. The mass balance equation (Eq. (1)) includes the following components:

$$P + D = RO + DD + ET_c \pm \Delta SW_c \quad (1)$$

where P is the precipitation and serves as the principal water addition to the crop and shrub root zone. D incorporates dew and atmospheric condensation, this component was ignored since it is negligible in semi-arid environments (Wallace, 1996; Wang et al., 2004). A portion of P might be lost by surface run-off (RO) and deep drainage (DD) that could eventually recharge the water table. ET_c is evapotranspiration and ΔSW_c is the change in profile water storage (Fig. 1).

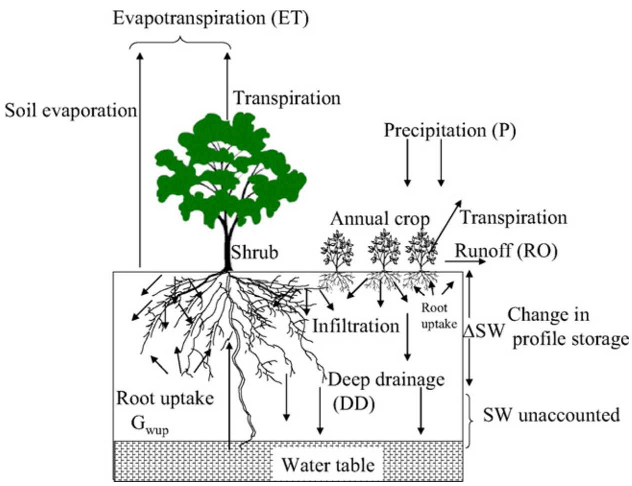

Fig. 1 – Plot water balance components.

From Eq. (1), change in profile soil water storage (ΔSW_c) can be conventionally derived algebraically (Eq. (2)):

$$\pm\Delta SW_c = P - (RO + DD + ET_c) \quad (2)$$

However, it is evident that the above equation does not account for any addition of soil moisture fluxes to the system resulting from ground water uptake or soil moisture extraction by shrubs beyond the maximum measured depth of 3.50 m (Fig. 1).

If the conventional equation (Eq. (2)) is used, this would result in the omission of ''unaccounted fluxes'' and an erroneous conclusion as to the contribution of shrubs to the overall field water balance. Hence, comparison between calculated changes in soil water storage (ΔSW_c) using Eq. (2) and actual measured field values (ΔSW_m) in both treatments underpins the impact or contribution of shrubs to the profile water regime. Notably some fluxes such as capillary rise from a water table were difficult to assess (Batchelor, 1984; Smith et al., 1992; Allen et al., 1994) and are not discussed herein.

To account for potential contribution of deep tap roots to the water balance, groundwater uptake (G_{wup}) was introduced in the overall water balance equation (Eq. (3)). The parameter G_{wup} incorporates water uptake by shrubs from the water table or from deep moist horizons beyond the measured maximum depth of 3.50 m. Hence, in crop–shrub plots, the actual observed change in profile storage (Eq. (3)) after ammending (Eq. (2)) was

$$\pm\Delta SW = (P + G_{wup}) - (RO + DD + ET_c) \quad (3)$$

The conventional approach (Eq. (2)) holds true for the sole-crop control plots since with no shrubs present, it is not necessary to account for G_{wup}. However, in crop–shrub plots, it is essential to account for the G_{wup} component as a contributing input flux by shrubs to the system. Ignoring of this component could lead to overestimation of the flux losses and consequently underestimation of flux gains in the system control volume.

The components of the water balance equation were determined by field measurements (P and ΔSW_m), or calculated (derived) from measured parameters (RO, DD and ET_c) in order to deduce G_{wup}. Precipitation (P) was measured daily by an on-site rain gauge. Surface run-off (RO) was considered negligible at the KMA field site, this approximation underestimated flux losses in the order of 1%. However, RO was significant at the Nioro site (Serpantié et al., 1992) and was considered an integral component of field flux losses. System ET_c was quantified by measuring soil evaporation using microlysimeters. Change in profile water storage (depletion or recharge) (ΔSW_m) was determined from neutron probe data to a depth of 3.50 m. Deep drainage (DD) that recharges the water table was determined from neutron probe moisture measurement (Fig. 1).

Methods used for quantifying each component in Eqs. (2) and (3) are discussed in greater detail below. After all fluxes were determined, a quantitative comparison between crop–shrub plots and sole-crop plots was used to assess the impact of shrubs on field hydrological fluxes. This was deduced from both measured and computed changes in profile soil water content (ΔSW_m) over the study period.

2.4. *Quantification of parameters*

2.4.1. *Precipitation*

Rainfall was monitored with a tipping bucket rain gauge (0.01 in. tip, TE525-L). This has an accuracy of ±1% at rates up to 1 in./h and a resolution of 1 tip. The accuracy of the instrument varies with rain intensity (Texas Electronics, Dallas, TX).

2.4.2. *Evapotranspiration estimation*

The FAO Penman–Monteith approach was used to estimate hourly and daily reference crop evapotranspiration, ET_o. This was computed from measured meteorological data; solar radiation, air temperature, relative humidity and wind speed. The FAO Penman–Monteith equation (Allen et al., 1998) used for hourly time steps (for a well watered crop) in this study (Eq. (4)) is

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma(37/(T_{hr} + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (4)$$

where ET_o is the reference crop evapotranspiration (mm h^{-1}), R_n the net radiation (MJ m^{-2} h^{-1}), G the soil heat flux density (MJ m^{-2} h^{-1}), T_{hr} is the mean hourly air temperature (°C), $(e_s - e_a)$ the hourly vapor pressure deficit of the air (kPa), Δ the slope of the saturation vapour pressure function (kPa $°C^{-1}$), γ the apparent psychrometric constant (kPa $°C^{-1}$) and u_2 is the average hourly wind speed (m s^{-1}) measured at 2 m above the soil surface.

Soil evaporation (E) was measured with micro-lysimeters (ML); these were constructed from PVC pipes that had dimensions of ~12.5 cm long and 7.3 cm internal diameter with a wall thickness of ~0.3 cm. The handling of the microlysimeters followed an approach similar to that proposed by Jackson and Wallace (1999). Soil MLs were installed and repeatedly weighed with a portable field balance (±0.1 g) at hourly intervals over a 12-h period and then replaced in the formed field holes. This was performed on six occassions during the cropping season. In this approach, evaporation rates were estimated for the micro-lysimeters gravimetrically. Bare-soil evaporation was calculated as the change in weight over time. One gram of water corresponded to 0.02 and 0.03-mm depth equivalent of water from the micro-lysimeters at the Keur Matar arame and Nioro sites, respectively. Three MLs were placed in each of the treatment plots to compare soil evaporation trends in sole-crop plots and crop–shrub plots. A short (5 cm high) plastic barrier was placed around the lysimeter to prevent dust deposition on the soil surface within the lysimeter. While this barrier is likely to give reduced values of evaporation (due to a boundary layer effect), this error did not significantly impact observed field values in studies conducted elsewhere (Savage et al., 1997) neither was there an evident effect in our study.

The transpiration component that contributes to crop evapotranspiration (ET_c) and crop–shrub evapotranspiration (ET_{c+s}) were measured using the LI-1600 Steady State Porometer (LI-COR Inc., Lincoln, NE, USA). During field sampling with the porometer, leaf conductance was measured by canopy profiling as the mean of six sunlit and six shaded leaves. This was accounted for while computing crop transpiration values.

Crop evapotranspiration, ET_c, was calculated by multiplying the reference crop evapotranspiration, ET_o, by a crop coefficient, K_c that depends on growth stage (Eq. (5)):

$$ET_c = K_c ET_o \tag{5}$$

where ET_c is the crop evapotranspiration (mm d^{-1}), K_c the combined crop coefficients for both shrub (K_b) and peanut (K_p) or millet (K_m), and ET_o is the reference crop evapotranspiration (mm d^{-1}) derived from meteorological data.

Both peanut and millet crop coefficients were obtained from the FAO database (FAO, 1998) for three crop growth stages. For the peanut crop: Initial stage $K_p = 0.4$ when crop has 10% ground cover, mid-season $K_p = 1.15$ with 10–75% crop ground cover at the peak water use period and late-season $K_p = 0.60$ when crop aging sets in before harvest. For the millet crop: initial stage $K_m = 0.4$ when crop has 10% ground cover, mid-season $K_m = 1.0$ with 10–75% crop ground cover at the peak water use period, late-season $K_m = 0.30$ when crop aging sets in before harvest. As crop coeffcients for the shrubs have not been previously measured, a shrub coefficient, K_b was derived from the difference between the combined crop–shrub ET_{c+s} and sole crop ET_c expressed as a ratio to the reference ET_o (Eq. (6)). Hence,

$$K_b = \frac{ET_{c+s} - ET_c}{ET_o} \tag{6}$$

To compute Eqs. (5)–(7), the following atmospheric variables were monitored: air temperature, relative humidity (Vaisala probe HMP 45C, Campbell Scientific, Logan, UT, USA) and wind speed and direction at 2 m above the soil surface (RM Young Wind sensor, 05103-L, Campbell Scientific, Logan, UT, USA). Solar irradiance was measured with a silicon diode pyranometer (LI-COR LI200X) while net irradiance was monitored with a net radiometer (Q7_1-L REBS Net Radiometer, Fritschen, Seattle, USA). All of the above parameters were monitored at hourly intervals and recorded with a CR10X data logger (Campbell Scientific, Logan, UT).

2.4.3. *Surface run-off*

Surface run-off (RO) was deduced using a spatially distributed interactive model called InterWET. The model gives a two-dimensional process level view of run-off using the Soil Conservation Service-Curve Numbers (SCS-CN) method (The Task Committee, ASCE, 1985). Measured site-specific hydrological properties were used as input parameters to assess run-off changes at both sites. Measured input parameters included soil infiltration rate, initial soil moisture content, soil texture, slope (topography) and land-use regime. From these parameters, the model approximates the run-off magnitude at a given site. On comparison with measured field values at the *Piliostigma reticulatum* site, the model underestimated run-off by a magnitude in the order of 4%.

2.4.4. *Deep drainage losses*

Deep drainage is defined as the downward movement of soil water below the rooting depth of plants and was estimated using a procedure similar to that proposed by Klaij and Vachaud (1992). In this study, the maximum depth (Fig. 2) of soil moisture measurements (Z_m) is 3.50 m and the maximum crop rooting depth (Z_r) is 1.10 m. In our field plots Z_m exceeds Z_r by a large margin. The amount of soil water stored in the profile from the surface Z_s down to the depth Z_m is denoted as S_{wm}. Similarly, the amount of soil water held in the root zone, that is, between the soil surface ($Z = 0$) and the maximum

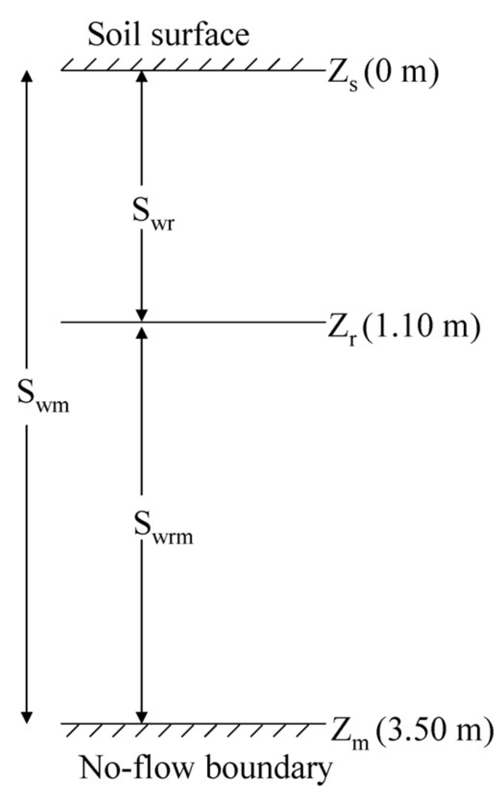

Fig. 2 – Conceptual schematic for deep drainage estimation in sole-crop plots. The no-flow boundary is only applicable during the dry season.

rooting depth (Z_r) is denoted by S_{wr} (Fig. 2). The difference between S_{wm} and S_{wr} yielded $S_{wrm.}$ The downward water flux across the plane defined by $Z = Z_m$ is considered negligible during the prolonged dry season. At both study sites, the soil moisture at Z_m remains sufficiently low so that the hydraulic conductivity can be considered to be negligible. Invoking Darcy's law, therefore the water flux at $Z = Z_m$ is also negligible.

Consequently, cumulative drainage D_r can be calculated on the basis of the change in total water stored in the profile between Z_r and Z_m, and calculated between time t and time $t + \Delta t$. Typically, soil water measurements were performed on a weekly basis.

$$D_r = S_{wrm(t)} - S_{wrm(t+\Delta t)} \quad (7)$$

From Darcy's law, deep drainage takes the following form (Eq. (8)):

$$D_r = (\Delta S_{wrm})\,\Delta t = q_r = -K(\theta)\left(\frac{\Delta H}{\Delta Z} + 1\right) \quad (8)$$

where q_r is the water flux through the imaginary line at $Z = Z_r$, Δt is the change is time, $K(\theta)$ the unsaturated hydraulic conductivity which is a function of the volumetric water content and $\Delta H/\Delta Z$ is the capillary head gradient at $Z = Z_r$. During the dry season, under low rainfall and high evapotranspiration conditions the capillary head gradient greatly exceeds the gravitational gradient and the corresponding low hydraulic conductivity reduces drainage to a negligible amount. However, during the rainy season moister soil permits the assumption of a unit hydraulic gradient ($\Delta H/\Delta Z \ll 1$) and simplifies Eq. (7), permitting the computation of hydraulic conductivity function for the profile. Consequently, with seasonal profile recharge, these established $K(\theta)$ functions were used in the calculation of drainage beyond the root zone when soil water content (S_{wrm}) at the maximum measurement depth (Z_m) begins to increase (Klaij and Vachaud, 1992).

2.4.5. *Soil water content and matric potential measurements*

Temporal and spatial variability in volumetric soil moisture content was monitored using a Troxler neutron probe (model 4330, Troxler Laboratories, Research Triangle Park, NC). Profile soil moisture storage (mm of water) was calculated by summing the water content for each depth range. Access tubes were placed contiguous to three shrubs close to the center of the plot in each of the crop–shrub treatments and in the center of each control plot. Measurements were conducted on a weekly basis at 0.10 m depth increments from the soil surface to a depth of 3.50 m. Profile stored water was calculated on a depth basis as the product of volumetric water content ($m^3\,m^{-3}$) and the depth interval (0.10 m) and expressed as millimeters of water for each depth range to the maximum depth at which the measurements were performed. Values for each depth were then integrated to get a mean value for both the upper 0–1.10 m depth range and the lower 1.10–3.50 m depth range.

To account for minute soil water changes in the profile, daily variations of soil water potential were measured within each of the two treatments using screen-cage soil psychrometers (Wescor, Logan, UT, PST-55; Briscoe, 1984), which were calibrated using standard salt solutions (Brown and Bartos, 1982). Matric potential values were used to estimate deep drainage losses beyond the effective rooting depth of annual crops during the dry season. Psychrometers were installed at 0.20, 0.40, 0.60, 0.80, 1.00 and 1.20 m. The psychrometers executed measurements on an hourly basis with a 30-s cooling time for the Peltier effect. Psychrometer data was logged and downloaded from a PSYPRO (Model PST-55, Wescor, Logan, UT) water potential system.

The neutron probe was calibrated by taking standard counts each time soil moisture was measured. This combined with field cored gravimetric soil samples enabled the derivation of two calibration curves for each site, one for the 0–0.10 m and the other for the 0.10–3.50 m (Eq. (9)).

The calibration took the form of

$$\theta_v = m^*\left(\frac{fc}{Sc}\right) + c \quad (9)$$

where θ_v is the volumetric water content ($m^3\,m^{-3}$). Gravimetric water content from field soil cores was converted from a weight basis to a volumetric basis by multiplying with the soil bulk density. The parameter m is the slope, Fc the neutron probe field count, Sc the standard count taken from a water drum, and c is the θ_v intercept.

2.5. *Data analysis*

Soil evaporation data were statistically analyzed with SAS V8 (2001) for the two treament factorial random block design. Since sampling was conducted on the same individuals over time (shrubs and crops), soil moisture data were analyzed using a repeated measures model (Lindsey, 1993). Pre-planned comparisons between treatment and control means was made using Fisher's protected least significant difference (LSD) test at $p < 0.05$. Two sample t-tests (SPLUS V6.1) were performed to evaluate the differences between yield. For comparison of ET results between measured and computed values in shrub and non-shrub treatments, a regression analysis was performed. Box-plots were used to assess treatment differences in soil evaporation from shrub and non-shrub treatments.

3. Results

3.1. *Shrub impact on water balance*

Control (sole-crop) treatments exhibited close agreement between the computed (Eq. (2)) and measured (Eq. (3)) changes in profile storage at both sites (Table 1). The two values being compared here are the differences in soil water storage between the conventional computed method and the measured values with the neutron probe. In the sole crop treatment, there was close agreement between the measured values with neutron probe and conventional computation. However, in the shrub–crop scenario; there was a magnitude of difference between the conventional computation method (not accounting for shrub effect) and measured field values. This suggests that there is a parameter that was overlooked in

Table 1 – Annual water balance components for millet and peanut for both sites with standard errors (±) along side data values

Components (mm)	Keur Matar Arame		Nioro	
	Control	Crop + shrub	Control	Crop + shrub
Millet (2003)				
P	242		986	
DD	82 ± 0.5	50 ± 0.7	53 ± 0.3	40 ± 0.4
ETc	173 ± 1.6	387 ± 3.2	544 ± 2.3	838 ± 2.4
RO	0	0	177 ± 2.3	97 ± 2.6
ΔSW_m (measured)[a]	−7 ± 1.2	−8 ± 1.3	208 ± 1.8	23 ± 1.9
ΔSW_c (computed)	−13 ± 1.1	−195 ± 2.5	212 ± 4.8	11 ± 3.9
Shrub impact (G_{wup})	–	187 ± 1.3	–	13 ± 2.2
Peanut (2004)				
P	288		792	
DD	97 ± 1.9	39 ± 1.6	43 ± 1.4	36 ± 1.8
ETc	184 ± 3.1	446 ± 3.5	499 ± 2.2	722 ± 1.7
RO	0	1 ± 0.1	59 ± 1.8	28 ± 1.6
ΔSW_m (measured)	5 ± 0.3	−7 ± 1.4	187 ± 1.6	17 ± 1.4
ΔSW_c (computed)	8 ± 1.2	−197 ± 5.2	190 ± 3.5	6 ± 2.2
Shrub impact (G_{wup})	–	190 ± 3.4	–	11 ± 1.6

[a] Negative signs before values indicate a deficit.

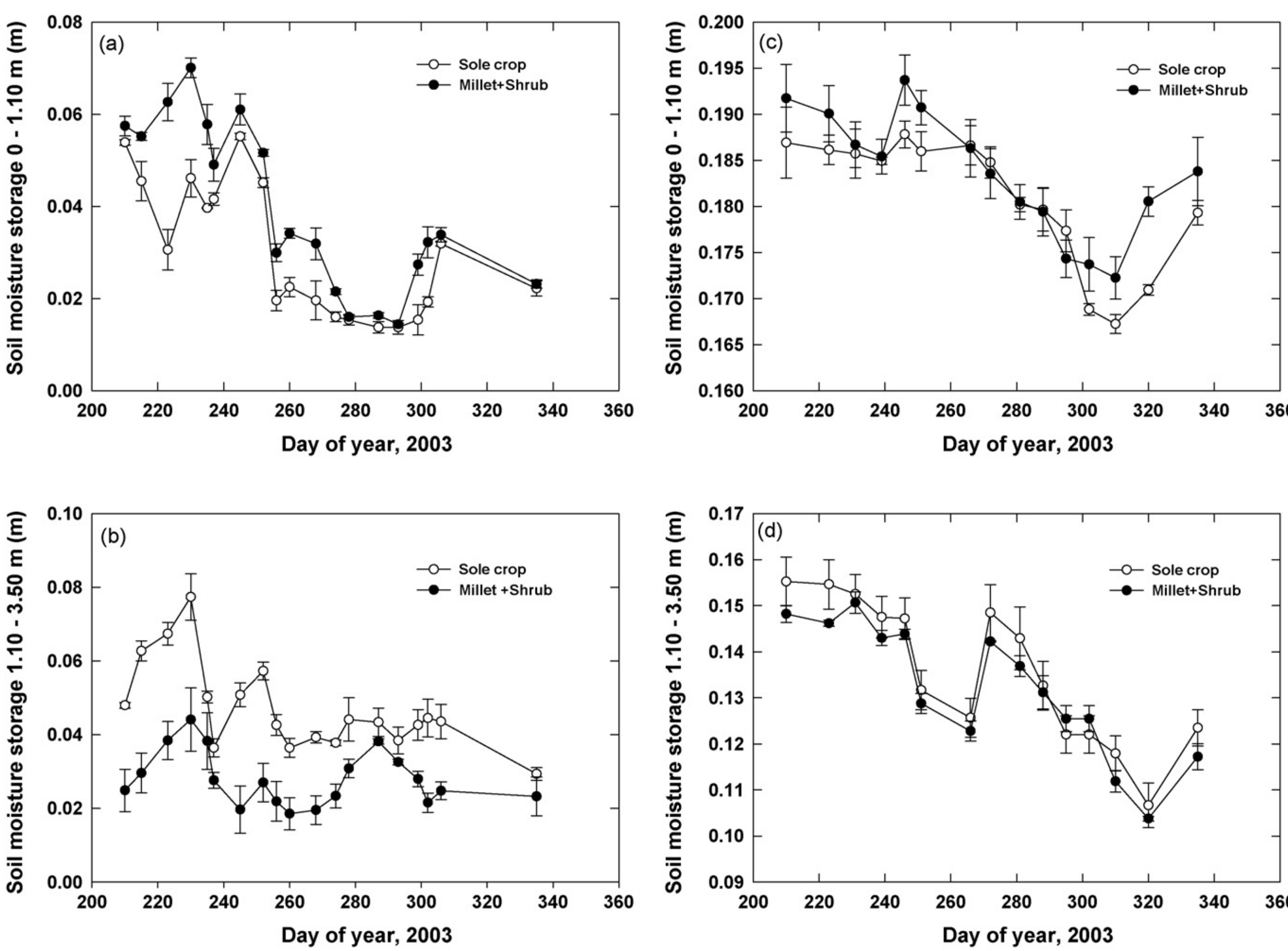

Fig. 3 – Variation of cumulative soil moisture storage at both study sites in 2004; KMA site (a) upper portions of the profile, 0–1.10 m, and (b) deep in the profile, 1.10–3.50 m. For the Nioro site (c) upper portions of the profile, 0–1.10 m, and (d) deep in the profile, 1.10–3.50 m.

the conventional computation method, which is G_{wup} due to shrub water uptake.

For the KMA site, soil moisture storage in the 0–1.10 m zone peaked between DOYs 230 and 250 (Fig. 3). For 2004, it peaked DOYs 220 and 260 then receded from DOYs 260 to 300, hence it peaked at 0.08 m and thereafter remained below 0.04 m (Fig. 4a). The 1.10–3.50 depth range showed a peak at the start of the measurements and declined consistently with no peaks in soil moisture storage across the season for the Nioro site with a low near DOY 310 (Fig. 4d). The low values (Figs. 3 and 4) indicate the driest value the profiles had attained with rises after rainfall recharge.

Soil moisture storage in crop–shrub plots appeared to differ to the control plots at both study sites for the 0–1.10 m zone and the 1.10–3.50 m zone (Figs. 3 and 4). For both study sites, the 0–1.10 m zone in the crop–shrub plots had higher storage than sole-crop control plots. Conversely, for the 1.10–3.50 m depth range the reverse was seen, with higher storage prevalent in the control plots than in the crop–shrub plots (Figs. 3b and d and 4b and d).

Invoking the water balance approach (Eq. (4)), supplemental seasonal shrub water uptake (G_{wup}) values (Table 1) were higher at the KMA site than at the Nioro site in both study years. Quantification of each parameter that was used in calculating the water balance results is presented below.

3.2. *Rainfall*

For the period 1996–2004, annual rainfall estimates were obtained from rain gauges close to both KMA and Nioro sites (Fig. 5). Long-term rainfall data for the period 1961–1995 were obtained from the Direction Nationale de la Météorologie (Dakar, Senegal). These data show that the mean annual rainfall in the period 1961–1995 for KMA and Nioro was 470 and 700 mm, respectively. Field data from this study revealed that KMA received less rain in 2003 than in 2004, and amounted to nearly 25% and 37% of what was received at Nioro in 2003 and 2004, respectively. Monthly rainfall distribution in terms of rainy days per month for both study years was close to the long-term averages at both sites.

The KMA site received a total of 242 and 289 mm in 2003 and 2004 resulting in 49% and 38% lower values respectively than the long-term average which indicates much drier conditions. Conversely, Nioro received 986 mm in 2003 which is 41% more than the long-term average of 700 mm and 792 mm in 2004 which was only 13% more.

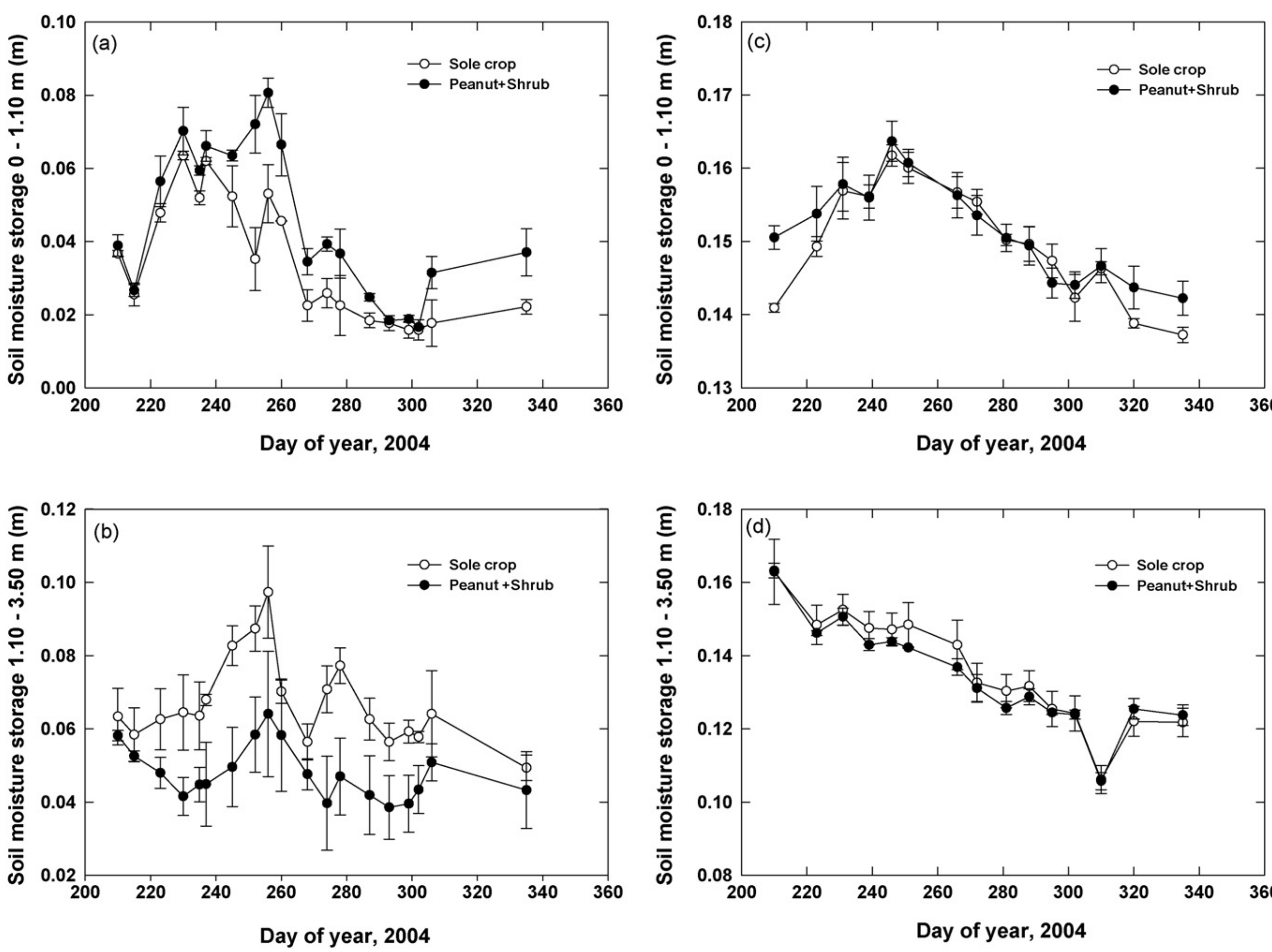

Fig. 4 – Variation of cumulative soil moisture storage at both study sites in 2003; KMA site (a) upper portions of the profile, 0–1.10 m, and (b) deep in the profile, 1.10–3.50 m. For the Nioro site (c) upper portions of the profile, 0–1.10 m, and (d) deep in the profile, 1.10–3.50 m.

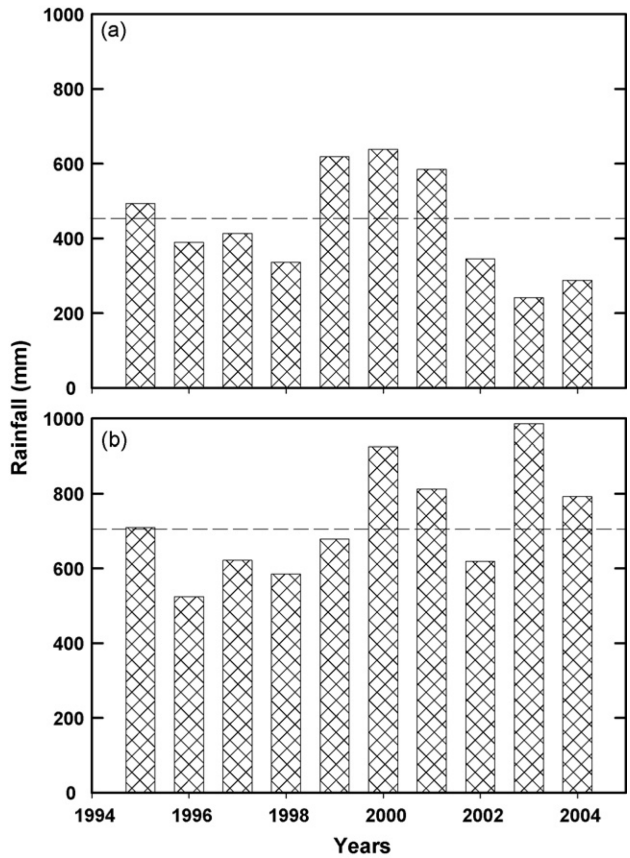

Fig. 5 – Decadal cumulative annual rainfall for rain gauges 1995–2004 at (a) Keur Matar Arame and (b) Nioro. Dotted horizontal lines show the decadal average value.

3.3. *Soil evaporation and crop transpiration*

Both measured evapotranspiration (ET_c) and reference evapotranspiration (ET_o) at KMA exhibited similar trends, with crop ET_c slightly higher than the reference ET_o though both peaked around 1400 h, West African Standard Time (WAST, Fig. 6a). Regression analysis for both ET_c and ET_o revealed a regression square (r^2) value of 0.95 for KMA site (Fig. 6b) and a value of 0.92 for the Nioro site (Fig. 6c).

Seasonal mean microlysimeter data revealed significant differences in soil evaporation; $P = 0.05$) between crop–shrub plots and sole-crops at both study sites in 2003 and 2004 (Fig. 7a and b). Soil evaporation in KMA sole-peanut plots for 2003 and 2004 was respectively 60% and 44% higher than in crop–shrub plots (Fig. 7a). Similarly, at Nioro in 2003 and 2004, soil evaporation values in sole-crops were respectively 57% and 52% higher than crop–shrub plots (Fig. 7b). While soil evaporation was lower in crop–shrub plots, it should be noted that these plots had greater net water consumption by plants, as depicted by the higher ET_c losses (Table 1), which holds true for both study sites during the study period.

3.4. *FAO PenMan–Monteith ET estimates*

At the KMA site, sole-crop (control) ET_c was 71% in 2003 and 64% in 2004 of the recorded precipitation (*P*) but for the crop–shrub intercrop, measured ET_c was higher than precipitation for both study years (Table 1). At Nioro, similar trends were observed with ET_c values generally higher than those for KMA site. Total daily ET_c values varied from approximately 2 mm d^{-1} (during initial crop growth) to 6.5 mm d^{-1} (at prolific crop growth phase) then dropped to approximately 3 mm d^{-1} (before harvest). The total daily ET_c depended on soil surface wetness characteristics in a given period. Higher values of ET_c were registered when the soil was moist and had high solar radiation loads.

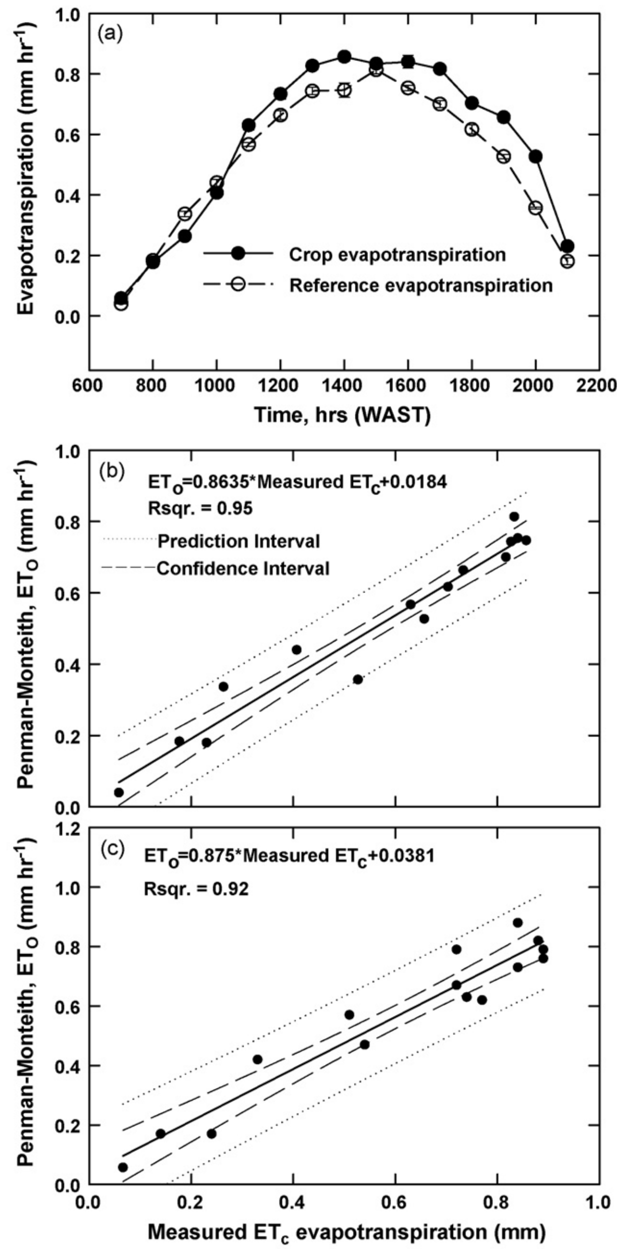

Fig. 6 – Measured and modeled ET dynamics at KMA (a and b); Nioro (c) sites, September 2004.

3.5. *Run-off components*

At the KMA site, modeled run-off (Table 1) was negligible, contributing less than 0.5% of the water flux losses from the

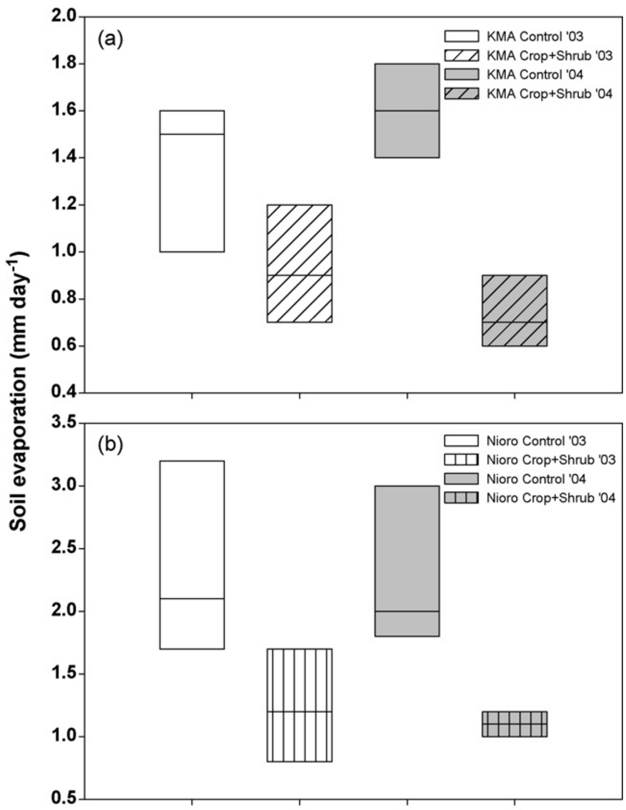

Fig. 7 – Box plots for mean seasonal site micro-lysimeter soil evaporation for (a) KMA in 2003 and 2004; (b) Nioro for 2003 and 2004 in control (sole crop) and crop + shrub treatments.

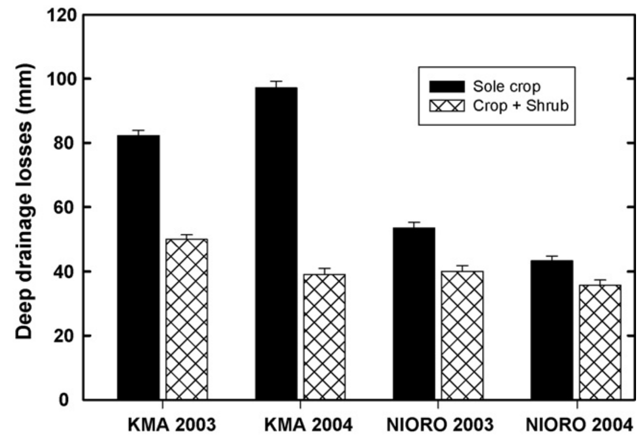

Fig. 8 – Cumulative deep drainage water losses below the potential maximum root zone in sandy soil for both sites with millet in 2003 and peanut in 2004.

system. Conversely, at Nioro higher run-off values were registered for both study years. Crop–shrub plots were associated with lower mean seasonal RO values than in sole crop treatments for both years at Nioro. In 2003, the mean seasonal RO value recorded for crop–shrub associations was approximately 45% lower than that observed in sole crops while in 2004, the RO value in crop–shrub plots was 53% lower than that observed in shrub plots. Modeled RO values were directly proportional to the rainfall amounts received.

The absence of run-off at the KMA site is attributed to the sandy nature of the soil with high infiltration rates. In addition, this was exercabated by prevalence of very low precipitation events. The meager run-off in such soils has further been documented in Niger, with soils having very high hydraulic conductivity (>100 mm h^{-1}) even with high intensity rainfall events (Klaij and Vachaud, 1992).

3.6. *Deep drainage losses*

Mean seasonal losses due to deep drainage (Eq. (8)) beyond the effective rooting depth of annuals (1.10 m) revealed that crop–shrub plots for 2003 and 2004, respectively, had 39% and 60% lower deep drainage losses (Fig. 8) than sole crop plots for the KMA site. In Nioro, crop–shrub plots for 2003 and 2004 respectively had 25% and 17% lower deep drainage losses than sole crop plots (Fig. 8). Although drainage losses occurred at both sites, seasonal losses were more pronounced at the KMA site than at Nioro which had 46% lower drainage losses. Mean seasonal standard errors bars (Fig. 8) suggest a fairly good agreement between the values reported within each treatment. Further details of seasonal deep drainage losses compared to other water balance components at both sites during the study period are presented in Table 1.

3.7. *Water balance calculations*

After assessing the principal water balance components (*P*, ET_c, RO and DD) as elucidated in the previous sections, changes in profile soil moisture storage (ΔSW) were then algebraically deduced using Eqs. (2) and (4). The difference between measured values (ΔSW_m) with the neutron probe and computed values (ΔSW_c) yielded the contribution of shrubs through ground water uptake (G_{wup}).

There was good agreement between ΔSW_c and ΔSW_m in the control plots (no shrubs) for both sites and both years (Table 1). However, there was a consistent lack of agreement between the derived (ΔSW_c) and observed (ΔSW_m) values for crop–shrub treatments (Table 1), which we attribute to deep water uptake by shrubs (G_{wup}) (Eq. (3)). Computed changes in profile storage (ΔSW_c) from water balance components were lower than the measured field values (ΔSW_m). This observation was more pronounced for the KMA site, with computed values having orders of magnitude differences from measured results. The Nioro site, however, exhibited little difference between the computed and measured values (within ±10%). This also alludes to the fact that the KMA site portrayed higher storage values in crop–shrub plots in the upper soil layers but lower values at depth as opposed to the Nioro site (Figs. 3 and 4).

4. Discussion

Computed field results revealed that there is significant upward movement of water (Table 1) from below the 3.5 m depth mark that needs to be accounted for in the water balance calculations. It is plausible that the apparent discrepancies between computed values and measured field values in ΔSW (Table 1) were due to shrub water uptake. This could have been either shrubs exploiting water resources beyond the maximum measured soil depth (3.5 m) or from direct tapping of water table resources. A closer examination of results in Table 1 and the 0–1.10 m depth range (Figs. 3 and 4) support this assertion. Soil moisture storage trends revealed higher storage below crop–shrub systems since more water was actually channelled through the profile during the rainy season. On the contrary, the reverse was realized for the 1.10–3.50 m depth range (Figs. 3 and 4), despite the higher infiltration rates below crop–shrub plots, sole crop plots had higher soil moisture storage at this depth range (Figs. 3 and 4).

Shrub roots seem to preferentially extract water from deeper soil layers (Kizito et al., 2006) hence the lower soil moisture storage observed at depth in crop–shrub associations as opposed to sole crop plots. Consistent with these findings is work done in Niger where *G. senegalensis* shrubs were reported to extract water deeper in the profile (Gaze et al., 1998). In addition, Seghieri (1995), working on rooting patterns of woody and herbaceous plants in savannah environments, reported complementary relationships between them. Based on soil suction measurements, Lehmann et al. (1998) also revealed that in an agroforestry system, both trees and annual crops utilized soil water from different soil layers in a complementary way. They reported that roots of intercropped trees reached deeper than did sorghum, whose maximum root length density was in the topsoil.

Results from this study suggest that crop–shrub treatments yielded higher plant-available moisture in the upper portions of the profile with diminished magnitudes of soil moisture stored in deeper layers among crop–shrub treatments due to shrub root water uptake (Kizito et al., 2006). Both crops and shrubs could have been extracting water from the upper profile soil zones but at different times over the growing season. At the Nioro site, crop–shrub treatments had twice the stored soil moisture at KMA by the end of the cropping season. This indicates that the profile at this site did not encounter significant profile water shortages and therefore clouded the positive ‘‘hydraulic regulation’’ role of shrubs at this site compared to those at KMA. In addition, both site and shrub species differences could be confounding factors in the results recorded from both sites.

Implicit in the moisture storage trends observed (Fig. 3) could be the ability for shrub roots to redistribute soil water resources to upper soil layers using their roots as conduits, commonly termed as hydraulic redistribution. Consistent with this idea, research performed elsewhere under semi-arid environments has reported vegetation systems (trees and shrubs) to perform hydraulic lift hence leading to soil water facilitation (Richards and Caldwell, 1987; Dawson, 1995; Caldwell et al., 1998; Jackson et al., 2000).

The error bars in Fig. 3 suggest the presence of statistical differences in the treatments (Fig. 3a and b). However, the overlapping error bars (Figs. 3c and d, and 4) suggests that the differences in moisture storage between treatments were not statistically significant. This could be a result of the variable rainfall regimes in both study years and site differences since statistical differences were more pronounce in the drier years than the wet years and likewise for the drier site (KMA) than the wetter site (Nioro).

The rainfall recorded for Nioro site was well above average, however, at KMA the rainfall was below average (Fig. 5) and sporadic. Previous work in the Sahel shows that rainfall is highly variable both spatially and temporally (Lebel et al., 1992; Sivakumar et al., 1993; Cuenca et al., 1996; Gaze et al., 1998).

No surface soil crusts were observed at either study site. At Nioro, modeled run-off (Table 1) in both study years was due to the higher rainfall amounts and heavier soil texture. However, at the KMA site, the absence of run-off site is attributed to the sandy nature of the soil with high infiltration rates and very low precipitation events (Klaij and Vachaud, 1992; Kizito et al., 2006). Consistent with findings of this study, previous crop water-balance research in the Sahel, on-station or in experimental plots, has often assumed run-off and run-on to be zero (Payne et al., 1990; Lal, 1991; Klaij and Vachaud, 1992). However, run-off results for the Nioro site (Table 1) indicate that caution is needed when considering the exclusion of run-off from water balance components. This also is true for on-farm conditions where the combination of crust-sensitive sandy soils (Casenave and Valentin, 1992; Cuenca et al., 1996), high intensity short duration rainfall events (Serpantié et al., 1992) and diminishing length of Sahel fallow periods (Rockström, 1995) result in a high risk for run-off generation (Wilcox et al., 1988).

There was considerable agreement between estimated mean hourly evapotranspiration and the measured values (Fig. 6). The Penman–Monteith equation tended to under-estimate annual crop ET for both study sites by approximately 13%. Despite this, the approach serves as an affordable quick reference tool for mean ET estimates in these resource-limited environments. Similarly, while working on grass ET in a semi-arid setting, Evett et al. (1994) reported under-estimation of grass ET by the Penman–Monteith equation to a magnitude of 25%.

Mean soil evaporation (*E*) data (Fig. 7) revealed higher soil moisture losses in sole-crop plots than in crop–shrub treatments. Hence, shrub treatments had approximately 50% diminished soil evaporation below crop–shrub canopies as compared to sole-crops. The higher plant density and greater canopy cover in crop–shrub treatments probably reduced the soil *E* component but this would imply greater transpiration (*T*) since there would be a bigger canopy volume in these plots. Consequently the total ET_c was elevated in crop–shrub plots (Table 1) despite having reduced losses of soil *E*. Even though the ET_c was greater for the shrub–crop treatment, there was 30% higher infiltration recharge and the net amount of water that recharges the soil profile was greater with the presence of the shrub component compared to without the shrub (Kizito et al., 2006).

From a management perspective at both sites, these ‘‘non-competitive’’ hedgerow shrubs subsequently reduce wind speed impact with lower evapotranspiration losses which is a viable and cost-effective approach. Windbreaks in the Sahel have been reported to reduce wind velocity that improves crop productivity (Dancette, 1966; Kainkwa and Stigter, 1994; Boffa, 1999). Both shrub species could be suitable candidates that would confer shrub-imparted micro-climatic benefits to cropping systems.

In both study years at both sites, drainage losses were higher in sole-crop plots than in crop–shrub plots (Fig. 8); sole crops had almost twofold higher drainage losses than did crop–shrub plots. In sole-crop plots, shallow roots effectively reduce the soil storage capacity, resulting in the penetration of water below the root zone and eventual deep drainage. Similar effects have been documented in semi-arid regions where vegetation was removed (Gee et al., 1994) or in places where native shrubs have been replaced with annual grasses (Kremer and Running, 1996; Seyfried et al., 2004).

The sandy nature at KMA could be implicated for the higher drainage losses encountered (Fig. 8). Conversely, the Nioro site received more than twice the rainfall received at KMA, hence higher drainage losses would be expected but this was not the case due to higher clay content levels in these soils. Comparing both study years at KMA, more deep drainage losses were encountered in 2004 than in 2003 due to the higher rainfall received in 2004 (Fig. 8; Table 1). Conversely, for the Nioro site, higher losses occurred in 2003 than in 2004, also due to higher yet sporadic precipitation received in 2003 at this site.

From a crop water-use and soil water management perspective, selective pruning of shrubs at the commencement of the rainy season could be a promising venture. Owing to the erratic and sporadic rainfall characteristics in the Sahel, it has been reported that if little rain is received, there could be competition between shrubs and annual crops for both water and nutrient resources (Gaze et al., 1998; Wezel, 2000). However, Wezel (2000) suggested that cutting back these shrubs to half the above ground biomass would minimize any possible competition with neighboring annuals. It has been suggested that selective pruning would still help confer shrub-related benefits (Kizito et al., 2006) and is a better option than the conventional human-induced uprooting and complete shrub removal for firewood and fencing. If shrub removal and destruction is not halted, these regions could potentially experience reduced profile recharge, increased surface water run-off and higher soil evaporation losses, resulting in long-term detrimental impact to ecosystem agricultural productivity.

5. Conclusion

Crop–shrub associations resulted in reduced soil evaporation. The higher soil moisture storage in crop–shrub treatments than in sole crop plots in the upper portion of the profile could indicate the presence of hydraulic redistribution. This, combined with the lower soil moisture storage recorded in crop–shrub plots than in sole crops deep in the profile, underlines the high level of complementary water use in crop–shrub associations. Higher soil moisture reserves appeared to overshadow the positive hydrological impacts of shrubs at the Nioro site.

Water balance results revealed that there was significant water movement to the upper portions of the profile from below the 3.5 m depth accounting for up to 45% of the shrub's water demands. Future work on water balance studies among crop–shrub associations needs to account for this often ignored yet vital link, the shrub contribution to system fluxes through ground water uptake (G_{wup}) or tapping soil moisture resources beyond the crop rooting depth also expressed as hydraulic redistribution. This also holds true for any modeling efforts in such Sahelian ecosystems.

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