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Water use efficiency and uptake patterns in a runoff agroforestry system in an arid environment

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Abstract. Water is the most limiting factor for plant production in arid to semiarid regions. In order to overcome this limitation surface runoff water can be used to supplement seasonal rainfall. During 1996 we conducted a runoff irrigated agroforestry field trial in the Turkana district of Northern Kenya. The effects of two different *Acacia saligna* (Labill.) H. Wendl. tree planting densities (2500 and 833 trees per ha), tree pruning (no pruning vs. pruning) and annual intercrops (no intercrop vs. intercrop: *Sorghum bicolor* (L.) Moench during the first season and *Vigna unguiculata* (L.) Walp. during the second season) on water use were investigated. The annual crops were also grown as monocrops. Water consumption ranged from 585 to 840 mm during the first season (only treatments including trees). During the second season, which was shorter and the plants relied solely on stored water in the soil profile, water consumption was less than half of that during the first season. Highest water consumptions were found for non-pruned trees at high density and the lowest were found for the annual crops grown as monocrops. Tree pruning decreased water uptake compared to non-pruned trees but soil moisture depletion pattern showed complementarity in water uptake between pruned trees and annual intercrops. The highest values of water use efficiency for an individual treatment were achieved when the pruned trees at high density were intercropped with sorghum (1.59 kg m^{-3}) and cowpea (1.21 kg m^{-3}). Intercropping and high tree density increased water use efficiency in our runoff agroforestry trial. We ascribe the observed improvement in water use efficiency to the reduction of unproductive water loss from the bare soil.

Introduction and background

African and Middle Eastern countries have large areas of desert and semi-desert lands that cannot be cultivated but are used to raise livestock usually sheep and goats. These areas are characterised by low and unpredictable rainfall as a result of which herbaceous and woody plant production is low (Noy-Meir, 1985). During drought periods, which are common in these areas, and even during regular years, herbaceous production is very low, ephemeral and of poor quality. Overgrazing of pastures is a common feature (Dodd, 1994). These areas are also characterised by low fuel resources and indiscriminate tree felling for firewood is widespread (Sauerhaft et al., 1998).

Overgrazing and tree felling leave the soil surface bare (Milton et al., 1994). The surface aggregates of soils of semiarid and arid zones are typically unstable. The beating action of raindrops destroys these soil aggregates and this results in the formation of a dense crust, which decreases the water intake capacity of the soil (Agassi et al., 1985). A large proportion of the rainfall is therefore lost as runoff water. The ensuing reduction of water in the soil profile will hamper the regrowth of plants especially trees. The loss of topsoil due to erosion during runoff events further decreases the productivity of the soil and increases the grazing pressure. As a result of this negative feedback desertification progresses and the predicament of the very people who depend on this natural resource worsens.

It is possible however to convey the runoff water into plots surrounded by walls. The 'trapped' water will infiltrate into the soil and become available for plant growth. There are usually only a few rainfall events (in some cases only one) which produce runoff during a wet season and the crops in these fields grow on stored water during the periods between floods. Under these types of climatic conditions, water is the limiting factor for growth, and plant biomass production is directly proportional to plant water uptake (Hsiao, 1973; Schulze, 1986). The aim of management strategies in runoff agriculture will obviously be to maximise biomass production per unit of water collected. This goal may be achieved by intercropping annuals into stands of trees grown on stored water (Lövenstein et al., 1991). The rationale of such an approach is that the annuals would utilise water from the topsoil layers in the alleys between tree rows while the trees could take up water from deeper layers due to their deep rooting system. This complementarity effect of the different rooting patterns of trees and annuals (Schroth, 1995) was studied by Huxley et al. (1994) who found niche differentiation for below ground resources in a Grevillea/maize hedgerow intercropping experiment.

The complementarity could be enhanced by tree pruning. Reducing or completely removing the canopy of the tree component before the start of the intercrop season may allow the intercrop to exploit topsoil water resources while the trees require little or no water. Later in the season trees can tap soil moisture from deeper soil layers (Eastham et al., 1990a). This would lead to a higher consumption of water by the system as a whole.

Natural and planted agroforestry systems have usually been studied under rainfed conditions, i.e. without the addition of runoff water (Belsky et al., 1993; Braziotis and Papanastasis, 1995; Eastham et al., 1990b; Kessler and Breman, 1991; Le Roux et al., 1995; Ong et al., 1996; Rao et al., 1997). Runoff agroforestry however is a system which differs from those mentioned above as both trees and crops rely on stored water for their growth and progressively deplete the soil layers from the top. The effect of this peculiar but promising technique on the water use efficiency and uptake patterns of the components of the system, and the system as a whole, had not been investigated to date. The potential of such a system for the extremely arid zones warrant their study. The objectives of the present study were to:

A) Characterise the water uptake patterns of trees and intercrops in a runoff agroforestry system;

B) Assess the degree of interaction between tree and intercrop water uptake patterns and the effect planting density and pruning have on them; and
C) Assess the water use efficiency of the runoff agroforestry system.

Material and methods

Location

The study was carried out near the town of Kakuma in North-Western Kenya (34′51° E and 3′43° N, altitude ca. 390 m a.s.l.). The natural vegetation is a thornbush savannah and consists of *Acacia reficiens* Wawra and *Dobera glabra* (Forssk.) Along the river courses gallery forests of *Acacia tortilis* (Forssk.) Hayne, *Acacia elatior* Brenan subsp. turkanae Brenan and *Ziziphus mauritania* Lam. occur. The soils are classified as *Calcaric Fluvisols*; they are deep and layered ranging from sandy to clayey in texture with high pH's of 8.2 to 9.2 and electrical conductivities which range from 0.035 to 1.362 (Sm^{-1}) (Lehmann et al., 1998a).

Experimental design

Three levelled basins (each approximately 200 × 30 m) were built in 1994. The levels inside the basins were approximately 40 cm below the surrounding area, thus allowing a maximum storage of 400 mm of runoff water per flood. Runoff water was diverted into the basins from a seasonal river course during flood events by means of shallow channels.

Eight treatments were imposed in which the interactions between pruning regimes, planting density of trees and intercropping were investigated. The experiment was laid out as a randomised complete block design (RCBD). There was an additional control treatment with the annuals planted as monoculture.

In December 1994 the trees (*Acacia saligna* (Labill.) H. Wendl.) were planted in an alley crop configuration: (4 m between rows) with either 1 m (High density = 2500 trees ha^{-1}) or 3 m (Low density = 833 trees ha^{-1}) distance between the trees in the row. Each of the three basins served as one block, divided into nine experimental plots. The individual plot size varied from 300 to 500 m^2 depending on treatments. In the centre of each plot a sampling area of 120, 144 and 100 m^2 for the high and low tree density and the monoculture, respectively, was established (equivalent to 30 trees for the high density and 12 trees for the low density).

Trees were pruned in April, August and November 1996. Concurrently with the pruning in November we harvested the trunks of the pruned trees and felled all trees which were not pruned previously (final harvest). From May to August 1996 trees were intercropped with sorghum (*Sorghum bicolor* (L.) Moench.) and from September to November 1996 with cowpea (*Vigna* *unguiculata* (L.) Walp.). The annual crop species were planted after the trees were pruned. Inter- and monocrops were harvested at physiological maturity (Table 1).

Weather data

The following climatic variables were automatically recorded in a small weather station in the immediate vicinity of the experimental plots: incoming short-wave radiation, dry and wet bulb temperature, wind speed and rainfall. Measurements were taken at 10 minute intervals and stored as hourly means. These values were used to compute daily values of potential evapotranspiration using Penman's formula (Penman, 1948). Rainfall was automatically recorded by a tipping bucket at 10 minute intervals during rainfall events.

Soil water data

Soil moisture monitoring

The soil moisture profile was monitored by means of a neutron probe (Wallingfold Soil Moisture Probe Type I.H. III). Aluminium access tubes were installed in the experimental plots from April to August 1995 at least eight months before the start of the measurements. The arrangement and number of tubes per plot differed between treatments. In the low density treatment a simplified approach of Wallace and Jackson's (1994) two dimensional grid sampling was followed: one tube was placed midway between two trees in the row (tree row position); one tube midway in the 4 m alley and perpendicular to the tree line (centre position); and one tube in the alley in the middle of a four-tree-cell, with 2.5 m distance to each tree (alley position). In the

Table 1. Record of relevant management events during 1996 in the runoff agroforestry field trial in Turkana, NW Kenya.

Management events	Date	Day of year
First pruning	4–6 April	95 to 97
Second pruning	28–30 August	241 to 243
Final harvest	19–21 November	324 to 326
Vegetation period of		
sorghum	5 May to 2 August	126 to 215
cowpea	10 September to 20 November	254 to 325
Flood irrigations		
first and second	18 and 20 April	108 and 110
third (partial)	28 April	118
fourth	26 May	146
fifth (partial)	4 August	216
sixth	23 August	235
seventh	2 September	245

high planting density treatments tubes were installed midway between two trees in the row (tree row position) and in the middle of the alley, with 2.06 m distance to each of the nearest four trees (alley position). In the annual monocrop plots one tube was placed in the centre of the plot (centre position). Measurements were taken in 20 cm intervals, starting at a depth of 10 cm, at biweekly intervals during the first season and at weekly intervals during the second season. The neutron probe was field calibrated against data obtained from destructive soil sampling.

Seasonal water use

Seasonal water use (WU) during the periods April to August and September to November 1996 was computed as:

$$WU_i = R_i + FI_i + SWCh_i \tag{1}$$

with R: rainfall; SWCh: change of soil water content (0–2 m soil depth) from beginning to end of each period; FI: the amount of water contributed via flood irrigations; and the subscript *i* denotes the season. FI's were estimated from standing water depths for individual plots following flood events and corrected for evaporation losses during ponding. SWCh values were averaged over the plot from tubes in different positions. We assumed that the drainage losses were usually negligible (Lehmann et al., 1998a and personal observations from soil moisture profiles). In order to monitor possible deep drainage we installed access tubes in two selected plots (light and medium textured soils) to 4 m soil depth. In the sandy plot we found no downward water movement below a depth of 2.3 m. In the loamy plot the soil moisture profile was closed at 2 m depth.

Soil water depletion

Soil water depletion (SWD) was computed from SWCh data for three soil layers and different plot positions during periods without floods. These periods occurred towards the later part of the sorghum season (6 June to 1 August 1996; DoY 158–214) and the entire cowpea intercropping season (9 September to 20 November 1996; DoY 253–326). We started soil moisture measurements when the sorghum intercrops were already in growing stage three to four (Vanderlip and Reeves (1972): growing point differentiation to final leaf visible in whorl) in the monocrop and pruned treatments and had only reached stage two (fifth leaf visible) in the non-pruned treatments. Deep drainage was assumed to be negligible and the measured depletion of soil water was therefore due to the evaporation from bare soil and the transpiration by plant cover (trees and annuals alone or their mixtures). The surface of the soil was dry at this stage and the fraction of water lost directly from the soil surface was probably only a small fraction of the overall water loss.

Water use efficiency

The conversion efficiency of the vegetation cover (sole crops or crop mixtures) to utilise water resources (soil water, rainfall or flood irrigation water) was defined as gross water use efficiency:

$$GWUE_i = \frac{PBM_i}{PWU_i} \tag{2}$$

where the subscript i denotes different seasons, PBM is plant biomass production per area and PWU is seasonal plant water use from the same area. Tree biomass production was estimated for the four trees growing closest to the access tubes using biometric equations (Droppelmann and Berliner, 2000). The biomass yields of the four trees were weighted proportionately to their position and distances to the access tubes and then averaged. The area per tree in the high and low planting density was 4 and 12 m^2, respectively. Intercrop and monocrop biomass yields were derived from direct sampling. The yields of the annuals were obtained from an area corresponding to the stand area of trees at high and low density, i.e. 3.5 and 10.5 m^2, respectively, and 1 m^2 in the annual monocrop plots. PWU (in m^3) was computed from seasonal water use data to a depth of 2 m multiplied by the corresponding area. Index of ground cover by tree canopies was computed as the ratio of cross-sectional canopy area to the soil surface area available to each tree (4 and 12 m^2 at high and low planting density, respectively). The canopy cross sectional area was computed for each tree using the maximum crown diameter measured at each date. The average of the four trees growing closest to the corresponding access tube was used to computed the above-mentioned ratio. Additional information on the biomass production of trees and intercrops in this trial has been presented by Droppelmann et al. (2000).

Statistical analysis

Treatment differences for seasonal water use and gross water use efficiency were analysed by One-Way ANOVA's and treatment factors (intercropping, pruning, tree planting density) for GWUE by Multi-Way ANOVA's. In case of significance the analysis of variance was followed by Tukey or LSD comparison of means as indicated in the text or tables. Interseasonal differences in GWUE between treatments were tested by two sample *T*-tests.

We compared water depletion patterns of two locations (within the tree row and in the middle of the alley between tree rows) for three different soil layers (from 0 to 0.6, 0.6 to 1.2 and from 1.2 to 1.8 m). In order to carry out the statistical analysis we assumed a randomised complete block design with split plots. The treatment replicates were regarded as main plots. Location and depth were regarded as subplots within each main plot. To account for differences in soil texture between plots we introduced the average percentage of sand in the different soil layers as a covariate.

Results

Climatic conditions

On the agro-climatic zone map of Kenya (UNEP, 1997), Turkana lies in the arid (P/E: 0.15–0.25) to very arid (P/E: < 0.15) zones. Our study site in Kakuma was located on the border between these two zones. For the Turkana region a bimodal rainfall pattern exists with 'long' rains from April to June and 'short' rains in October and November, although rainfall distribution is in general highly erratic. In January and February, which is also the hottest period of the year, rainfall probability is very low. An annual mean of 318 mm $year^{-1}$ based on 14 years of data has been reported (W.I. Powell, Turkana Drought Contingency Unit, unpublished data).

Daily rainfall, daily averages of potential evapotranspiration (PET), wind speed and minimum/maximum temperature during the trial period in 1996 are presented in Figure 1. Average PET from April to November was 7.9 mm day^{-1}. PET ranged from 8 to 11 mm day^{-1} for periods without rain. The daily average wind speed was usually above 2.5 m s^{-1} for dry periods and below

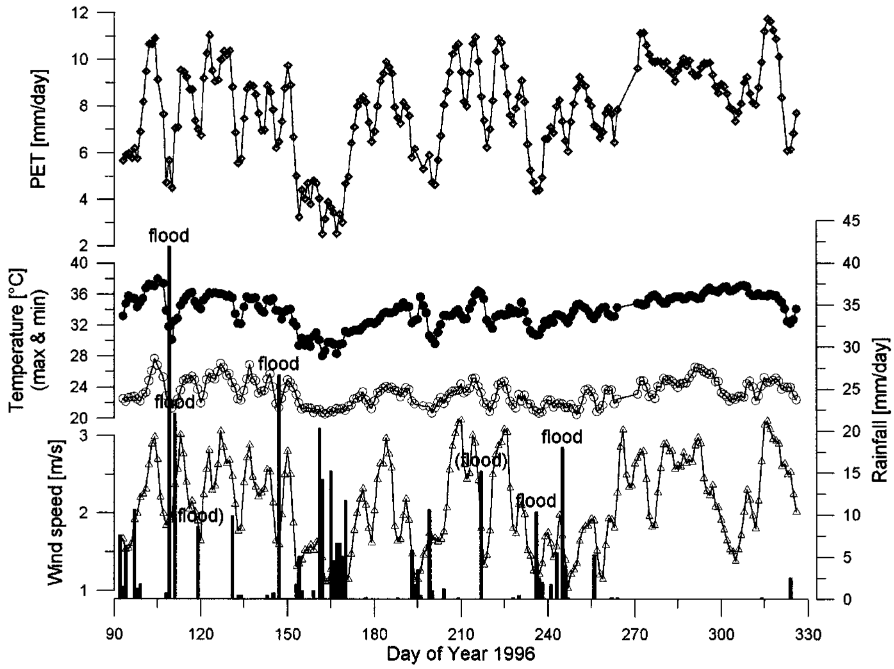

Figure 1. Daily average values of minimum and maximum temperatures, wind speed, Penman potential evapotranspiration (three day moving average) and rainfall during the relevant period of 1996 for Kakuma, Turkana, NW Kenya. Rainfall events that generated floods are indicated (brackets denote partial floods).

1.5 m s^{-1} during rainy periods. Average daily temperature for the whole trial phase was 28.4 °C with average maximum and minimum of 34.0 and 23.3 °C, respectively.

In 1996 rainfall was slightly above average (330 mm $year^{-1}$). Sixty nine percent of rainfall fell during the first season from April to August and only 2% during the second season from September to November. The remaining rainfall occurred mainly in the month of August, i.e. between the first and the second season. The relatively even distribution of rainfall events, yielding at least 5 mm between April and June (approx. day of year (DoY) 90–170), was atypical for the Kakuma location.

Seven rainstorms in 1996 generated runoff floods. Two heavy rainstorms occurred in mid April (41.9 and 22.1 mm), followed by a relatively small rainstorm (8.6 mm) a week later which did not flood all experimental plots. At the end of May a rainfall event of 26.7 mm resulted in a fourth flood about three weeks after the sowing of sorghum. The flood did not affect the establishment of the crop. The average water input for all plots via flood irrigations in April and May 1996 was 722 mm (Table 2). In August the plots received one partial flood (not reaching all plots) on the 5th, and one complete flood on the 23rd of that month (15.2 and 10.4 mm of rainfall, respectively). After tree pruning the plots were flooded again on the 2nd of September (18.0 mm of rainfall). Average water input during August and September was 623 mm. During the vegetation cycle of the cowpeas, from the 10th of September to the 20th of November, only 8 mm of rainfall fell.

Seasonal water use

WU in the tree treatments during the first period ranged from 585 to 840 mm (Table 3). Differences between individual treatments were not statistically significant. However, pruned trees used less water than trees in non-pruned treatments (671 and 753 mm respectively), but the difference was not statistically significant at $\alpha = 0.05$ ($P = 0.076$). Intercropped treatments generally had a slightly higher WU than the non-intercropped treatments but the differences were not significant. The sorghum monocrop had the lowest WU of only 360 mm. The WU was significantly different between individual blocks because they received different amounts of FI's. In the first block WU was

Table 2. Potential evapotranspiration and rainfall in Kakuma, Turkana, NW Kenya for the two growing periods in 1996 and the corresponding average amounts of water supplied by flood irrigations (± standard deviation).

	April to August	September to November
Potential evapotranspiration (mm)	903	676
Rainfall amount (mm)	229	8
Contribution via flood irrigations	722 (± 200)	623 (± 57)

Table 3. Total water use (in mm) in the different treatments of the runoff agroforestry field trial in Turkana, NW Kenya for the periods April to August (trees intercropped with sorghum) and September to November (trees intercropped with cowpea); (± standard deviation).

		April to August	September to November
High density			
Pruned	Sole trees	651 (± 193)	181 (± 97)
	Intercropped	680 (± 182)	241 (± 84)
Non-pruned	Sole trees	840 (± 257)	350 (± 176)
	Intercropped	758 (± 206)	264 (± 40)
Low density			
Pruned	Sole trees	584 (± 249)	264 (± 48)
	Intercropped	768 (± 301)	260 (± 21)
Non-pruned	Sole trees	695 (± 176)	240 (± 96)
	Intercropped	718 (± 256)	308 (± 79)
Monocrop		360 (± 114)	197 (± 91)

lowest (462 mm); and in block two WU was lower (710 mm) than in block three (846 mm) during the first season.

Approximately 70% of the annual rainfall fell within the four months from April to July (see Figure 1). However, water use was larger than rainfall during this season and depended on the amount of runoff water harvested (FI). The available soil moisture was depleted to the lowest level measured in all plots at the beginning of April, the end of the main dry season in 1996. In Table 4 the fractions of plant available moisture at the start and end of the two experimental periods in each treatment are presented. The amounts of residual water in the soil profile corresponded to the trends observed for WU. In intercropped pruned treatments at either density less water remained in the soil than in non-intercropped pruned treatments. Residual moisture was higher for low density treatments. Therefore trees at high density exploited the soil water more than trees at low density.

The sole source of water available to the plants during the second period was the moisture stored in the soil (Table 2). No flood occurred during this period and rainfall was negligible. WU was less than half that of the first season which lasted about one third longer. Extraction of water from the soil profiles was higher than during the first season in corresponding treatments. In the pruned treatments sufficient amounts of water (18 to 37% of available water) remained in the soil for the following dry season (Table 4). However, only 3 to 13% of available water remained in the profiles of non-pruned trees. The residual water in the cowpea monocrop was 25% but varied greatly between replicates.

Table 4. Fraction of plant available soil moisture (difference, expressed in percent, between the absolute maximum and minimum measured soil water contents) in the various treatments of the runoff agroforestry field trial in Turkana, NW Kenya.

	DoY	April 95	August 214	September 253	November 326
High density					
Pruned	Sole trees	5 (± 3.0)	33 (± 3.3)	93 (± 6.1)	37 (± 5.2)
	Intercropped	4 (± 1.2)	24 (± 2.2)	93 (± 6.7)	28 (± 11.0)
Non-pruned	Sole trees	5 (± 3.6)	16 (± 1.1)	94 (± 6.0)	3 (± 2.3)
	Intercropped	14 (± 7.7)	18 (± 1.4)	91 (± 9.4)	10 (± 5.2)
Low density					
Pruned	Sole trees	3 (± 0.7)	55 (± 7.4)	95 (± 5.0)	32 (± 3.3)
	Intercropped	3 (± 1.6)	37 (± 7.9)	95 (± 5.2)	18 (± 5.3)
Non-pruned	Sole trees	4 (± 1.6)	32 (± 2.7)	94 (± 5.9)	13 (± 5.2)
	Intercropped	10 (± 9.4)	26 (± 8.6)	92 (± 8.3)	8 (± 6.6)
Monocrop		73 (± 3.3)	49 (± 14.9)	95 (± 4.8)	25 (± 23.3)

Data is presented for the beginning and the end of each cropping cycle (April & August and September & November for the seasons during which sorghum and cowpea were the respective intercrops; DoY 141 (20th of May) was chosen as the beginning of the season for the sorghum monocrop). (± standard deviation).

Patterns of soil water depletion

General effects on SWD

Despite differences between the two seasons, as described above, the SWD had some common patterns as the split plot analysis reveals (Table 5). In both seasons the SWD was significantly greater in non-pruned tree treatments than in pruned treatments. There was a general decrease in SWD from the top to the bottom soil layers. Only during the cowpea season did we find weakly significant differences between tree planting densities: SWD was greater in the low density than in the high density treatments.

Tree pruning × soil depth interactions were significant in both seasons. SWD of non-pruned trees was significantly different between all three layers (both seasons $P = 0.0001$). SWD for pruned trees decreased significantly (both seasons $P = 0.0001$) from layer one (0–60 cm) to layer two (60–120 cm) but not from layer two to layer three (120–180 cm). In layer three SWD was not different between pruning treatments. When trees were not pruned SWD was higher in layer one ($P = 0.0001$) and in layer two ($P = 0.001$ for the sorghum season and $P = 0.0001$ for the cowpea season) than SWD in the corresponding layers of pruned treatments. We found no further significant interactions during the cowpea season between treatment factors (intercropping, pruning and density), location and/or depth.

Table 5. Levels of significance (*P*-values) for soil water depletions (SWD) from the runoff agroforestry field trial in Turkana, NW Kenya obtained from an ANOVA with a split plot design.

Main/sub factors and interaction	Sorghum	Cowpea
Density	ns	0.0568
Pruning	0.0442	0.0053
Depth	0.0001	0.0001
Pruning × Depth	0.0005	0.0118
Density × Location	0.0261	ns
Density × Pruning × Location	0.0486	ns
Density × Intercropping × Location	0.0465	ns

The factors intercropping, pruning and density were applied to the main plots and the factors depth and location to the subplots. The analysis was carried out for the later half of the sorghum vegetation cycle (DoY 158–214) and for the entire cowpea vegetation cycle (DoY 258–325); (ns = not significant).

Specific interactions during the sorghum season

During the sorghum season additional interactions between tree density, location, pruning and intercropping were found (Table 5). In the pruned treatments SWD was not affected by tree density and/or location. However, SWD in non-pruned treatments was different between locations and between densities. At high density the larger SWD occurred in the alley (P = 0.059) but at low density it occurred in the tree row (P = 0.021). SWD in the same location but at different densities were also significantly different: tree row SWD was smaller and alley SWD was larger at high density compared to low density (P = 0.069 and 0.018, respectively).

SWD of non-pruned high density treatments in the tree row and the alley were larger than for the matching locations in the pruned treatments (P = 0.064 and P = 0.0001, respectively). At low density the SWD was significantly larger (P = 0.022) for non-pruned trees at the tree row location but not in the alley location.

Significant interactions between density, intercropping and location occurred only within the low density treatments. SWD was larger in the tree row of non-pruned sole trees when compared to the alley location in the same treatment (P = 0.002) and was greater than both locations in the intercropped treatments (tree row and alley; P = 0.016 and 0.025, respectively). Intercropped treatments had greater SWD in the alley than non-intercropped treatments but the differences were not statistically significant.

Spatial and temporal trends of complementarity in SWD

Water loss in pruned treatments was primarily from the uppermost soil layer. This is the layer where trees and intercrops are most likely to compete for resources. In order to visualise the development of SWD we plotted differences in soil water content (WC) between tree row and alley locations against time. In Figures 2 and 3 these developments are presented for pruned trees

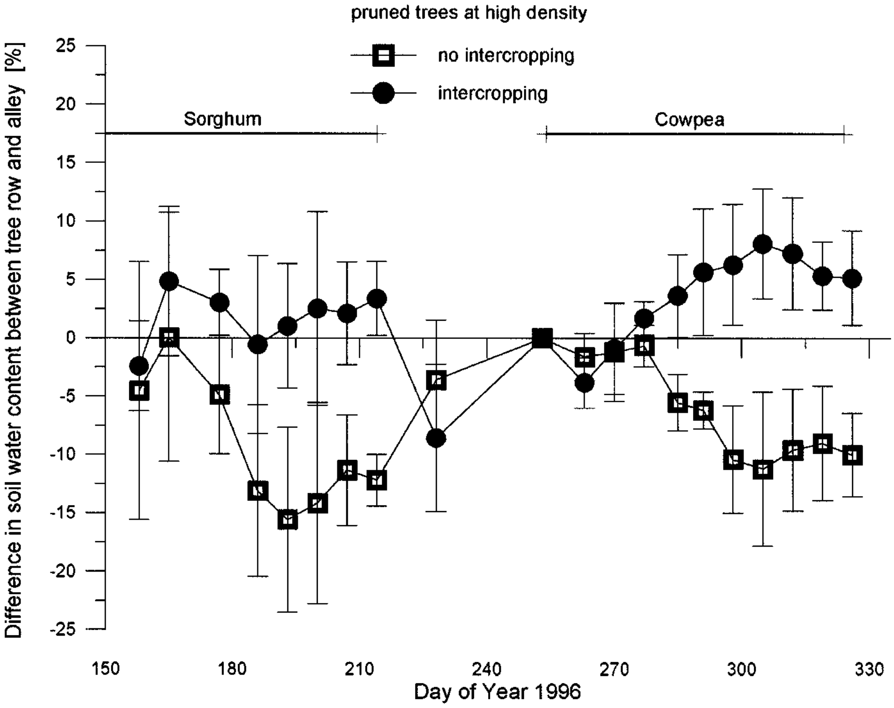

Figure 2. Differences in water content in the topsoil layer (0–60 cm) between the tree row location and the alley location for pruned trees at high density with either intercropping or no intercropping in the runoff agroforestry field trial in Turkana, NW Kenya during 1996. Plotted values in the figures are average differences between tree row and alley measurements (n = 3). A positive value indicates a greater water content in the tree row and a negative one a greater one in the alley. (Error bars indicate standard deviation).

at high and low density, respectively. The WC's for all measurement dates at the different locations were normalised with the corresponding data of the 9th of September (on this date we measured the highest water content during 1996 and the smallest differences between locations within plots).

During the first part of the sorghum season (DoY 126–157) frequent rains prevented the development of any spatial differences in normalised WC's. But later in the season when plants were mostly relying on water uptake from stored moisture, differences between locations developed. Towards the end of both seasons normalised WC's were 10 to 15% higher in the alley of non-intercropped pruned trees at high density than those in the tree row (Figure 2) indicating that considerable amounts of soil moisture remained in the soil of the alley location. At low density this trend was less marked (5 to 10%; Figure 3).

In the intercropped treatments WC's did not differ very much between locations during the later part of the sorghum season. By this time the pruned

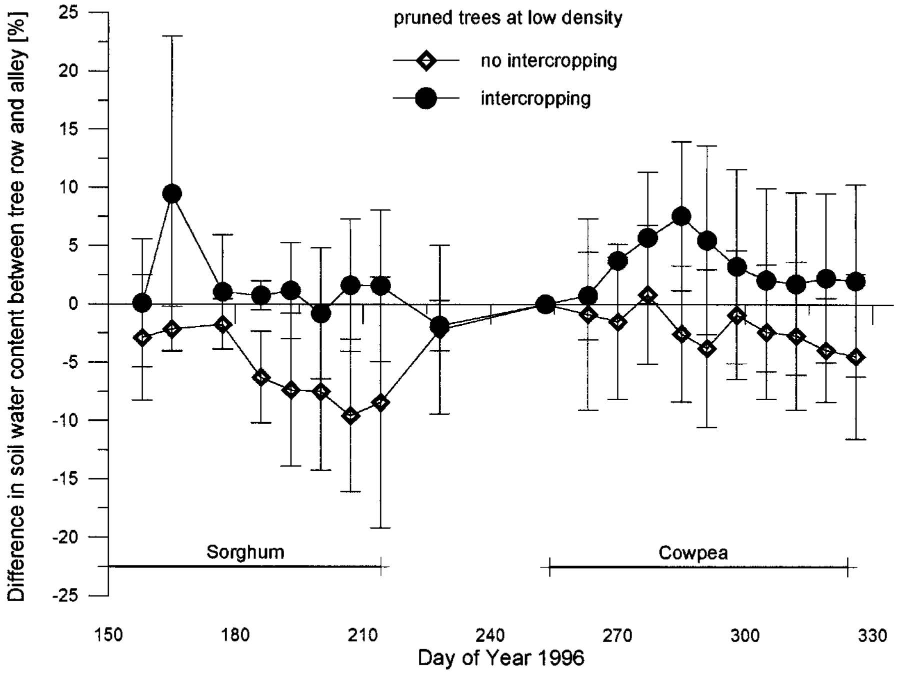

Figure 3. Differences in water content in the topsoil layer (0–60 cm) between the tree row location and the alley location for pruned trees at low density with either intercropping or no intercropping in the runoff agroforestry trial in Turkana, NW Kenya during 1996. Plotted values in the figures are average differences between tree row and alley measurements (n = 3). A positive value indicates a greater water content in the tree row and a negative one a greater one in the alley. (Error bars indicate standard deviation).

trees had again transpiring canopies (Figure 4) which acted as equally strong sinks in the tree row as the sorghum intercrop in the alley. However, during the cowpea season differences in normalised WC's developed between the tree row and the alley after pruning of the trees. The cowpeas acted as a stronger sink for soil moisture than the trees at the beginning of the season as can be seen by increasing positive values for these treatments in Figures 2 and 3. Towards the end of the season this trend was reversed due to the regrowth of tree canopies and hence higher transpiration by the trees.

Soil water data (not presented here) show that considerable amounts of water were lost from the bare soil in the alleys of non-intercropped pruned trees. These unproductive evaporation losses occurred mainly at the beginning of the season following flood irrigations when the soil cover by the completely defoliated trees was negligible (Figure 4). The faster development of a soil cover by the cowpea crop compared to regrowth of pruned trees reduced the evaporation losses in this location and hence led to temporal complementarity in soil water resource exploitation. The comparison of the inter-

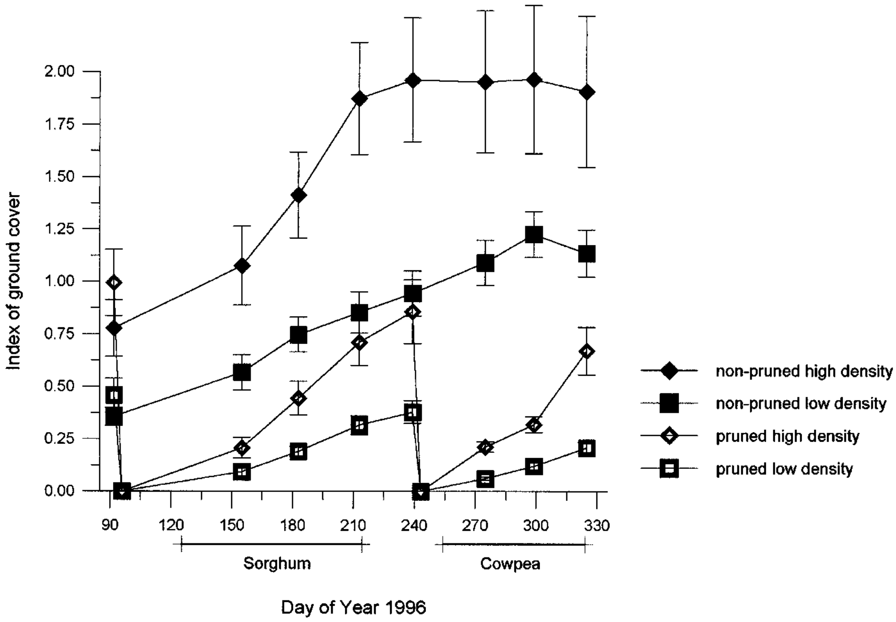

Figure 4. Index of ground cover in the runoff agroforestry field trial in Turkana, NW Kenya during 1996. Error bars indicate standard error of the mean (n = 3).

cropped and non-intercropped treatments at the end of each season indicates spatial complementarity in water use between trees and annuals. Sole trees did not exploit the alleys to the same extent as the tree row location. Conversely intercropping of pruned trees resulted in a more homogeneous soil water exploitation of the topsoil layer.

Water use efficiency

Results of the gross water use efficiency (GWUE) analysis are presented in Tables 6, 7 and 8. We compared GWUE between treatments within each season and GWUE of all treatments between seasons. The GWUE values for all treatments during the two seasons are given in Table 6. The *p*-values (two sample *T*-tests) in Table 6 suggest that there were no differences in GWUE between seasons for all tree treatments. Only the GWUE of annuals grown as monocrops were significantly different (P = 0.006) between seasons. The GWUE for sorghum was higher (1.94 kg m^{-3}) than for the cowpea (0.35 kg m^{-3}).

GWUE's in the tree treatments during the first season ranged from 0.58 kg m^{-3} for non-intercropped pruned trees at low density to 1.59 kg m^{-3} for intercropped pruned trees at high density. These two treatments were statistically different from one another (Tukey-test following One-Way ANOVA;

Table 6. Gross water use efficiency (GWUE) of all treatments (in kg m^{-3}) in the runoff agroforestry field trial in Turkana, NW Kenya for the first (sorghum) and second (cowpea) season.**

Season	Pruning of trees				No pruning of trees				
	High density		Low density		High density		Low density		Annual as
	Sole trees	Intercrop	Sole trees	Intercrop	Sole trees	Intercrop	Sole trees	Intercrop	Sole crop
First	0.92 bc	1.59 ab	0.58 c	0.83 bc	1.26 abc	1.43 abc	0.88 bc	0.95 abc	1.94 a
Between season	*P* = 0.867	*P* = 0.428	*P* = 0.197	*P* = 0.635	*P* = 0.933	*P* = 0.488	*P* = 0.079	*P* = 0.956	*P* = 0.006
Second	0.98* a	1.21* a	0.36 a	0.72 a	1.18 a	1.13 a	1.18 a	0.97 a	0.35 a

Note:
* $N = 2$; missing data for one replicate.
** $n = 3$.
P-values correspond to a two sample *T*-test between seasons for each treatment (values in one row followed by the same letter are not significantly different at $\alpha < 0.05$).

Table 7. Results of the Multi-Way-ANOVA for gross water use efficiency (GWUE) of the first season (sorghum intercrop) from the runoff agroforestry field trial in Turkana, NW Kenya.

Source	DF	sum of squares	*F*-value	*P*-value
Intercropping	1	0.504	4.82	0.040
Pruning	1	0.141	1.35	0.259
Density	1	1.43	13.71	0.001
Residual	20	2.09		
Total	23	4.16		

Table 8. Results of the Multi-Way-ANOVA for gross water use efficiency (GWUE) of the second season (cowpea intercrop) from the runoff agroforestry field trial in Turkana, NW Kenya.

Source	DF	sum of squares	*F*-value	*P*-value
Intercropping	1	0.060	0.12	0.734
Pruning	1	0.009	0.18	0.679
Density	1	1.497	2.99	0.101
Residual	18	9.008		
Total	21	10.654		

Note: total N equals 22 due to missing data from two plots.

$\alpha = 0.05$). All other tree treatments were not significantly different from each other. During the second season the GWUE data showed greater variability and therefore no differences between treatments were found.

However, during the first season, the Multi-Way-ANOVA for treatment factors (intercropping, pruning and density) revealed that the intercropped treatments and tree treatments at high density had higher GWUE's than non-intercropped and low density treatments (Table 7). In the second season none of the treatment factors had a statistically significant effect on GWUE (Table 8). The overall variation during the second season was much higher than during the first one. No interactions between treatment factors were found in either season.

The higher GWUE in the intercropped treatments (1.20 kg m^{-3}) during the first season was due to the combination of the trees and the water efficient sorghum intercrop. Non-intercropped treatments had an average GWUE of 0.91 kg m^{-3}. The low GWUE of the cowpeas resulted in a lack of intercropping effect on GWUE during the second season. However, cowpea intercropped and pruned treatments had somewhat higher GWUE's than non-intercropped pruned treatments (Table 6). The overall GWUE analysis showed no effect of pruning during both seasons but GWUE's of non-intercropped pruned trees were consistently lower than non-intercropped non-pruned ones (Table 6). The only difference between these treatments was in the size of the tree canopy (Figure 4). Therefore lower evaporation losses in the non-pruned treatments account for higher GWUE. Treatments at high density had a higher GWUE (1.30 kg m^{-3}) than at low density (0.81 kg m^{-3}) during the first season ($P = 0.01$; Table 7) but not during the second season ($P = 0.101$; Table 8).

Discussion

Water resource capture in a runoff agroforestry system

The major limiting factor in dry areas for crops in general and intercropped systems in particular is water availability. Govindarajan et al. (1996), McIntyre et al. (1997) and Rao et al. (1997) state that the two main reasons for reduced yields from annuals in agroforestry systems are the development of water deficits for the annual crop during its vegetative phase (due to competition with the trees) and a smaller soil water recharge at the beginning of the wet season (compared to sole cropped systems). These two phenomena were used by the authors to explain low yields of the annual crops in agroforestry systems under rainfed conditions in semiarid Kenya (annual rainfall: 750 mm).

In our study 722 mm and 623 mm of water were made available to the plants during the first and second season, respectively. This was achieved by means of runoff water harvesting in a location that received only 330 mm of rainfall for the whole year. The stored runoff water accounted for 74% of the seasonal water use from April to August and for 99% during the second period from September to November. The combined water sources (rainfall plus flood irrigation) were enough to satisfy the high evaporation demand of the atmosphere during both seasons (903 and 676 mm PET for first and second season, respectively) in Kakuma. The soil profile was fully recharged before the sowing of the intercrop in each season. Furthermore the use of runoff water allowed a second growing period during the short rain season which is traditionally not used by the local population because of its high production risk.

Runoff agroforestry offers a number of advantages over rainfed systems located in arid environments. The main advantages of runoff agroforestry are that an increased amount of water is made available to the plants and that moisture is available in deeper layers of the soil profile. In rainfed systems plants inevitably compete for soil moisture in the topsoil, hence spatial complementarity rarely occurs in semiarid environments (Rao et al., 1997). Additionally adverse effects of rainfall interception losses from the tree canopy (Wallace, 1996), and thus a heterogeneous water distribution in the soil profile due to stem flow, which are major factors in conventional rainfed agroforestry, are negligible in runoff agroforestry systems.

Tree/crop interactions

Available water resources were not exploited in the same way and to the same extent in the different treatments in our study. Non-pruned treatments generally used more water and took up water from deeper soil layers than pruned trees. Non-pruned trees at different densities exploited water from different locations during the second part of the sorghum season. Trees at low density still took up water mainly from underneath the tree row whereas in the high density treatments trees additionally tapped soil water resources in the alley. This is also reflected by a higher total water use at high density.

The statistical analysis showed no significant pruning × intercropping × location interactions as expected. Five-way interaction comparisons between locations in intercropped and non-intercropped pruned trees showed differences but the necessary α value of 0.001 required for this kind of comparison was not met. However, in Figures 2 and 3 the temporal and spatial complementarity in water use in the topsoil of intercropped pruned trees at both densities can be observed. We did not find any complementarity effect in non-pruned treatments. When trees were not pruned their competitive advantage was too great for the annual intercrops to get established and grow properly as indicated by the high index of ground cover of non-pruned trees (Figure 4). Pruned trees and annual intercrops most likely took up water from the same soil zones but at different times during the season. Intercropped and pruned trees at high and low density left behind about one quarter to one third of the available soil water after the cropping season. This indicates that no acute water shortages for trees and annuals occurred when trees were pruned and that soil moisture was rather shared than competed for. These facts are supported by Lehmann et al. (1998b), who showed for the same runoff agroforestry system that trees and annual crops utilised soil water from different soil layers in a complementary way based on soil suction measurements and that the roots of intercropped trees reached deeper than sorghum, which had its maximum root length density in the topsoil.

Conversion efficiency of water resources

Wallace (1996) proposed that combining trees and annuals directly improves water use in semiarid regions mainly because of a higher efficiency in rainfall utilisation by reduced evaporation losses from the bare soil. The higher ground cover in intercropped treatments probably reduced unproductive direct soil evaporation in our trial and contributed in this way to the improved GWUE of intercropped pruned tree systems. Morris et al. (1990) showed that, after the harvest of wet paddy rice (a situation similar to runoff irrigated systems), the same amount of water can be lost from the soil profile by evaporation or drainage as would be used by crops during the following dry season. In a similar runoff agroforestry experiment conducted in Israel with *Acacia saligna* the overall WUE for non-pruned trees was equal to our values but for pruned trees WUE was approximately twice as high (Degen and Berliner, 1997). The trees in Israel were pruned and flood irrigated during the cold winter season when potential evaporation rates are low. This underlines the important role of direct and unproductive water losses from the bare soil in tropical arid environments with high evaporation rates throughout the whole year such as the Turkana region in NW Kenya.

Water use efficiency as well depended on planting density of the trees in our study. Similarly a higher conversion efficiency for trees planted at high density (2150 trees ha^{-1}) compared to lower densities (304 and 82 trees ha^{-1}) was reported by Eastham et al. (1990b) in a tree/pasture agroforestry system. Their explanation was that pasture transpiration was decreased under the tree canopy at high density leading to reduced below ground competition and hence trees at high density were able to maintain a lower root:shoot ratio. However, the improved GWUE of trees at high density in our trial was most probably related to lower evaporation losses from the bare soil due to the larger and denser canopy of these treatments when compared to the canopies of trees at low density (Figure 4). The gross water use efficiency in our study was improved by high tree density and the presence of an intercrop when trees were pruned. In both cases the evaporation losses from bare soil were reduced and the net water consumption by the plants increased.

Conclusion

The use of runoff water for supplemental irrigation of agroforestry systems in dry areas has proven to be beneficial for plant growth and forms a feasible production system. Both, intercropped and sole, stands of trees at high planting density consumed the highest amount of water.

Complementarity in water use was found between pruned trees and annual intercrops. The water use efficiency of the agroforestry system was not affected by the pruning of the trees but by their planting density and the presence of an intercrop.

Intercropping of pruned trees at high density resulted in the highest water use efficiency in our trial. We ascribe the observed improvement in water use efficiency of this runoff agroforestry system to the reduction of unproductive water loss from the bare soil.

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