The influence of different *Acacia senegal* agroforestry systems on soil water and crop yields in clay soils of the Blue Nile region, Sudan

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**A B S T R A C T**

The purpose of this study was to test the hypotheses that (1) the tree *Acacia senegal* competes for water with associated agricultural crops, and the soil water content would vary spatially with tree density and type of management; (2) the microclimate created by trees would favourably affect the soil water content and improve the growth of associated agricultural crops. Trees were grown at 5 m x 5 m or 10 m x 10 m spacing alone or in mixture with sorghum or sesame. Soil water content was measured using a neutron probe at three depths, 0–25, 25–50 and 50–75 cm; and at different stages of crop development (early, mid, and late). Crop growth and yield and the overall system performance were investigated over a 4-year period (1999–2002). Results showed no significant variation in the soil water content under different agroforestry systems. Intercropping also resulted in a higher land equivalent ratio. No significant variation was found between yields of sorghum and sesame when these crops were grown with or without trees. The averages crop yields were 1.54 and 1.54 t ha\(^{-1}\) for sorghum; and 0.36 and 0.42 t ha\(^{-1}\) for sesame in intercropping and pure cultivation, respectively. This suggests that at an early stage of agroforestry system management, *A. senegal* has no detrimental effect on agricultural crop yield. However, the pattern of resource capture by trees and crops can change as the system matures. There was little competition between trees and crops for water suggesting that in *A. senegal* agroforestry systems with 4-year-old trees the clay soil has enough water to support the crop growth over a whole growing season up to maturation and harvest.

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**1. Introduction**

Over the last few decades, land use in the Sudan has been characterized by large-scale land degradation and loss of tree cover. These two processes are interrelated and caused by human activities such as wood harvesting, overgrazing and land clearing for farmland expansion. Deprived farmers respond to the declining land productivity by abandoning their existing degraded cropland and moving to new land for cultivation of their rainfed agricultural crops.

In the clay plains of the Blue Nile region in Sudan, extensive mechanized rainfed cultivation of sorghum, sesame, sunflower and other annual crops is practiced. Large areas have been completely cleared of tree cover. The productivity of these field crops has declined because of the loss of soil fertility (El Houri, 1979). As there is little deposition, accumulation or
decomposition of soil organic material in this dryland environment, the natural soil fertility can only slowly recover (Ardö and Olsson, 2003). As a result, much of the abandoned farmland left after unsustainable mechanized farming has been given to the national forest service (Forest National Corporation, FNC) for reforestation.

Land degradation in this area has already had serious effects on the well being of the rural population. Problems in crop cultivation here have led to food shortage, lack of fodder and wood fuels, and general poverty. The traditional production of gum arabic from the acacia trees of this agroforestry system is an off-season income-generating activity for most of the farmers in this region. Gum yields have decreased, however, because of biotic, physical, socio-economic and institutional reasons (Barbier, 2000). There is a need to look at this traditional dryland management from a more holistic perspective. Proper integration of the gum-yielding tree into the production system needs to be evaluated and studied from a crop and tree physiology viewpoint, since, in contrast to western Sudan where agroforestry is practiced on sandy soil, in the Blue Nile clay plains Acacia senegal (L.) Willd. has only recently been introduced into farming systems. Understanding the water balance of the system is of paramount importance for the future management and sustainability.

In semiarid areas water availability is a primary factor controlling plant growth and productivity processes (e.g. Kramer and Kozlowski, 1979; Bewley and Krochko, 1982). Specifically, it has been observed that in dry environments about 90% of the diameter growth in woody plants is attributed to water availability (Zahner, 1968).

Over two-thirds of the land area of Sudan receives the annual rainfall during 3 months, and there are large variations in the amount and distribution of rainfall. Rainfall variability and the occurrence of prolonged periods of drought are characteristics that must be recognized in the planning and management of natural and agricultural resources (Jackson, 1989).

The traditional A. senegal agroforestry system practiced for centuries in the Sudano-Saharan zone can be seen as a complex and dynamic resilient system reacting to a wide variety of long-term external changes and short-term disturbances related to climate, topography, soils, geomorphology, herbivores, fires and human intervention (Ballal et al., 2005). An important general conclusion has been that, in dryland environments, the effects of global climate change are of primary concern and the main attention is directed towards management and policy improvements (IUFRO, 2004). Moreover, considerations for adaptation to climate change have been discussed for Africa by Olufayo et al. (1998) an in Sudan in particular by Abdalla et al. (2002).

A. senegal is a leguminous agroforestry tree species belonging to the subfamily Mimosoideae with a wide natural distribution in the Sudano-Saharan zone of Africa (Raddad, 1987; Raddad et al., 2005). The tree is highly variable; with four distinct varieties recognized (Wickens et al., 1995). The variety senegal with which we are concerned here is the main source of gum arabic and a well-established traditional agroforestry tree component (Raddad et al., 2005).

1.1. Soil water availability and drainage

The amount of available water is low in sand, higher in clay and maximal in loamy and silt soils. In clay soils, the drainage is often poor, and clay soils containing less than 10–15% air volume at field capacity may have insufficient aeration for plant growth (Soil Survey Staff, 1996).

The typical clay soil of the Blue Nile region is alkaline and dries during the dry season forming deep cracks. With the advent of the rains, the clay absorbs water mainly through these cracks and swells, which closes the cracks. After this, water penetration is extremely slow, and temporary flooding or water logging is frequently experienced, especially after heavy showers (El Hour, 1979).

It has been confirmed (cf. Lott et al., 2003) that agroforestry systems can greatly increase the rainfall water utilization as compared to that in annual cropping systems. Nevertheless, careful consideration of the trade-offs between loss of crop production and additional value provided by tree products is of paramount importance. It has been proposed that compartmentalisation of soil water into the topsoil and subsoil, respectively, may lower the competition between woody plants grasses or annual crops, since woody plants presumably have the exclusive use of subsoil water and thus do not affect much the establishment or growth of associated crops (Walker et al., 1981; Smit and Rethman, 2000).

Tree species selection and the management and spatial arrangement of trees are key factors in determining the feasibility of dryland agroforestry systems. Gregory (1996) has shown that P. juliflora (Sw.) DC. did not much reduce the soil water content in the crop rooting zone and consequently showed less competition with sorghum as compared with A. nilotica (L.) Willd. in an agroforestry system. The two leguminous tree species therefore showed different types of root morphology and density distribution with depth. Such effects have important implications for modelling of tree-crop competition and interaction.

A. senegal has a deep root system that makes it capable of efficiently using the soil water resources; the presence of this tree may thus enhance the productivity of the whole production system. The diverse patterns observed in the growth and development of natural A. senegal trees are presumably a result of ecological adaptation (Raddad and Luukkanen, 2006). However, little is known on how site or climate factors influence the balance between above and belowground biomass production components or how these factors affect the gum production in A. senegal.

The soil water content is extremely important for crop growth, and the soil water storage (SWS) before sowing of an annual crop plays an essential role in crop growth and yield. Likewise, increasing of the SWS before sowing can contribute to crops developing larger and deeper root systems that can add to the utilization of the available soil water (Li et al., 2001). However, the opposite has been reported for northern Nigeria by Oluwasedemire et al. (2002).

On drylands, evaporation from the soil surface can reach up to 30–60% of the total amount of rainfall (Wallace, 1991). Annual crops often use only a small fraction of the available rainfall or stored soil water reserves. Incorporation of woody perennials, such as A. senegal, into a farming system can
increase the overall biomass productivity (Ong et al., 1992; Wallace et al., 1995; Livesley et al., 2004). This could be achieved by the trees using stored water reserves outside the cropping seasons, or when a greater proportion of the rainfall within a cropping season is used in transpiration instead of being lost through evaporation, runoff or draining into deeper soil layers (Ong et al., 1992). In contrast, Mungai et al. (2001) reported negative effects of alley cropping under semi-arid conditions in eastern Kenya. Gain in total biomass production can also be achieved when modification of the microclimate by trees increases the water use efficiency of the crop (Brenner, 1996; Elfadl, 1997; Livesley et al., 2004).

The principal aim of the present study was to provide new knowledge on the potential use of A. senegal in dryland agroforestry systems on clay soil. In addition, the aim was to analyze the water-use characteristics of two agricultural crops commonly used in dryland agroforestry in Sudan, sorghum, and sesame. An attempt was made to determine the effect of trees on crop performance and the general availability of water for agricultural crops in clay soils. The ultimate aim was to provide guidance for designing suitable agroforestry systems for clay soils in Sudan.

Our hypotheses were:

1. A. senegal competes for water with agricultural crops, and the soil water content would vary spatially depending on tree density; competition for water would also depend on tree spacing and management.

2. The microclimate created by trees in the agroforestry system would favourably affect the soil water content and thus improve the growth of associated agricultural crops and the overall productivity of this intercropping system.

2. Materials and methods

2.1. Site description

The study site was located in the Blue Nile State near Ed Damazin town (34°23'E, 11°47'N, 470 m above sea level). The climate at the site is typical semi-arid, with a mean annual rainfall (May–October) of 736 mm. The mean annual temperature is 28.1 °C, and the length of the growing season for the main agricultural crops is 82 days. The soil consists of dark cracking clay (vertisol) that extends to at least 15 m in depth.

Clay content of the soil is 40–60%, soil organic carbon (OC) is 0.324% and N is 0.024%. The natural vegetation is woodland with Acacia seyal (L.) Wight & Arn. as characteristic woody species (El Amin, 1990).

2.2. Experimental design

The site was first cleared of trees shrubs and grass, and then deep-ploughed with chisel plough and twice with a wide-level disc plough.

Seeds of A. senegal originating from Bout (local provenance) were directly sown on agricultural land on 20 July 1999 at a spacing of 5 m × 5 m (400 trees ha⁻¹) or 10 m × 10 m (100 trees ha⁻¹). Simultaneously, agricultural crops were sown between the acacia trees. Sorghum variety ‘Wad Ahmed’ was sown at 0.75 m spacing between rows and 0.3–0.5 m within rows, and sesame variety ‘Kenana 2’ at 0.75 m spacing between rows and 0.2–0.3 m within rows. This intercropping with sorghum and sesame was repeated annually between 1999 and 2002 in a rotational manner. Pure crops and A. senegal stands were also established using the same spacings, so as to provide control treatments; plot size was 30 m × 30 m. Weeding was carried out annually as required during the growing season. No fertilizers were applied. Trees were managed annually by removing the lower branches, and the first systematic pruning was applied when trees were 3 years old. Trees were tapped for gum arabic using the traditional axe as tool for the first time when they were three and a half years old.

Annual crops in the experimental plots were harvested at physiological maturity. Small sample plots (6 m × 6 m, representing 4% of the plot area for crop harvest) were laid out at the centre of each plot. Heads were harvested, sun-dried and threshed, and later the grain and seed yields were calculated in (kg ha⁻¹); this was done annually.

About 10 plants were randomly selected from these sample plots for measurements of plant height and number of shoots (in sorghum) and (in sesame) number of branches and number of capsules. The experimental design used was a randomized complete block design with four replications.

2.3. Soil water content

At the establishment of the field trails in 1999, initial soil samples were taken from different soil depths (0–25, 25–50, 50–75 cm) for a complete soil analysis in the Land and Water Research Centre Laboratory, Agricultural Research Corporation, Wad Medani, Sudan. The soil water retentivity curve was also determined. Soil water content was determined gravimetrically for the first year and later using a neutron probe (Model 4300 depth moisture gauge type Troxel, USA). Pits were dug using metal cores (Eijkel Kamp, Giesbeek), and aluminium access tubes were installed to 1.2 m soil depth. Tubes were installed at 0.3-m distance from the nearest tree in the centre of the plots. There was one tube per plot (0.09 ha) because of logistics limitations. Measurements of soil water were taken periodically during the morning hours at depths of 0–25, 25–50 and 50–75 cm. This was done as, to give a real pattern of soil water characteristics during each cropping season and at different crop development stages, for example, during crop emergence, initial crop stage, stem elongation, flowering, grain or capsules setting, physiological maturity and harvest (Ferreras et al., 2000). Neutron probe counts on water were converted to soil water content (mm) based on calibration performed using soil water content samples (R² = 0.63, P = 0.0007; Fig. 1).

Water use (WU), defined as the initial soil water content minus the final soil water content added with precipitation, was calculated for whole system from the measured soil water content for all treatments.

Initial and late soil bulk densities (BD) for the same three depths were determined by the cylinder method, whereby undisturbed soil samples were collected by means of metal core sampling cylinders of known volume and then oven-dried at 105 °C for 48 h. The oven-dry weight of the soil sample...
was divided by the volume of the cylinder to obtain the bulk density, expressed as \( \text{g cm}^{-3} \) \( (\text{Mg m}^{-3}) \) (Blake and Hartge, 1986). The rainfall at the site was also recorded throughout the study (1999–2002) using a rain gauge.

2.4. Calculations

Water use efficiency (or precipitation use efficiency, PUE) is usually defined as the ratio between crop yield (generally economic yield) and the amount of water used to produce that yield:

\[
PUE = \frac{GY}{ET} = \frac{GY}{P - \Delta SWS - R - D}
\]

where \( GY \) is the grain or seed yield, \( ET \) actual evapotranspiration, \( P \) the precipitation, \( \Delta SWS \) the difference of soil water storage between harvest and seedling stages, \( R \) the surface runoff, and \( D \) is the soil water drainage from the root zone during the growing season (Zhang et al., 2004). In the Blue Nile region, \( R \) and \( D \) were assumed to be negligible, and for that reason; they were omitted from the equation. Since a full account of ET losses was not possible, the PUE was assessed following Moore et al. (1988) in terms of \( GY \) for sorghum or sesame added by the \( A. \) senegal yield, as a function of the effective rainfall during the same year. The effective rainfall is assumed 80% of the total rainfall (Doorenbos and Pruitt, 1975; Sudan Meteorological Department, 2002).

The land equivalent ratio (LER) is the ratio of the area under monocropping to the area under intercropping, at the same level of management that gives an equal amount of yields. The sum of the fractions of the yields of the intercrops relative to their mono-crop yields provides a measure of the overall effectiveness of the mixed systems, expressed as:

\[
LER = \frac{X_i}{X_s} + \frac{Y_i}{Y_s},
\]

where \( X_i \) and \( Y_i \) are the component yields in either an intercrop (i) or mono-crop (s) system. When \( LER = 1 \), intercropping has no advantage over monocropping. When \( LER < 1 \), the system is suffering from competition, \( LER > 1 \), the production per unit of land surface occupied is higher than for the mono-crop (Mead and Willey, 1980; Ong et al., 1996; Baldy and Stigter, 1997).

2.5. Data analysis

An analysis of variance (ANOVA) was performed as needed, using the general linear model (GLM) procedure of the statistical software SPSS 12.0.1 for Windows 2000. Regression analysis was done using the JMP 3.2 statistical package (SAS, 1997). Tukey’s HSD test and Student’s t-test were performed to determine possible statistically significant differences between means. The significance level applied, if not otherwise mentioned, was \( P < 0.05 \).

3. Results and discussion

3.1. Rainfall and natural vegetation characteristics

The distribution of the amount of rainfall during the study period (1999–2002) is shown in Fig. 2. The mean annual rainfall during this period was 702 mm, 34 mm less than the mean annual rainfall for the last 30 years. Rainfall was the main effective contributing source of recharging soil water, since the surface or groundwater is not directly available to the plants. Rainfall patterns differed greatly among the years. In recent years, there has been a clear southward movement of isohyets coupled with more frequent droughts. This may be either a consistent trend or just a stage in a long cycle. In any case, this situation combined with overgrazing and removal of the tree cover for various purposes is causing a similar effect in the boundaries of all recognized ecological zones. There are also changes in the species composition of the dryland vegetation. Some species that once were dominant or very conspicuous have greatly decreased, some almost approaching the edge of extinction (Mahmoud et al., 1996).

3.2. Soil texture and characteristics

The dark cracking clay soil at the research site was rich in bases but poor in nitrogen and organic matter. The soil was alkaline with a pH ranging between 7.2 and 7.7 in the topsoil (0–75 cm). This soil is hard when dry and very sticky when wet. The infiltration rate was found to be low (0.1 cm h\(^{-1}\)), and therefore the soil was highly prone to waterlogging. The field capacity was high (45%, w/w), but the permanent wilting point was also high (21%, w/w); accordingly, the available water was about 24% w/w (Fig. 3).

3.3. Soil water content

The soil water content averaged over the profile (0–75 cm) for the period 1999–2002 is shown in Fig. 4a–c. Results indicated no statistically significant differences \( (P = 0.94) \) caused by different types of agroforestry systems. Fig. 4b shows soil
water content as a function of time and depth. It is worthwhile to mention that during the growing season June to October there were no soil cracks at this site. However, the use of a neutron probe for soil water determination in cracking clay soils needs special awareness (e.g. of sampling density, calibration strategy), in particular, after the rainy season and when cracks start to develop on the topsoil (cf. Ibrahim et al., 1999). Under these experimental conditions, it seems that *A. senegal* trees and agricultural crops were in direct competition for soil water.

The SWC was significantly higher in the lower soil strata during the dry season, since the topsoil dried much faster than the subsoil layers. Similar results are reported by Smit and Rethman (2000) and Li et al. (2001) for the semi-arid savanna of southern Africa. The influence of rainfall on SWC was greater in the upper soil strata as compared to the subsoil layers during the rainy season (May–October). That was probably due to a combination of factors such as a high soil BD, differences in infiltration rate and the physical properties that appeared to control the infiltration process. Alternatively, it could be due to soil evaporation and water extracted by crops (Kinama et al., 2005). Nonetheless, the soil water level showed a trend towards a slightly more favourable one in the intercrop systems than the one observed in mono-crop cultivation during stages of crop growth (Fig. 4a).

The ability of *A. senegal* to survive and produce a considerable amount of leaf biomass under the soil water regimes now studied indicates that the *A. senegal* trees are physiologically adapted to drought conditions (Raddad and Luukkanen, 2006).

### 3.4. Water use

The water use was greatest in 1999 and 2001 (the years with the highest annual rainfall), and very low in 2002 when rainfall was exceptionally low (498 mm; Fig. 4d). Any conservation of soil water achieved with the use of acacias can be assumed to be more useful during drought years as compared to years with normal or above-normal rainfall under the conditions prevailing in the Blue Nile region. Under an *A. senegal* agroforestry system with trees 4 years of age, the clay soil contained enough water to support crop growth for the whole growing season.

### 3.5. Crop growth

As seen from the growth data for sesame shown in Fig. 5, there were no statistically significant differences between the effects of agroforestry systems on plant height, number of branches or number of capsules (Fig. 5a, c, and e). However, significant variation ($P < 0.001$) was found in the plant height and the number of capsules between years (Fig. 5b, d, and f). This obviously affected the seed production and the total crop yield. The interaction between treatments and years did not significantly affect the variables measured.

Similarly, the growth variables for sorghum showed no statistically significant differences caused by the type of agroforestry system or lack of it, or by interaction between treatment and year (Fig. 6a–d). However, the year alone caused significant variation ($P = 0.002$, $< 0.001$) in plant height (only 1999 being statistically different from the other years) and the number of shoots.
3.6. Crop yield

Weight measurements of grain and stover in sorghum and seeds and stalks in sesame showed no significant differences between treatments. The sesame stalk production suggested some variation caused by intercropping, but it could not be confirmed statistically (Fig. 7a and b). Neither the grain nor the stem production variation in sorghum could be explained by the annual rainfall totals, and the rainfall distribution within the year must obviously also have had an effect. Fig. 2 shows that there was quite a difference in this variation between the years. Likewise, the yield variation caused by the different treatments shown in Fig. 7b cannot be explained by the rainfall totals either. The highest sorghum grain yields averaged over the treatments were obtained during the first and the second year of observation (1999 and 2000; 1.48 and 2.05 t ha⁻¹, respectively). Both years had a reasonable total amount and an even distribution of rainfall, whereas the remaining years, respectively, one with a high and another with the lowest rainfall (cf. Fig. 2), showed lower yields.

Fig. 4 – Soil water content averaged over the profile as affected by (a) different agroforestry systems, (b) time, and (c) different soil depths. (d) Water use of Acacia senegal in different agroforestry systems. In (a) and (d) Sg: sorghum; Se: sesame; C: control; 5: 5 m × 5 m spacing; 10: 10 m × 10 m spacing. Bars indicate standard error (Blue Nile region, Sudan).
Sesame seed and stalk production was significantly affected by the rainfall distribution during the years of study (1999–2002). This obviously reflects the sensitivity of sesame to water. Significant variation was also found in the seed yield of sesame between the years. The highest and lowest average seed yields were observed in 1999 and 2001 (0.64 and 0.14 t ha$^{-1}$, $P < 0.0001$), respectively, while the rainfall totals showed only a small difference between these years. The amount of precipitation during July and August, i.e. the critical time for flowering and capsules setting in sesame, was however, moderate in the year 1999 (cf. Fig. 2).

In this study, the crop (grain or seed) yields were not influenced by intercropping with trees, regardless of crop type or tree density. This probably reflects the fact that the agroforestry systems tested were still young. Based on general information available from the Blue Nile (Raddad, unpublished data), intercropping with A. senegal could possibly continue for more than 5 years without a risk of yield reduction. Obviously, there was little competition for water between trees and crops, even if water normally is the limiting factor for crop growth on dryland (Feng and Epstein, 1995). The results show a sensitivity of sesame to excessive water: a low sesame yield

Fig. 5 – Effects of different A. senegal agroforestry systems on sesame in the Blue Nile region, Sudan: (a and b) plant height, (c and d) number of branches, and (e and f) number of capsules, in different treatments and years, respectively. 5 m × 5 m and 10 m × 10 m refer to tree spacing. Bars indicate standard error.
was observed during 2001, which had a high rainfall, particularly in August.

Usually as trees grow older their water-use increases. Dawson (1996) has suggested that the water use by trees of different size is proportional to their leaf area.

Trees seem to utilise the water in the topsoil rather than that below. Present data show that there is no detrimental effect of competition between trees and crops during an early stage of agroforestry system development. Under an A. senegal agroforestry system with trees 4 years of age, the clay soil had enough water to support the crop growth for the whole growing season up to crop maturation and harvest.

High yields have been observed from pearl millet (Pennisetum typhoides Rich), cluster bean (Cyamopsis tetragonoloba (L.) Taub) and cowpea (Vigna unguiculata (L.) Walp.) in association with the tree Prosopis cineraria (L.) Druce (Kumar et al., 1992; Kaushik and Kumar, 2003). Reddy and Sudha (1989) have reported increased crop returns from a tree–crop combination as compared to mono-crops. However, Droppelmann et al. (2000) and Ong et al. (2000), reported that the yield of intercrops (Sorghum or Vigna) in combinations with pruned trees were similar to their yields when grown as mono-crops. This shows that there can be complementarity in resource use between different agroforestry system components. Negative effects of tree hedges and alley cropping designs on the yields of annual intercrops have been found at the tree/crop interface in most studies carried out in semi-arid regions under rainfed conditions (cf. Rao et al., 1991; Jama et al., 1995; Sanchez, 1995; Govindarajan et al., 1996; Mungai et al., 2001).

A reduction in sesame yield during 2 years of high rainfall (with 625 and 824 mm of precipitation, respectively) was probably because sesame does not grow well in poorly drained and heavy clay soil like that commonly found in the Blue Nile region. Langham and Wiemers (2002) reported that, in sesame, excessive water is not beneficial, and extended periods of rainfall or high atmospheric humidity may cause leaf diseases. Sesame plants standing in water for not more than a few hours may be killed. In contrast, sesame may grow well in areas with 400–500 mm of annual precipitation and will also respond to irrigation if properly applied (Langham and Wiemers, 2002). However, the reduction in yield in the year with a lower rainfall (498 mm) could be due to the variability and distribution of the rainfall over that year.

Sorghum failed to produce a higher than average grain yield in 2001, which was a year with a long rainy season and a high total rainfall (824 mm). The erratic rainfall in July and August in that year may, however, have adversely affected the sorghum yield. Nevertheless, sorghum yields in the agroforestry systems were higher as compared to the yields of sorghum grown alone, which could be explained by the fact that the beneficial effects of microclimate improvements (e.g., a lower temperature and a lower evaporation loss) were greater in the agroforestry systems than in the system with sorghum alone.
Our study suggests that intercropping of *A. senegal* with annual crops is advantageous in terms of crop yield and diversity. In contrast to *A. senegal* stands of trees or to crop monoculture, an *A. senegal* agroforestry system can produce two different crops at different times of the year from the same piece of land. Regulation of tree spacing seems to be an effective management tool for increasing the overall biomass and productivity per area in rainfed dryland farming and for restocking of the gum belt with *A. senegal* trees.

3.7. Precipitation use efficiency

Table 1 clearly shows that, within the error limits, there were no differences in PUE between sorghum or sesame crops and intercrops of sorghum and sesame, respectively. Many researchers (e.g. Hatfield et al., 2001) have stated that, in rainfed agriculture, the WUE is closely linked to the effectiveness of the use of rainfall, since there is no other source of water and since water is a key production constraint in dryland areas such as those in the Blue Nile region. Consequently, successful crop production in this area must fully and efficiently utilize the existing rainfall, which is frequently limited and variable both in quantity and in distribution. The present data show that there is no damaging effect of the competition between trees and crops during an early stage of agroforestry system development.

<table>
<thead>
<tr>
<th>Tree/crop system</th>
<th>PUE (mean and standard error, kg ha(^{-1}) mm(^{-1}) rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. senegal</em> 10 m × 10 m/ sorghum</td>
<td>3.11 ± 0.615</td>
</tr>
<tr>
<td>Sorghum</td>
<td>2.91 ± 0.686</td>
</tr>
<tr>
<td><em>A. senegal</em> 5 m × 5 m/ sorghum</td>
<td>2.64 ± 0.274</td>
</tr>
<tr>
<td>Sesame</td>
<td>0.76 ± 0.188</td>
</tr>
<tr>
<td><em>A. senegal</em> 5 m × 5 m/ sesame</td>
<td>0.74 ± 0.216</td>
</tr>
<tr>
<td><em>A. senegal</em> 10 m × 10 m/ sesame</td>
<td>0.73 ± 0.232</td>
</tr>
<tr>
<td><em>A. senegal</em> 5 m × 5 m</td>
<td>0.12</td>
</tr>
<tr>
<td><em>A. senegal</em> 10 m × 10 m</td>
<td>0.024</td>
</tr>
</tbody>
</table>
Thus, it is also justifiable to define agricultural performance in terms of crop production per unit of water used (e.g. in kg m⁻³ or € m⁻³; cf. Bessembinder et al., 2005).

### 3.8. Land equivalent ratio

In the LER data, the gum yield of *A. senegal* was added to the yield of agricultural crops. Results showed variation among the different agroforestry systems (Table 2). The highest and lowest LER values (2.29, 0.55) were observed in agroforestry systems where *A. senegal* was intercropped with sesame in a spacing of 10 m × 10 m or 5 m × 5 m during the years 2002 and 2001, respectively. High LER values without fertilizer application indicate good resource utilization and resource sharing by *A. senegal* intercropped with agricultural crops. Our results suggest that intercropping of agricultural crops such as sorghum and sesame with *A. senegal* under the Blue Nile environmental conditions maximises the use of available resources; at an early stage of agroforestry system development, *A. senegal* seemed to have no detrimental effect on crop yield. However, the pattern of resource capture by trees and crops may change as the system matures. Many authors (e.g. Rao et al., 1990, 1991; Jama et al., 1995; Ong et al., 2000) have reported similar results of LER values higher than unity in intercropping systems.

### 3.9. Soil bulk density

The bulk density of the soil in agroforestry systems did not differ significantly from that found under sorghum or sesame crops after 4 years of observation (Fig. 8). However, there was a gradual increase in soil bulk density with time. This increase in the uppermost soil layer (0–25 cm) amounted to 8.6%, 14.3% and 19.3% in the *A. senegal* intercropping systems, *A. senegal* tree system and mono-crop system, respectively. Bulk density values that limit or impede plant root growth depend on factors such as soil water and soil organic matter content (Pabin et al., 1998; Lampurlanes and Cantero-Martinez, 2003), and they are known to have a range between 1.46 and 1.90 Mg m⁻³ (Campbell and Henshall, 1991). The increase now observed in the soil bulk density with time might be attributed to the fact that the soil possibly was under restructuring process and later, after an equilibrium had been reached, it could probably again decrease. It could also be due to removal of plant residue for fodder, which could result in a low organic matter content and delay the soil restructuring processes. Similar results have also been obtained by previous investigators (Kinsella, 1995; Lampurlanes and Cantero-Martinez, 2003).

![Fig. 8 – Initial and late soil bulk density after 4 years of cropping at the upper soil depth (0–25 cm).](image)

### 4. Conclusions

Intercropping of agricultural crops with *A. senegal* is more efficient in terms of utilization of the available resources than monocropping. This is indicated by the high land equivalent ratio (LER) and similar precipitation use efficiency (PUE) values found in the agroforestry systems.

Crop yield and diversity in the agroforestry systems studied indicated enhanced and efficient utilization of the available resources by intercrops as compared to sorghum and sesame crops.

There was little competition for water between trees and crops, even though water normally is a limiting factor for crop growth under the environmental conditions prevailing in the Blue Nile region. However, this has an implication to the effect that intercropping of sorghum or sesame with *A. senegal* could possibly continue for more than 5 years...
without risk for crop yield reduction. Future research should be employed to clarify the maximum extent of the intercropping period. It should also address the belowground competition between A. senegal and agricultural crops under these harsh conditions.

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