Journal of Arid Environments (1998) **38**: 479–492

Runoff irrigation of crops with contrasting root and shoot development in northern Kenya: water depletion and above- and below-ground biomass production

Johannes Lehmann*‡, Klaus Droppelmann† & Wolfgang Zech*

**Institute of Soil Science and Soil Geography, University of Bayreuth, 95440 Bayreuth, Germany*
†Blaustein Institute, University of the Negev, Sde Boqer, Israel

(*Received 29 January 1997, accepted 20 November 1997*)

In a runoff irrigation system using levelled basins, the water uptake patterns of different plant species (*Acacia saligna* (Labill.) H. L. Wend. and *Sorghum bicolor* (L.) Moench.) with contrasting root and shoot development were compared. Rainfall amounts during 1995 led to enough runoff water for realizing two cropping cycles. The amount of irrigation water was sufficient to fill the moisture-depleted zone in the upper 1·5 m to field capacity. The total above-ground biomass production of sorghum equalled the biomass production of *Acacia* during the cropping season. Soil water depletion was higher in soils cropped with *Acacia* and showed a different spatial and temporal pattern than the annual crop. Total root length density of sorghum was two times higher than that of *Acacia*, but the root system of sorghum was shallower than the tree root system. Water uptake patterns are discussed with respect to the contrasting above- and below-ground growth strategies of the two plant species.

Keywords: *Acacia saligna*; irrigation; northern Kenya; roots; soil water; *Sorghum bicolor*

Introduction

In semi-arid areas, precipitation may be extremely variable. Without irrigation, crop yields are generally low and very unreliable. Water harvesting has proved to be an inexpensive and effective way of increasing biomass production in many arid and semi-arid regions in West Africa (Tabor, 1995), southern Africa (Carter & Miller, 1991) or India (Gupta, 1994). In runoff irrigation, the surface runoff water after a heavy storm is guided into levelled basins. The standing water is allowed to infiltrate deep into the soil profile, increasing the plant-available soil moisture. Crops or trees sown after the flood are then able to utilize this additional soil water and, in this way, produce more biomass and higher yields (Evenari *et al.*, 1968).

‡Corresponding author.

0140–1963/98/030479 + 14 $25.00/0/ae970352

Patterns of soil water use depend on different factors such as soil and plant properties and climatic conditions. In the Negev, Israel with winter rains, water content below *Acacia salicina* Lindl. and *Eucalyptus occidentalis* Endl. was higher in the topsoil than in the subsoil at the end of the growing season (Zohar *et al*., 1988). But in the Indian Desert, volumetric water content in a young plantation of *Azadirachta indica* A. Juss. was lower in 0–0·25 m than in the underlying soil layers after the rainy season (Gupta, 1994). Root distribution plays an important role in plant water uptake, which can vary according to soil properties, plant species, planting density or water regime. In a humid savanna the maximum root length density of several tree legumes was found in the upper 0·1 m (Schroth *et al*., 1995). Some tree species in an arid region of north-west India, however, had their maximum root length at 0·15–0·3 m or deeper (Toky & Bisht, 1992). In irrigation systems, the root distribution may change according to the water supply; little is known about water and root distribution in runoff irrigated fields. The strongly contrasting growth patterns of annual and perennial crops may face different constraints under runoff irrigation. Sorghum showed decreasing root length densities with increasing depth in several studies in temperate regions (Van Noordwijk & Brouwer, 1991). This may have effects on water uptake and biomass production in arid environments.

The objectives of this study were first, to relate the pattern of water input to soil moisture changes in a runoff irrigation system in northern Kenya, as little is known about soil moisture changes under runoff irrigation; second, to compare biomass production of *Acacia saligna* at two planting densities (2500 and 833 trees ha^{-1}) and *Sorghum bicolor*; and third, to examine the relationships between above- and below-ground biomass production and soil moisture depletion, comparing plant species with contrasting root and shoot development, since root distribution may strongly affect soil moisture depletion and biomass production under the specific conditions of runoff irrigation.

Study site and methods

Location

The study was carried out near Kakuma in northern Kenya (34° 51' E; 3° 43' N, altitude 620 m a.s.l.). The natural vegetation is a thornbush savanna with *Acacia tortilis* (Forsk.) Hayne, *Acacia reficiens* Wawra. and *Ziziphus mauritiana* Lam. The rainfall distribution generally is bimodal with a first maximum during April and May, and a second usually in September and October, with a mean annual precipitation of 318 mm (from 14 years; W. I. Powell, and Turkana Drought Control Unit, unpubl. data), and 302 mm in 1995 (Fig. 1(a)). The experimental site is located on a floodplain in the vicinity of the foothills of a nearby mountain range (Lehmann *et al*., 1996). The soils are calcareous Fluvisols (FAO, 1990); they are deep and loamy, sometimes sandy, with high pH and EC, and low organic carbon and nitrogen contents (Table 1). The sodium adsorption ratio (SAR) of the saturation extract is very high, especially in the subsoil.

Experimental design and treatments

The few scattered bushes of *Acacia tortilis* covering the experimental site were removed prior to the study. During March to June 1994, the runoff irrigation system was built using a design of levelled basins (Fig. 2). The irrigated plots were built 0·4 m lower than the original soil surface. Bunds with an average height of 1·5 m surrounding the plots were constructed with the soil material from the excavation and compacted manually. Entrances to the channels and plots were reinforced with metal drums and sand bags. Four basins, each 210 × 30 m, were laid out on the contour. Eleven treatments with an individual plot size of 13 × 24 m (with boundary strips of approx. 5 m between plots) were arranged within each of the four basins in a randomized complete block design irrigated by a channel guiding runoff water to the basins. Two treatments had to be taken out of the design due to technical difficulties. The runoff water originated from the lower and middle slopes (maximum inclination 5°) of a nearby mountain range and combined to form a seasonal stream, which fed the irrigation channel. Surplus water during heavy storms flowed out of the channel through the spillway (Fig. 2). The ratio of cropping area to runoff area was about 1:100.

In December 1994, *Acacia saligna* was planted in rows 4 m apart with a 1 or 3 m distance between trees within the row, resulting in planting densities of 2500 and 833 trees ha^{-1}, respectively. In 1995 and 1996 two cropping cycles were planted with *Sorghum bicolor*, in May and in September. The nine investigated treatments comprised sole-cropped and intercropped *Sorghum bicolor* and *Acacia saligna* with and without pruning in four replications (Table 2). In 1995, the effects of planting density and plant species on biomass production were examined (Table 2), and only the second season from September to December 1995 is presented in this paper. Pruning and intercropping were studied only during 1996 and are not described here.

On 12 September 1995 sorghum was sown in rows 0·5 m apart with 0·25 m distance between plants in the row (Fig. 1(d)). Sorghum was harvested from 10 to 15 December, and total biomass production and grain yield were measured. Subsamples

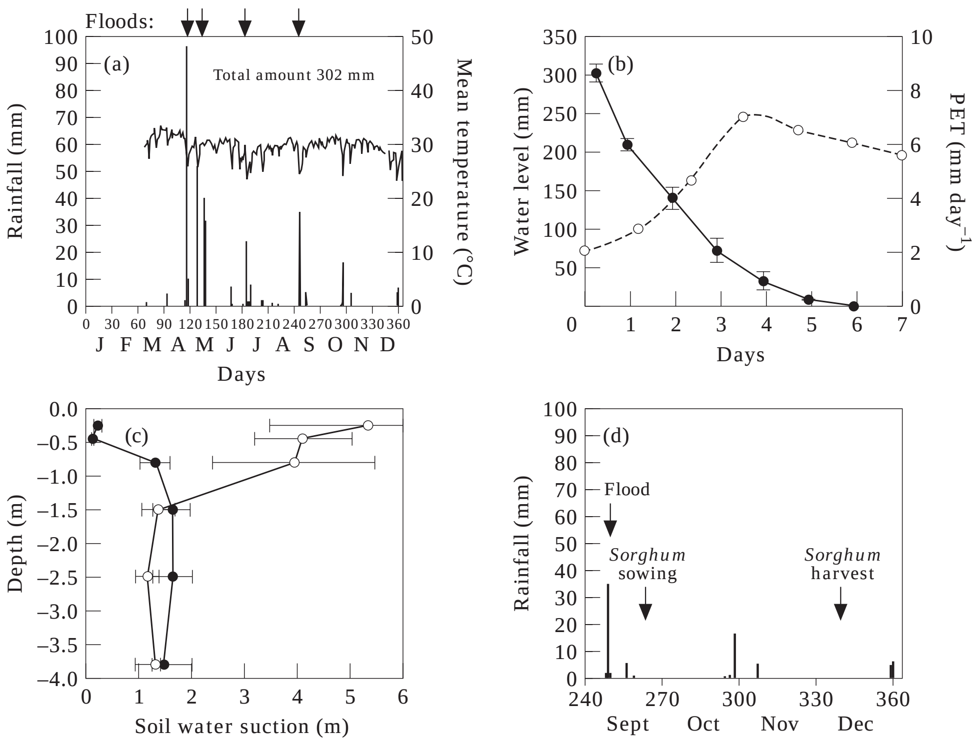

Figure 1. Water input into the basins: (a) rainfall during 1995; (b) infiltration curve of the flood water (●) and potential evapo-transpiration (PET) (○) from 5–11 September; (c) suction head in the first basin before (○) and after (●) the flood (*N* = 3 to 6, see text); and (d) synchronization of flood event, precipitation and planting of sorghum. Values are means and standard errors.

Table 1. *Chemical and physical soil properties at the experimental site near Kakuma, northern Kenya*

Depth (m)	Horizon	Bulk density (Mg m^{-3})	Stone content (w/w %)	Particle size distribution (%) coarse sand 600–2000	mid sand 200–600	fine sand 60–200	coarse silt 20–60	fine silt 2–60	clay <2 mm
0–0·07	Ah	1·50	0	0·4	2·9	35·4	32·8	16·5	12·0
0·07–0·14	2A	1·38	0	1·3	10·5	65·5	12·3	4·4	6·0
0·14–0·3	3Ah	1·25	0	1·8	1·7	16·9	40·3	20·9	18·4
0·3–0·6	3Bt	1·34	0	0·0	0·1	10·9	46·5	27·0	15·5
0·6–1·07	3Btn	1·36	0	0·4	0·3	3·8	40·3	26·5	28·7
1·07–1·7	4Btz1	1·44	2	1·8	6·6	23·5	31·0	14·9	22·2
1·7+	4Btz2	1·41	2	0·6	2·2	16·2	41·4	22·7	16·9

Depth (m)	pH H_2O	Organic C (g kg^{-1})	N (g kg^{-1})	EC* (S m^{-1})	SAR*	Ca (mg l^{-1})*	Mg (mg l^{-1})*	Na (mg l^{-1})*	Cl (mg l^{-1})*	SO_4 (mg l^{-1})*
0–0·07	8·6	5·3	0·42	0·054	3·8	18·1	4·0	68·1	11·0	22·0
0·07–0·14	8·9	2·5	0·21	0·035	3·1	17·2	1·3	49·5	13·9	15·5
0·14–0·3	8·6	6·4	0·62	0·043	3·0	25·2	5·8	63·4	8·0	15·4
0·3–0·6	8·9	5·1	0·43	0·056	6·2	15·1	5·6	110·0	11·9	37·6
0·6–1·07	9·2	8·0	0·56	0·185	20·1	17·9	3·8	357·8	78·1	444·8
1·07–1·7	8·7	5·3	0·32	0·581	27·1	141·5	29·9	1361·0	559·4	1185·0
1·7+	8·2	2·3	0·24	1·362	26·6	555·0	111·7	2622·0	2080·8	1210·0

*Measured in the saturation extract.

were weighed and dried at 80°C for 48 h, and biomass production was corrected for the measured water content.

In order to determine tree biomass production without harvesting the trees, above-ground biomass was calculated on 1 October and 15 December using a non-destructive method: a correlation of trunk diameter at 0·2 m above the ground with total above-ground dry matter obtained from trees grown in fields adjacent to the experimental plots (biomass = 131·65 × (diameter)^2 – 83·4; R^2 = 0·87**; N = 46; K. Droppelmann, unpubl. data) was used to determine the tree biomass of 30 trees plot^{-1} in the experimental fields by measuring the trunk diameter only.

A meteorological station (Campbell Scientific 21X Micrologger) automatically recorded rainfall and rainfall intensity (Electric Rain Gauge Transmitter TRP-525M), solar radiation (LI 200 X LI-COR), wind speed and direction, and dry and wet bulb temperature. Tensiometers were inserted at 0·45 and 1·50 m depth, and gypsum blocks at 0·1 m depth below the tree canopy and in the alley 2 m from the tree row. In one replicate per treatment, additional tensiometers were installed at 0·25, 0·8, 2·50 and 3·80 m depths and at a 1 m distance from the tree row. Tensiometer readings were corrected for insertion depth and water level in the tubes. The gypsum block readings were converted to soil water suction with a combination of individual calibration at 0·1, 0·3, 1, 5 and 15 bars in the laboratory and the manufacturers' calibration. Measurements were taken weekly.

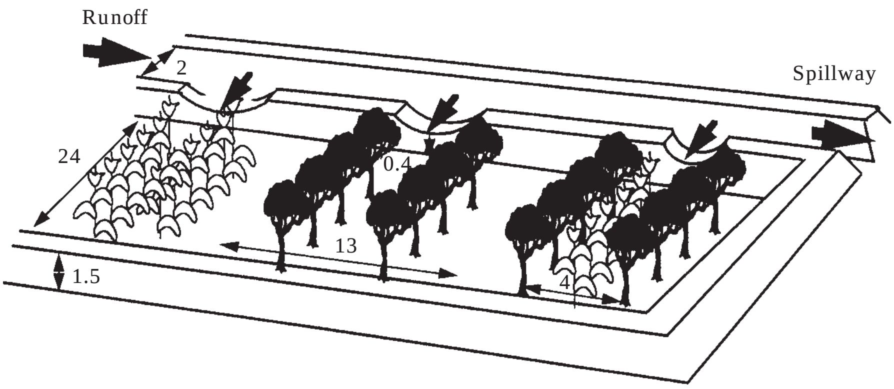

Figure 2. Schematic outline of the runoff irrigation system with *Acacia saligna* and *Sorghum bicolor* in sole and intercropped treatments (intercropping was done in 1996); distances in m.

Table 2. *Explanation of the treatments investigated in 1995 and 1996; H = high, L = low planting density; P = pruning, NP = no pruning; I = intercropping, NI = no intercropping with* Sorghum bicolor

	Cropping system	Tree planting density	Intercropping	Pruning	Investigated in:
1	Alley cropping	H	I	P	1996
2	Alley cropping	L	I	P	1996
3	Alley cropping	H	I	NP	1996
4	Alley cropping	L	I	NP	1996
5	*Acacia* monoculture	H	NI	P	1996
6	*Acacia* monoculture	L	NI	P	1996
7	*Acacia* monoculture	H	NI	NP	1995/96
8	*Acacia* monoculture	L	NI	NP	1995/96
9	*Sorghum* monoculture	–	–	–	1995/96

Root sampling and processing

At sorghum flowering (15–25 November), root distribution was determined by destructive sampling at 0–0·15 and 0·15–0·3 m with a metal core auger (0·08 m diameter) and at 0·3–0·6, 0·6–0·9 and 0·9–1·2 m depths with an Edelmann drill auger (0·06 m diameter) in three replicates. The use of the drill auger was necessary as the core auger was too difficult to remove from greater depths. In the tree plots, samples were taken at 0–0·25, 0·25–0·75 and 0·75–2 m distance from the tree row and at the same depths as in the sorghum plots. Instead of specific distances, a range was chosen, as this procedure allows the calculation of root length density (root length in a known volume) per unit area. Three samples per depth and position were obtained and combined. Then, a weighed subsample was washed over a 0·5 mm sieve as described by Schroth & Kolbe (1994). As it was necessary to use a drill auger in the subsoil, the soil density could not be determined from the root sampling procedure. To calculate the root length density, soil density at 0·15–0·3 m depth was taken for all sampling depths below 0·3 m. The obtained values were verified with bulk densities measured in soil pits after the experiment. Live and dead roots were separated according to visual (colour, presence of intact cells) and mechanical criteria (elasticity, stability). In cases of uncertainty, the roots were inspected with a microscope. The root length was then measured with the line intersection method according to Tennant (1975). The excavated roots came exclusively either from the trees or sorghum as the plots were weeded each week to ensure the absence of roots other than from *Acacia saligna* or sorghum.

Soil analysis

Soil samples were taken from a representative, undisturbed profile next to the experimental plots (one profile for site characterization; for depths see Table 1). C and N were analysed with an automatic C/N analyser. Ca^{2+}, Mg^{2+} and Na^{+} were determined in the saturation extract by atomic absorption spectrometry (Varian); Cl^{-} and SO^{2-} were measured with a rapid flow analyser (Alpkem). SAR was calculated from the cation concentrations in the saturation extract (Landon, 1991).

Statistical analysis

Biomass production, soil water suction and root length density were compared by analysis of variance using a randomized complete block design (Little & Hills, 1978). A multiple comparison of means was included with the Duncan-test (Little & Hills, 1978). Three-way ANOVA were computed with the factors species × depth × time and position × depth × time in order to determine the effect of species (sorghum or *Acacia*) or position (canopy or alley) on soil water suction. Two-way ANOVA were computed for individual depths (Table 3). Root length density per unit area was compared among species and depths using a two-way ANOVA.

Results

Water input and soil water dynamics

Out of 36 rainfall events, six recorded over 20 mm in 1995; four times these rains produced a flood (Fig. 1(a)). There were also four floods in 1994. During the 1995 season, the runoff irrigation plots (Fig. 2) filled three times to a level of 300 mm; and once in July (day 187) to a level of 50 mm. After a single flood such as September 1995 (day 248), the water infiltrated within 6 days (Fig. 1(b)). With a daily potential evapo-

Table 3. *Levels of significance according to analyses of variance, computing the soil suction with two- and three-way ANOVA, and using a randomized complete block design: species = sorghum and* Acacia; *time = sampling dates day 249 to 331; depth = 0·1, 0·45 and 1·5 m; position = under the tree canopy and in the alley (2 m distance from the tree).* *$p < 0{\cdot}05$, **$p < 0{\cdot}01$, ***$p < 0{\cdot}001$; *empty cells indicate non-performed interaction according to the statistical design (see also* Statistical analysis *in* ***Study site and methods****)*

Source	Three-way ANOVA species × depth × time	Three-way ANOVA position × depth × time	Two-way ANOVA species × time 0·1 m depth	Two-way ANOVA species × time 0·45 m depth	Two-way ANOVA species × time 1·5 m depth
Blocks	**	***	**	***	***
Main effects					
Time	***	***	***	***	**
Position		***			
Depth	***	***			
Species	***		***	***	*
Interactions					
Time × position		NS			
Time × depth	***	***			
Time × species	**		**	***	NS
Species × depth	***				
Depth × position		***			
Species × depth × time	**				
Depth × position × time		NS			

transpiration of 2–7 mm (Fig. 1(b)), 265 mm of water infiltrated into the soil each time when the basins were completely filled. The infiltrating water decreased the soil water suction only up to a depth of 0–0·8 m. Below 1·5 m, the soil water suction remained constant (Fig. 1(c)).

At 0·1 m depth, the soil water suction increased immediately after the flood had infiltrated (Fig. 3). In the sorghum plots, the values reached a plateau at 30 m (pF 3·5; Fig. 3(a), day 269) very quickly and remained constant for the next 30 days. In the tree plots, however, soil water suction increased continuously. The same difference could

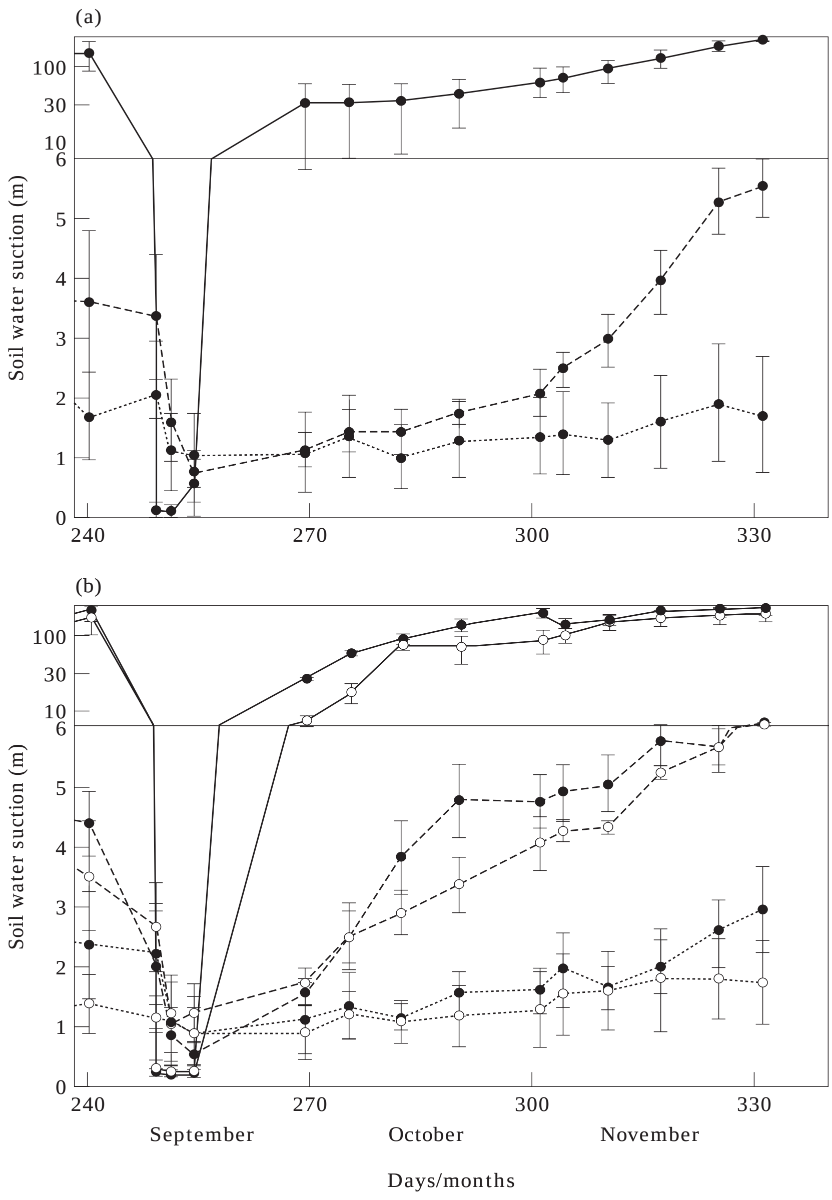

Figure 3. Dynamics of soil water suction under (a) sorghum and (b) *Acacia* ((●) = tree, (○) = alley) from day 240 (28 August) to 340 (6 December) at 0·1 m (—), 0·45 m (−−−) and 1·5 m (····). Note the linear (lower part) and logarithmic (upper part) presentation of soil water suction. Values are means and standard errors.

be observed at 0·45 m depth for tree as well as sorghum plots, though without the initial rapid increase. At 1·5 m depth, the soil water suction increased in the tree plots at tree position, while in the sorghum plots it remained the same. Throughout the whole vegetation period, the soil water suction was higher in soils in tree-only plots than in sorghum plots at 0·1, 0·45 and 1·5 m depths at $p < 0{\cdot}001$, $p < 0{\cdot}001$ and $p < 0{\cdot}05$, respectively (Table 3). Also, the trees took up more water under the canopy than in the alley ($p < 0{\cdot}01$). This effect did not change with time (non-significant interaction time × position; Table 3). Interactions of blocks and other factors were not detected (data not shown).

Biomass production

During 1995, two cropping cycles could be realized, of which only the second one is discussed in this paper. Throughout the presented growing season of sorghum (October to December 1995), dry matter yield of sorghum was only slightly higher than biomass production of trees with high planting density (2500 trees ha^{-1}) during the same time; both being significantly higher than trees planted at 833 trees ha^{-1} ($p < 0{\cdot}01$; Fig. 4). Within 12 months of tree planting (December 1994 to 1995), total biomass production of the trees amounted to 4·8 t DM ha^{-1} and 3·0 t DM ha^{-1} for high and low planting density, respectively (Droppelmann, unpubl. data). Whereas the biomass production per unit area was higher with 2500 trees ha^{-1}, the biomass production per plant was higher with 833 trees ha^{-1} (3535 ± 524 g DM $tree^{-1}$) than with 2500 trees ha^{-1} (1911 ± 262 g DM $tree^{-1}$; $p < 0{\cdot}01$). The total grain yield of sorghum amounted to 0·3 t DM ha^{-1}.

Root distribution

The majority of roots in the tree plots are found at 0–0·15 m depth and at a 0–0·25 m distance from the tree (Fig. 5). Total root length densities decrease with increasing distance from the tree; at 0·25–0·75 m and 0·75–2 m distances, the maximum root length density is at a depth of 0·15–0·3 m with a slight secondary maximum at 0·6–0·9 m. For sorghum, the highest root length density is found in the topsoil (0–0·15 m). The total root length of sorghum (ha^{-1} 1·2 m^{-1}) is two times higher than

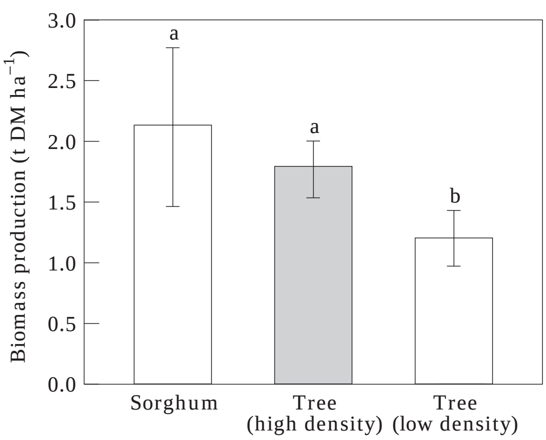

Figure 4. Above-ground biomass production of *Acacia saligna* with high (2500 trees ha^{-1}) and low (833 trees ha^{-1}) planting density and of *Sorghum bicolor* during October to December 1995. Bars with the same letters are not significantly different at $p < 0{\cdot}05$; values are means and standard errors.

that of the *Acacia* ($p < 0{\cdot}05$). When calculated per ha and 0–0·15 m depth, the total root length is three times higher. Trees and sorghum had a slightly different depth distribution of root length density (significant interaction species × depth; $p < 0{\cdot}1$). At sorghum flowering (15–25 November), the ratio of live to dead roots is higher for sorghum (8) than for trees (4·5), with the maximum ratio under sorghum (19) and under *Acacia* (8) at 0·6–0·9 m.

Discussion

Water input

With rainfall distribution showing only a slight seasonality in 1995, there is no distinct level of daily rainfall to predict a flood: however, above 40 mm, rainfall always resulted

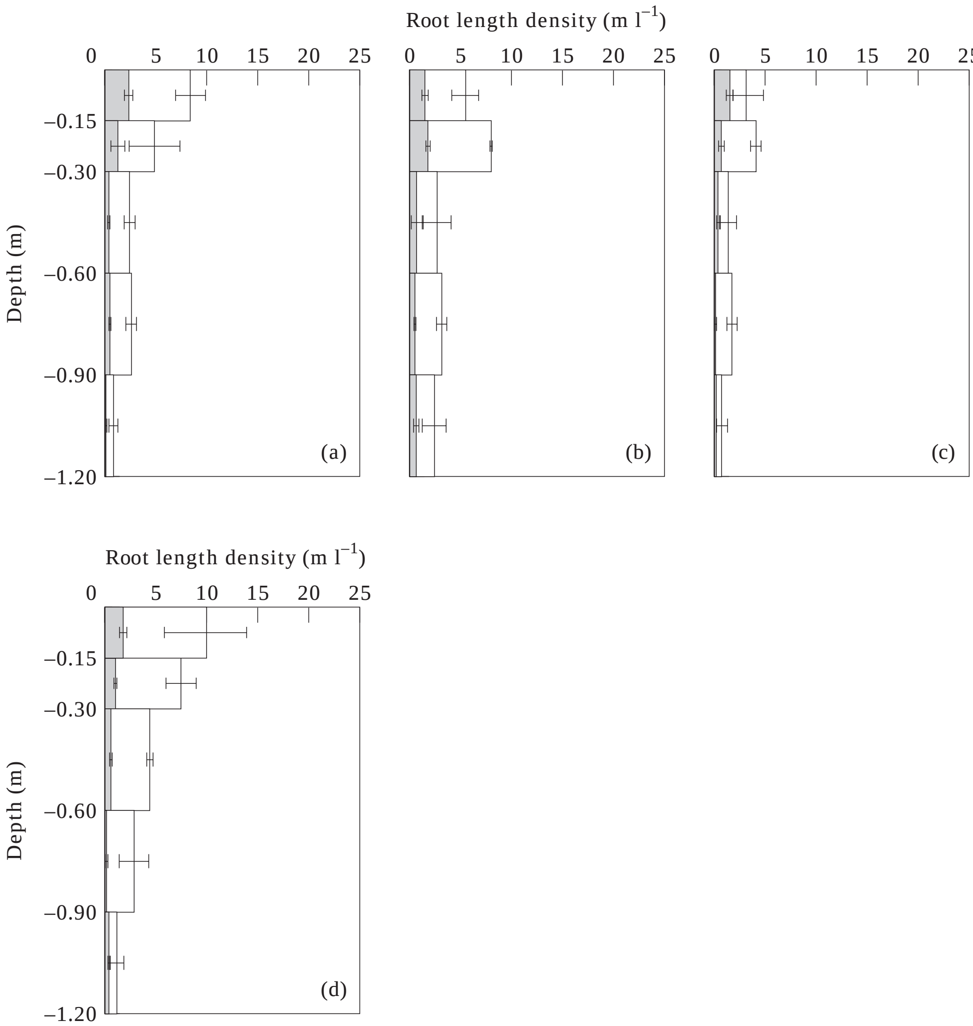

Figure 5. Root length density of *Acacia saligna* at (a) 0–0·25 m, (b) 0·25–0·75 m and (c) 0·75–2m from the tree row and (d) *Sorghum bicolor* at sorghum flowering (15–25 November 1995; $N = 3$). Values are means and standard errors. (☐) = total roots; (▩) = dead roots.

in a flood in 1995. Between 20 and 40 mm, a flood may or may not occur. Carter & Miller (1991) suggested a rainfall–runoff threshold for flooding of 20 mm day^{-1} for their experimental sites in Botswana. For 1994/95, the total number of floods was sufficient for two cropping cycles each year, in April/May and in August/September. According to our own observation, the local population of Turkana crops sorghum only during the first rains of each year, in May/June, but never in the second half of the year. Using runoff irrigation, it was possible to crop two times per year.

During a flood, the runoff irrigation system could usually be filled. If it was not possible to fill the basins completely, this was due more to the water level of the stream than the duration of the flood. Water distribution within and between the basins was very homogeneous for the plots presented in this study (Fig. 1(b)). Evaporation losses were kept at a minimum due to the fast infiltration despite the high SAR and Na content of the soil (Table 1). With the majority of particles being in the coarse silt and fine sand fraction (Table 1), the moderate amounts of Mg and Ca seemed to have been high enough to stabilize the soil structure. The amounts of especially Na, however, decreased rapidly after 1 year of irrigation to below a critical level for soil structure (Landon, 1991; data not shown). With the high amounts of percolating water, nutrient leaching may become a problem in the future. A decrease in soil fertility due to removing of topsoil was not expected as the Fluvisol did not register lower C and N contents in the subsoil when compared to the topsoil (Table 1).

Soil water recharge is only visible in the topsoil (Fig. 1(c)) for all treatments and not significant in the tree position (Fig. 3(b)). Still, there is water flow into the subsoil, though it is entirely determined by the unsaturated conductivity. In the range of –1·2 to –2 m water suction, as in the subsoil (Fig. 1(c)), however, the unsaturated conductivity is low with 1–0·001 mm day^{-1} (computed after Jackson, 1972). During the 20 days after the flood when the water potential was higher in 0–0·8 m than 1·5–3·8 m, a maximum of 20 mm water could have percolated into the subsoil. Thereafter, crops have to rely entirely on the water stored in the soil during the flood as there was no rainfall in the 40 days after the flood had infiltrated.

Biomass production

Total dry matter production of the trees was very high in the first year after planting. Comparatively, in a runoff irrigation system in the Negev, *Acacia salicina* plantations with 1250 and 833 trees ha^{-1} produced less than 3 t ha^{-1} after 1 year and less than 5 t ha^{-1} in the first 2 years after planting (Lövenstein *et al*., 1991). In the Negev, annual precipitation and mean annual temperature are lower than in northern Kenya and may be responsible for the lower biomass production. In the humid and sub-humid tropics, biomass production of trees in hedgerow intercropping usually amounts to 2·4–7 t ha^{-1} $year^{-1}$ (Young, 1989).

Trees planted in low density have more available soil volume and produced more biomass per tree; this may be an effect of more available soil water. This accelerated growth, however, cannot compensate for the reduced amount of trees per unit area. Total above-ground biomass production of sorghum was low compared to results from semi-arid India with 6·1 t ha^{-1} (Singh *et al*., 1989) or arid Niger with about 10 t ha^{-1} (Tabor, 1995). The low dry matter production in our study was also reflected by a low grain yield of 0·3 t ha^{-1}. Klemm (1989) reported 0·5 to 2·8 t ha^{-1} grain yield for traditionally- and runoff-irrigated sorghum in Mali. With microcatchments in Niger, sorghum grain yield was as high as 1·9 t ha^{-1} (Tabor, 1995). Both biomass production (for fodder) and food production are important for the local Turkana tribe. Normally, the Turkana are only able to harvest once per year, and in the second half of the year not at all. Compared to the traditional cropping system, runoff irrigation improved biomass production and grain yield.

Soil water dynamics

Even without plant water uptake, soil water suction reaches values of –30 m (pF 3·5) at a 0·1 m depth 2 weeks after saturation (Fig. 3(a); day 269). The sorghum plants obviously were not developed enough to cause this increase, so soil water depletion must presumably be caused by capillary rise and evaporation from the soil surface. This may be responsible for the reduced plant growth of the annual crop. At a water suction of pF 3·5, plant growth of even a drought-resistant species (like *Sorghum bicolor*) may be reduced. The trees also take up water from greater depths (1·5 m) and are not as much affected by moisture depletion in the topsoil as sorghum.

In addition, the dynamics of soil water uptake differs greatly between the tree and the annual crop. Whereas sorghum does not take up much water from 0·1 m depth in the 20 days following the flood, the trees immediately use soil water from this depth. The same pattern can be observed at 0·45 m depth, although soil water loss by capillary rise is observed less than from 0·1 m. The tree root system is already developed after the flood, whereas sorghum roots still need 30 days until they are able to absorb soil water at 0·45 m depth. In 1·5 m depth, soil water uptake of sorghum seems unlikely, whereas trees can take up water from the whole soil profile (1·5 m). As a result, total water uptake of sorghum was significantly lower than that of the trees. Contrastingly, under semi-arid conditions in Zambia, *Leucaena leucocephala* (Lam.) de Wit and *Flemingia macrophylla* hedgerows depleted the same amount of moisture as maize plants (Chirwa *et al*., 1994).

At our site, trees did not withdraw water from as low in the profile as reported from the Negev by Lövenstein *et al*. (1991) or Zohar *et al*. (1988). This may be due to the juvenile tree plants in our study; another explanation is the higher amount of rainfall events in northern Kenya which do not cause a flood and wet only the topsoil, and the consequently high water supply at 0·25–0·8 m.

Root distribution

The root length density is in the same order of magnitude as in other studies for both crops and trees (Van Nordwijk & Brouwer, 1991; Schroth & Zech, 1995). The sorghum roots do not make use of the whole soil depth. Consequently, restriction of the root system to the topsoil and its new development after the flood leads to a growth reduction if there is no rainfall for 40 days after the flood had infiltrated, as in the 1995 season. This restriction is seen as a growth strategy and is not influenced by a high EC in the subsoil, since the EC decreased drastically during the first year (data not shown), or by a higher nutrient content in the topsoil (Table 1). The trees, however, with their permanent root system, can exploit a larger soil volume and are not as susceptible to dry spells as the annual crop. They may not rely on the water in the topsoil as much as the crop: in semi-arid Australia, the relative contribution of subsoil tree roots to total water uptake increased when the topsoil dried out (Eastham *et al*., 1990).

The root distribution of trees can also differ between environments. In a humid tree savanna in Cote d'Ivoire, Schroth *et al*. (1995) found the maximum root length of nine tree legumes in the upper 0·1 m of the soil. In an arid region in north-western India, five out of 12 tree species had more roots in 0·15–0·3 m than in 0–0·15 m (Toky & Bisht, 1992). Hansson *et al*. (1994) concluded that soil water availability is probably the main factor for changes in species' inherent growth strategy. Drip-irrigating *Eucalyptus* plantations in Portugal decreased the mean rooting depth and increased root counts per unit area (Kätterer *et al*., 1995).

The higher root length density of sorghum than the trees is in contrast to the higher soil water depletion in tree plots than in the sorghum plots at the end of the vegetation period ($p < 0{\cdot}01$). Petrie *et al*. (1992) found no higher water uptake with increasing root length density. Shein & Pachepsky (1995) even concluded that total root length density seems to be an insufficient indicator of drought tolerance; root structure and root distribution play a more important role. We wish to extend this conclusion: not only the physiological properties of the root system but also the temporal root development of different species are determining factors for the amount of water taken up in a given soil substrate, and not the root length density alone.

Although the soil surface layer (0–0·15 m) is dry at sorghum flowering, the proportion of live sorghum roots is still very high compared to that of the tree roots, and may indicate an advantage for the sorghum when little rains wet the topsoil (Taylor, 1983). This cannot compensate, however, for the lack of a subsoil root system as shown by the lower water uptake and the relatively poor sorghum development and grain yield.

Conclusions

The implemented water harvesting system is able to collect runoff efficiently and enable two sorghum cropping cycles per year, after the floods in April/May and August/September. This is a valuable improvement of traditional land use systems in northern Kenya, doubling the planting seasons. Soil water uptake of the trees and the annual crop differed in their spatial and temporal patterns. This could be explained by their different rooting systems. As seen from the soil water dynamics, sorghum root development is too slow to make use of the soil water in the topsoil (0–0·15 m) before it is lost by evaporation. Also, the timing of planting seems to be extremely important in the dry and hot environment of northern Kenya. Trees take up less water from the alley than from soils under the tree row and are able to better utilize water in the subsoil, in contrast to sorghum. Increasing the planting density reduces the biomass production per tree but increases biomass production per unit area. These results indicate an advantage of combining annual crops and trees with respect to biomass production per unit area.

We are indebted to the German Ministry of Economic Cooperation (BMZ) for funding this work within the German Israel Agricultural Research Agreement (GIARA), the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) and the International Centre for Research in Agroforestry (ICRAF) for their co-operation and invaluable logistic support. Ute Küper's help in the field and laboratory is highly appreciated.

References

Carter, D.C. & Miller, S. (1991). Three years of experience with an on-farm macrocatchment water harvesting system in Botswana. *Agriculture and Water Management*, **19**: 191–203.

Chirwa, P.W., Nair, P.K. R. & Nkedi-Kizza, P. (1994). Pattern of soil moisture depletion in alley cropping under semiarid conditions in Zambia. *Agroforestry Systems*, **26**: 89–99.

Eastham, J., Rose, C.W., Cameron, D.M., Rance, S.J., Talsman, T. & Charles Edwards, D.A. (1990). Tree/pasture interactions under three tree spacings in an agroforestry experiment. II. Water uptake in relation to rooting patterns. *Australian Journal of Agricultural Research*, **41**: 697–707.

Evenari, M., Shanan, L. & Tadmore, H. (1968). Runoff farming in the desert. I. Experimental layout. *Agronomy Journal*, **60**: 29–32.

FAO (1990). *Soil Map of the World,* revised legend. Rome: FAO. 119 pp.

Gupta, G.N. (1994). Influence of rain water harvesting and conservation practices on growth and biomass production of *Azadirachta indica* in the Indian desert. *Forest Ecology and Management*, **70**: 329–339.

Hansson, A. -C., Zhao, A.F. & Andren, O. (1994). Fine-root growth dynamics of two shrubs in semiarid rangeland in Inner Mongolia, China. *Ambio*, **23**: 225–228.

Jackson, R.O. (1972). On the calculation of hydraulic conductivity. *Soil Science Society of America Proceedings*, **36**: 380–382.

Kätterer, T., Fabiao, A., Madeira, M., Ribeiro, C. & Steen, E. (1995). Fine-root dynamics, moisture and soil carbon content in a *Eucalyptus globulus* plantation under different irrigation and fertilisation regimes. *Forest Ecology and Management*, **74**: 1–12.

Klemm, W. (1989). Bewässerung mit Niederschlagswasser ohne Zwischenspeicherung im Sahel. Ph.D. dissertation, University of Karlsruhe, Karlsruhe, Germany. 117 pp.

Landon, A. (1991). *Bookers Tropical Soil Manual*, (2nd Edn). New York, U.S.A: Longman Scientific Publ. 456 pp.

Lehmann, J., Droppelmann, K., Küper, U., Berliner, P., Nyabundi, J.O. & Zech, W. (1996). Optimizing biomass production in a runoff agroforestry system in Northern Kenya. In: *GTÖ, Proceedings of the Annual meeting of the German Society for Tropical Ecology*, 2–5 Feb 1995, Hamburg, Germany.

Little, T.M. & Hills, F.J. (1978). *Agricultural Experimentation*. New York: John Wiley. 350 pp.

Lövenstein, H.M., Berliner, P.R. & van Keulen, H. (1991). Runoff agroforestry in arid lands. *Forest Ecology and Management*, **45**: 59–70.

Petrie, C.L., Kabala, Z.J., Hall, A.E. & Simunek, J. (1992). *Water transport in an unsaturated medium to roots with differing local geometries. Soil Science Society of America Journal*, **56**: 1686–1694.

Schroth, G. & Kolbe, D. (1994). A method of processing soil core samples for root studies by subsampling. *Biology and Fertility of Soils*, **18**: 60–62.

Schroth, G. & Zech, W. (1995). Root length dynamics in agroforestry with *Gliricidia sepium* as compared to sole cropping in the semi-deciduous rainforest zone of West Africa. *Plant and Soil*, **170**: 297–306.

Schroth, G., Kolbe, D., Balle, P. & Zech, W. (1995). Searching for criteria for the selection of efficient tree species for fallow improvement, with special reference to carbon and nitrogen. *Fertilizer Research*, **42**: 297–314.

Shein, E.V. & Pachepsky, Ya. A. (1995). Influence of root density on the critical soil water potential. *Plant and Soil*, **171**: 351–357.

Singh, R.P., Ong, C.K. & Saharan, N. (1989). Above and below ground interactions in alley-cropping in semi-arid India. *Agroforestry Systems*, **9**: 259–274.

Tabor, J.A. (1995). Improving crop yields in the Sahel by means of water-harvesting. *Journal of Arid Environments*, **30**: 83–106.

Taylor, H.M. (1983). Managing root systems for efficient water use: an overview. In: Taylor, H.M. (Ed.), *Limitations to Efficient Water Use in Crop Production*, pp. 87–113. Madison, WI: ASA, CSSA and SSSA.

Tennant, D. (1975). A test of a modified line intersect method of estimating root length. *Journal of Ecology*, **63**: 995–1001.

Toky, O.P. & Bisht, R.P. (1992). Observations on the rooting patterns of some agroforestry trees in an arid region of north-west India. *Agroforestry Systems*, **18**: 245–263.

Van Nordwijk, M. & Brouwer, G. (1991). Review of quantitative root length data in agriculture. In: McMichael, B.L. & Persson, H. (Eds), *Plant Roots and Their Environment*, pp. 515–525. Amsterdam, The Netherlands: Elsevier.

Young, A. (1989). *Agroforestry for Soil Conservation*. Wallingford, U.K: CAB International. 276 pp.

Zohar, Y., Aronson, J.A. & Lövenstein, H. (1988). Cultivation of multipurpose trees in rain water harvesting systems in the arid zone of Israel. *Commonwealth Forestry Review*, **67**: 339–349.