

Impact of agroforestry parklands on crop yield and income generation: case study of rainfed farming in the semi-arid zone of Sudan

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Abstract

National food security has been a major policy goal in Sudan since the country gained its independence in 1956. One of the fundamental reasons is to ensure the social welfare for people living in rural areas. In this study we aimed to analyse how farmers secure their food and generate income in the semi-arid Sennar State in Sudan, using two selected sites, El Dali and El Mazmum, as examples. We interviewed 281 randomly sampled household heads, of which 145 at El Dali and 136 at El Mazmum, between July and November 2011. We identified four distinct land use systems, of which three consist of monocropping and one of cultivation in agroforestry parklands. Several statistical techniques and economic analysis were applied on the study data. Our results show that, in the two areas, the highest average yields over a ten-year period for the three crops studied, sorghum, pearl millet and sesame, were achieved in agroforestry system, except for the case of sesame at El Mazmum. Economic returns for the farmers, as indicated by net present value or benefit/cost ratio, followed the same pattern. The study concludes that farmers should rely more on agroforestry to improve their food security and cash income generation. Land use and land right policies, which currently discourage farmers from growing trees on their lands, should be revised, so as to give more incentive to them to adopt ecologically and economically more sustainable land use practices.

Keywords: Rainfed farming; Agroforestry parklands; Herbicides; Land use policy

Introduction

Sudan remains the second largest country of the African continent after the emergence of South Sudan as an independent country in 2011. Currently it occupies an area of approximately 1.9 million km². The majority (70%) of Sudan's people lives in rural areas and depend on products from mainly rainfed crop cultivation, livestock management and forest products for their livelihood. Despite the fact that Sudan is considered to have a significant potential to contribute to international food security with its agricultural production, many problems remain in providing sufficient food even for its own people (Mohamed 2011).

Food security has been a major national policy goal in Sudan since the country declared its independence in 1956. However, several challenges stand in the way of fully attaining this, for instance, the environmental instability as exemplified by recurrent droughts (Aldeshoni 2005; Ibnouf 2011). Droughts accelerate the human-induced environmental degradation caused by poor agricultural crop management and overgrazing, as well as unsustainable firewood collection and charcoal production (Elsiddig 1999). Other factors leading to food insecurity in Sudan include continued conflicts, inequality of development and the generally low agricultural production capacities (Abu Raida 2013).

Sudan's farming systems are commonly classified into three major categories, namely, (1) irrigated, (2) mechanised rain-fed, and (3) traditional rain-fed systems. Agriculture contributes to the Gross Domestic Product (GDP) both directly (30.6% of GDP) and indirectly, by influencing activities in other sectors (CBOS 2013). It is, nevertheless, considered to be the cornerstone in promoting economic growth and welfare of society in the country (Sharawi 2006).

In the 1940s, mechanized rainfed farming, which was hardly known earlier in the country, was initiated on the vertisols of the Gadarif region in eastern Sudan. The main crops grown in commercial farming were and still are sorghum (*Sorghumbicolor*) and sesame (*Sesamumindicum*). The production in this region accounts for about 65% of the country's sorghum, 53% of the sesame, and 5% of the pearl millet (*Pennisetumglaucum*). Historically, the eastern clay plains have been a source of sorghum not only for meeting domestic needs but also for export (MEPD 2003).

Empirical evidence from different locations suggests that rural households engage themselves in multiple activities and rely on diversified income portfolios (Ibnouf 2011). Accordingly, livestock husbandry stands after agricultural crop production as a major secondary economic activity; together they are often integrated into agro-pastoral management regimes.

A considerable number of farmers in the clay plains have adopted a crop monoculture system in their farm production, obviously in order to ensure an annual access to arable land and to earn fast cash income. Farm productivity of this system has decreased due to many factors, such as the lack of commercial fertilizers, variability of rainfall and the inadequate use of agricultural chemicals for crop protection (Luukkanen et al. 2006).

Maintaining and re-establishing agroforestry practices on drylands in Africa is known to lead to improved crop and livestock production with less inputs in terms of commercial fertilisers; this is especially beneficial for smallholder farmers (Parwada et al. 2010; for a global overview cf. Nair and Garrity 2012).

In the Sudan clay plains, crops are commonly grown under a patchy cover of scattered trees. Farmers often protect naturally-regenerated trees during clearing, tillage and weeding because of the benefits they provide, such as food, fodder, non-wood products such as gums, and wood for tools and furniture as well as for energy, medicines and shade (Boffa et al. 2000). In the case of acacia trees on farmlands in central Sudan, their nitrogen fixation and contribution to the soil organic material content improve the soil fertility and hence the crop yields (Gibreel 2013; Fadl and Ahmed 2015). The resulting landscape, known as agroforestry parkland, is defined by a more or less regular occurrence of well-grown trees scattered on cultivated or recently fallowed fields (Pullan 1974; Boffa et al. 2000).

Agroforestry parkland systems based on naturally regenerated acacia trees and irregularly distributed cultivated land are considered as a main component of the farmland landscape in the whole central Sudan region. However, few financial analyses (cf. Sharawi 2006) have been carried out on the revenues from these systems in comparison with other land use systems.

In the present study we attempted to approach, in the central Sudan context, the following questions: (1) What are the ultimate benefits of an economic analysis on land use systems to local people; (2) Which economic factors guide the farmers' choice of cultivated crops plants; and, (3) Preliminarily, what are the current and future challenges to food security and income generation, especially in relation to current land use policies.

Using Sennar State in Sudan as the target area, the general aim of the present study was to identify and analyse the land use systems practiced by farmers, so as to provide, based on economic analyses, guidance for improving the crop yields and income generation, and to provide information that can be used in land-use policy development.

Specifically, the aim was to determine the socio-economic impacts of cultivating subsistence food crops and cash crops with different land use systems under clay plain conditions. Ultimately, the specific aim was to identify land use and cropping systems which would provide the highest financial profitability for the local farming households.

Materials and methods

Study area

Sennar state, about 300 km south of the capital Khartoum, is located in the south-east corner of the country between longitudes 32° 58' and 34° 42'E and latitudes 12° 5' and 14° 7'N. It is bounded in the north and south by Gezira state and Blue Nile state, respectively, Gadarif state to the east, to the west by White Nile state, and Upper Nile state in South Sudan (Fig.1).

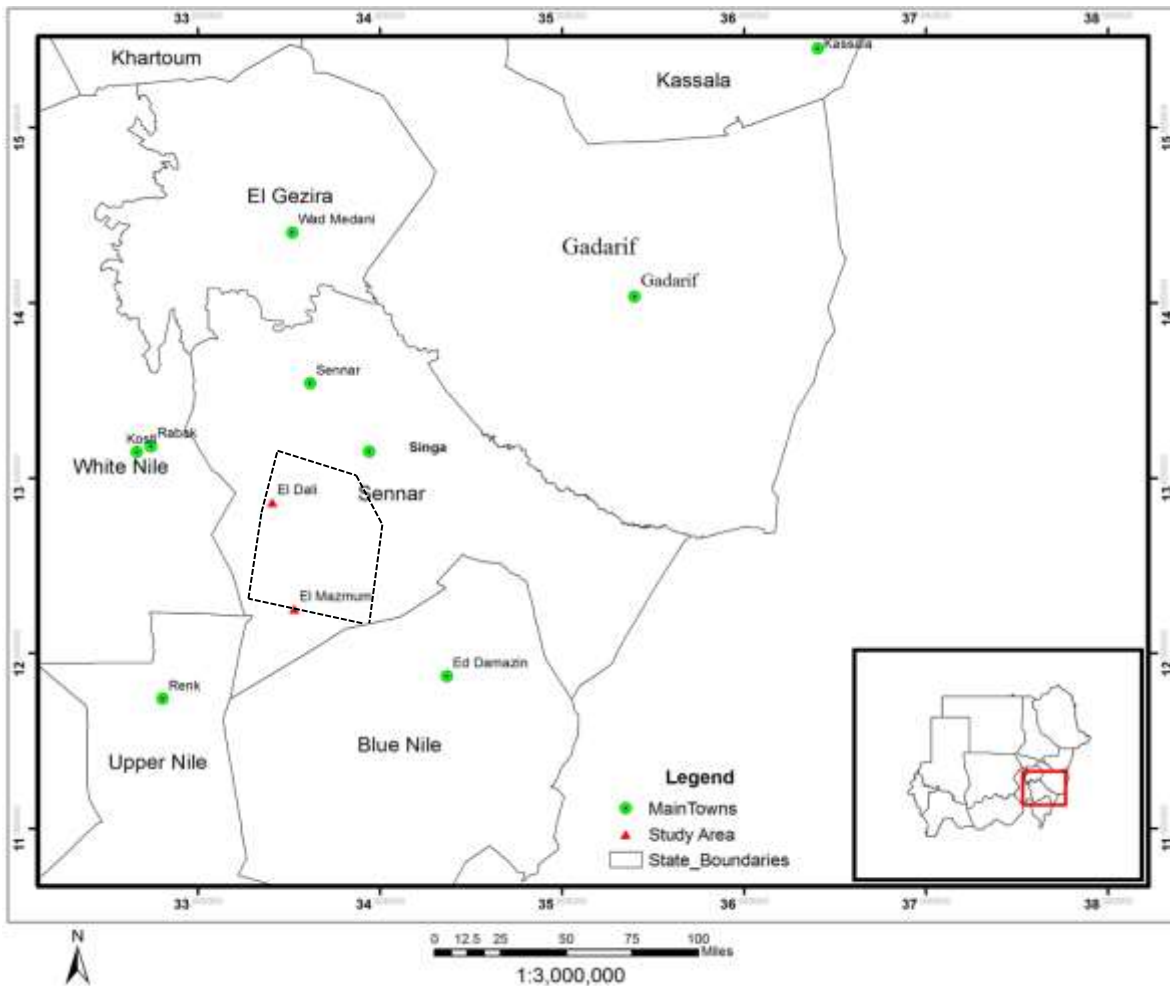


Fig. 1 Map of the research area (indicated by dotted line and showing the El Dali and El Mazmum study sites) in Sennar state, Sudan.

Topography, soil type and climate

The topography of Sennar state is generally flat, and the whole area is endowed with a diverse irrigated and rain-fed resource base. The main agricultural data for the state show that rain-fed farming largely dominates the agricultural land use (90%), with only 10% of farms being under irrigation. Forests and natural rangelands represent 13% of the total land area of the state (IFAD 2010). Tree species frequently existing in the entire study area are *Acacia mellifera* (known locally as kitir; the dominant tree species), *A. seyal* (talh), *A. senegal* (hashab) and few of *Balanites aegyptiaca* (heglig). The soils in the study area consist of dark alkaline clay, which, as typical vertisols, swells and becomes sticky when wet but develops wide and deep cracks when dry (Ahmed et al. 2012). The climate in the state is semi-arid; the dry summer season extends from March to May with average daily temperatures of 32 to 40°C and a relative humidity of about 25%. The rainy season begins early in June and continues until October. Winter begins in November with average daily temperatures of 20–25°C (Sudan Meteorological Services 2005, unpublished).

Study site

This study was conducted in nine villages in El Dali and El Mazmum areas which together form a so-called “locality” in Sennar State (Fig. 1). This locality is characterized by an expansion of both rain-fed mechanised and subsistence farming, which together occupy an area of 606,000 ha (MAAWI 2011). The major crops cultivated include sorghum (locally known as dura; the dominant crop), sesame, and pearl millet. Tree species commonly occurring in the two specific research sites are *Acacia mellifera* and *A. senegal* in which we observed natural irregular distribution throughout all farmland. The annual total precipitation over the ten-year period of our study in our specific study areas varied between 300 and more than 700 mm (Fig. 2).

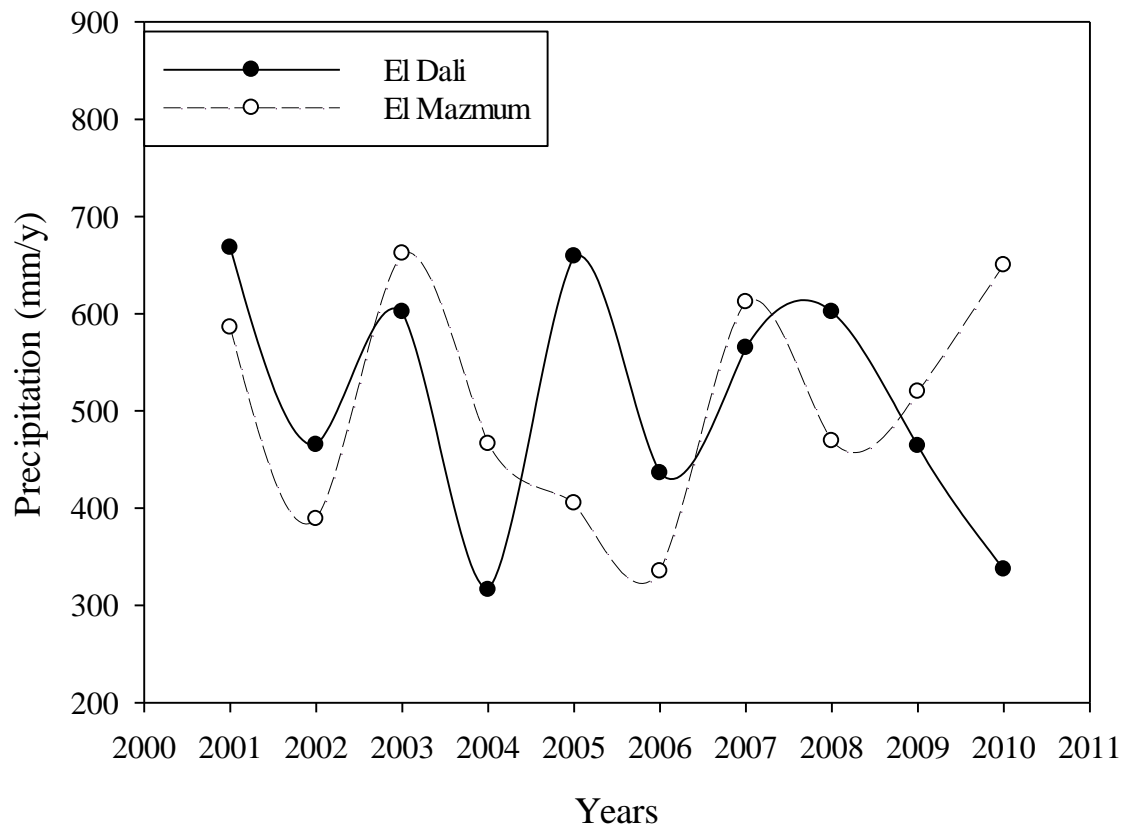


Fig. 2 Average annual precipitation (mm) at El Dali and El Mazmum study sites in Sennar State, Sudan, between 2001 and 2010 (source: MAAWI, 2011).

Preliminary data collection

Prior to data collection, we conducted an initial survey which enabled us to visit all twenty villages comprising the El Dali - El Mazmum locality and to get permission for our study from their leaders. This preliminary survey also aimed to ensure that the questions in the final questionnaire were easily understood by all respondents.

Data collection and sampling

Data were collected between July and November 2011. The pre-testing survey and the information provided by village leaders indicated that the numbers of households substantially differed among the villages. Accordingly, we used the method of constant interval (El Abass 2006) as shown in Equation 1 to categorise these villages into

large, medium or small, based on the number of households in each. This penultimate step was to facilitate and identify the target villages and respondents in them:

$$I = \frac{SV+LV}{3} \quad (1)$$

where I = interval, SV= smallest village, LV= largest village

We then randomly selected nine villages which nearly represented 50% of the total of villages in the study area. Similarly, a total of 281 household heads were randomly selected; 145 from El Dali and 136 from El Mazmum; they were interviewed face to face (cf. Table 1). The household survey covered structured and tested questions on general socioeconomic characteristics (Table 2), farming systems and processes related to crop management (Tables 3, 5 and 6). Data on crop yields for this study were provided by respondents from their annual field estimates and records.

Table 1 Selection of households (HH) and villages at El Dali and El Mazmum study sites in Sennar state, Sudan.

Household/village characteristic	SV	MV	LV	Total
Number of households in village	125–766	767–1408	>1408	
Total no. of HH in El Dali	461 (3) ^b	659 (1)	1783 (1)	2903 (5)
HH selected from El Dali (no.)	23 (3)	33 (1)	89 (1)	145 (5)
Total no. of HH in El Mazmum	558 (2)	503 (1)	1666 (1)	2727 (4)
HH selected from El Mazmum (no.)	28 (2)	25 (1)	83 (1)	136 (4)

Village categories: SV= small village, MV=medium village, LV= large village.

^b Figures in parentheses indicate the number of villages selected.

Prior to analysis, screening and preliminary results showed incomplete information from 11 respondents. Accordingly, the final results are based on the information from the remaining 270 respondents.

Data analysis

Data on household characteristics and farming systems and other processes related to crop yields in the two study areas were analysed using IBM SPSS statistics 22 (IBM corp. 2013). Similarly, this statistical package was used to determine the minimum, mean and maximum of land holding size and the crop yields of sorghum, millet and sesame between 2001 and 2010 from different land use systems in the two study areas.

After data collection we identified and continued to analyse four land use systems that were commonly practiced by households in the two study locations: i) monoculture by leaseholders (MLH), which represents a group of farmers who cultivate sole crops on their own land but under the customary law; ii) monoculture by landless farmers (MLL), which refers to those agrarians who rent farmland annually from leaseholders to cultivate crops (farmers in neither category used herbicides); iii) monoculture by leaseholders with herbicide use (MLHU), this

includes farmers who own their farmland under customary law and have used herbicides to increase their crop yields; and iv) leaseholders in agroforestry parklands (LHAP) under customary law, with scattered, deliberately retained natural trees, mainly *Acacia mellifera* and *A. senegal*, on their farms.

In IBM SPSS statistics 22, we used one-way analysis of variance (ANOVA) to compare means of sorghum, millet and sesame yields from 2001 to 2010 in different land use systems between the two study areas. Similarly, an independent-sample t-test, at $P \leq 0.05$ significance level, was used to examine the variation in mean sorghum, millet and sesame yields between land use systems within each of the two study areas. Results of the independent-sample t-test were used to create bar graphs with significant differences indicated, for sorghum, millet and sesame yields pairwise between different land use systems in each of the two areas.

Economic analysis

A financial cost/benefit analysis was performed using a 12% annual discounting rate, which represents the mean alternative rate of return to financial private investment throughout the country during the study period. This analysis was carried out for sorghum, millet and sesame yields in the four different land use systems practiced at the two areas. Based on information on household costs and incomes in Tables 5 and 6, calculations were made to obtain the net present value (NPV) and benefit/cost ratio (B/C ratio) as profitability criteria. The NPV and the B/C ratio are expressed in Equations 2 and 3 (Gittinger 1982):

$$NPV_i = \sum_{n=0}^N (B_n - C_n) * \frac{1}{(1 + i)^n} \quad (2)$$

$$B/C \text{ ratio} = \frac{\sum_{n=0}^N B_n * \frac{1}{(1 + i)^n}}{\sum_{n=0}^N C_n * \frac{1}{(1 + i)^n}} \quad (3)$$

where B_n , C_n equal the annual benefit and cost, i the discounting rate; and n the number of years.

It is relevant to notice that the acacia trees in these agroforestry parklands systems are not under silvicultural management and no inventory data were found about their age or number per unit area. It was, however, observed that the trees were distributed irregularly with a distance between trees approximately varying from 10 up to 50 m. Therefore, neither tree establishment or removal costs nor any income from their harvest was included in the financial analysis.

Results

Socioeconomic characteristics of households

The socioeconomic data obtained from household heads in El Dali and El Mazmum areas are shown in Table 2. Results revealed that all those interviewed were full-time farmers, except two household heads in El Mazmum who had other income-generating activities in addition to farming. More than 88% of the households in the two areas managed their own land under the customary law (i.e. they were leaseholder farmers), and the rest rent a piece of land annually from leaseholders to secure their food and cash income. Households could lease land from the government through a formal contract which is renewed every ten years. In addition, they paid annual rents to the government against access to the land and for the right to benefit from the trees that stand on that particular land during the contract period.

As seen in Table 2, nearly one-third of the households in the two study areas had a land holding size less than 42 hectares. In contrast, a few farmers were in the possession of exceptionally large holdings, which is indicated by the maximum land area figures in Table 4. For 61% of all households the family size ranged between 8 and 15 persons. More than half of all families (56 and 62% in El Dali and El Mazmum, respectively) had sole crop cultivation as their primary source of income generation, while the remaining households considered animal husbandry as another source of income generation alongside with crop cultivation. In El Dali cattle was the preferred type of livestock, while in El Mazmum sheep or goats were favored.

Table 2 Socioeconomic characteristics of households at El Dali and El Mazmum study sites in Sennar state, Sudan.

Variable	Frequency (% in parenthesis)	
	El Dali	El Mazmum
Status of land holding		
Leaseholders	131 (92.9)	115 (89.1)
Annual rent	10 (7.1)	14 (10.9)
Total	141 (100)	129 (100)
Land holding size (ha)		
< 42	48 (34.1)	47 (36.4)
42–167	80 (56.7)	66 (51.2)
>167	13 (9.2)	16 (12.4)
Total	141 (100)	129 (100)
Persons in household		
1-7	41 (29.1)	42 (32.6)
8-15	87 (61.7)	79 (61.2)
> 15	13 (9.2)	8 (6.2)
Total	141 (100)	129 (100)
Head of household		
Male	141 (100)	127 (98.4)
Female	0 (0)	2 (1.6)
Total	141 (100)	129 (100)
Occupation		
Famer	141 (100)	127 (98.4)
Famer +Employer	0 (0)	2 (1.6)
Total	141 (100)	129 (100)
Age(years)		
<40	20 (14.2)	31 (24)
40-50	92 (65.2)	71 (55)
>50	29 (20.6)	27 (21)
Educational level		
Khalwa (pre-school)	5 (3.5)	11 (8.5)
Primary	31 (22)	46 (35.7)
Secondary	61 (43.3)	52 (40.3)
University	44 (31.2)	20 (15.5)
Total	141 (100)	129 (100)
Generation of income		
Crop production	79 (56)	80 (62)
Crop and livestock production	62 (44)	49 (38)
Total	141 (100)	129 (100)
Animal husbandry		
Cattle	45 (32)	23 (17.8)
Cattle and sheep or goats	14 (10)	25 (19.4)
Camels	3 (2)	1 (0.8)
No livestock	79 (56)	80 (62)
Total	141 (100)	129 (100)

Farming systems and crop yields

Results on application of farming systems and operations related to crop cultivation in the two study areas are summarized in Table 3. Monoculture cropping dominated as a farming system in both areas. Only 21% of the households in El Dali and 42% of those in El Mazmum were involved in crop cultivation in agroforestry parklands belonging to rain-fed agricultural schemes and consisting of three distinct components, i.e. the naturally regenerated and largely unmanaged acacia trees, as well as agricultural crops and/or animals. Livestock could access the farmland only after the harvest in the dry season and then forage on crop residues (Fig. 3).



Fig. 3 Crop residues serve as primary animal feed during the dry season at the El Dali and El Mazmum study sites in Sennar state, Sudan. (Photo: present study.)

All households in the two areas now studied cultivated sorghum to secure their annual subsistence food needs, as well as sesame or millet as cash crops. External workers alone did the weeding on 60% of the farms in El Dali and on 70% of those in El Mazmum, obviously mainly then on larger farms, while smallholders seemed to at least partly rely on their family members to carry out such work.

Sole manual harvesting was used by 95% of the households in El Dali, but, in contrast, 94% of the farmers in El Mazmum used both manual and mechanical means to harvest their crops. As reported by the households in the two areas, El Dali is situated closer to the main towns (cf. Fig. 1) from which labour is to some extent available even when the rains make the local roads impassable.

There was a considerable difference in the willingness to use herbicides for weed control between the two sites. In El Dali 44%, but, in contrast, in El Mazmum only 14% of them felt no constraints in using them. Households that did not use herbicides justified their choice in different ways (Table 3). Having only a small area of farmland and thus being able to use manual weeding was mentioned as a reason by 15 and 21% in El Dali and El Mazmum, respectively. For 20% of the El Dali farmers and 38% of those in El Mazmum herbicides were claimed to be either too expensive, inaccessible, or having a negative impact on agricultural yield. Those engaged in farming in agroforestry parklands generally concluded that weeds were not a serious enough threat to justify herbicide use.

Table 3 Farming systems and management practices at El Dali and El Mazmum study sites in Sennar state, Sudan. MLH= monoculture by leaseholders, MLL= monoculture by landless farmers, MLHU= monoculture by leaseholders with herbicide use, and LHAP= leaseholders in agroforestry parklands.

Variable	Frequency (% in parenthesis)	
	El Dali	El Mazmum
Households involved in land use		
MLH	48 (34)	55(42.6)
MLL	10 (7)	14 (10.9)
MLHU	62 (44)	18 (14)
LHAP	21 (15)	42(32.5)
Total	141(100)	129 (100)
Main crop cultivation		
Sorghum with millet and/or sesame	141 (100)	129 (100)
Other crops	0 (0)	0 (0)
Total	141 (100)	129 (100)
Sources for removing weeds		
Family	27 (19.1)	19 (14.7)
Hired	85 (60.3)	90 (69.8)
Family + hired	29 (20.6)	20 (15.5)
Total	141 (100)	129 (100)
Grain collection		
Manual	134 (95)	8 (6.2)
Manual + machinery	7 (5)	121 (93.8)
Total	141 (100)	129 (100)
Agroforestry parkland pattern		
Trees + crops	9(6.4)	27 (21)
Trees + crops + animals	12 (8.5)	15 (11.6)
Not adopted	120 (85.1)	87 (67.4)
Total	141 (100)	
Reasons hindering herbicides use		
Small size of farm	30 (21.2)	20 (15.5)
Cost or accessibility of herbicides	28 (19.8)	49 (38)
Less weeds in agroforestry parkland	21 (15)	42 (32.5)
No constraints	62 (44)	18 (14)
Total	141 (100)	129 (100)

Variations in sorghum, millet and sesame yields (as an average for the period from 2001 to 2010) between El Dali and El Mazmum, separately for each different land use type, are shown in Table 4. Some of the differences between the two sites were, for all three crops studied, highly significant, as indicated by one-way ANOVA analysis. For instance, sorghum yields in a monoculture system (MLH) in El Dali were significantly higher (at $P \leq 0.05$) than those in the same system in El Mazmum (Table 4). Interestingly, for farmers using herbicides (MLHU), the sorghum yields indicated opposite results, i.e. significantly better harvests in El Mazmum.

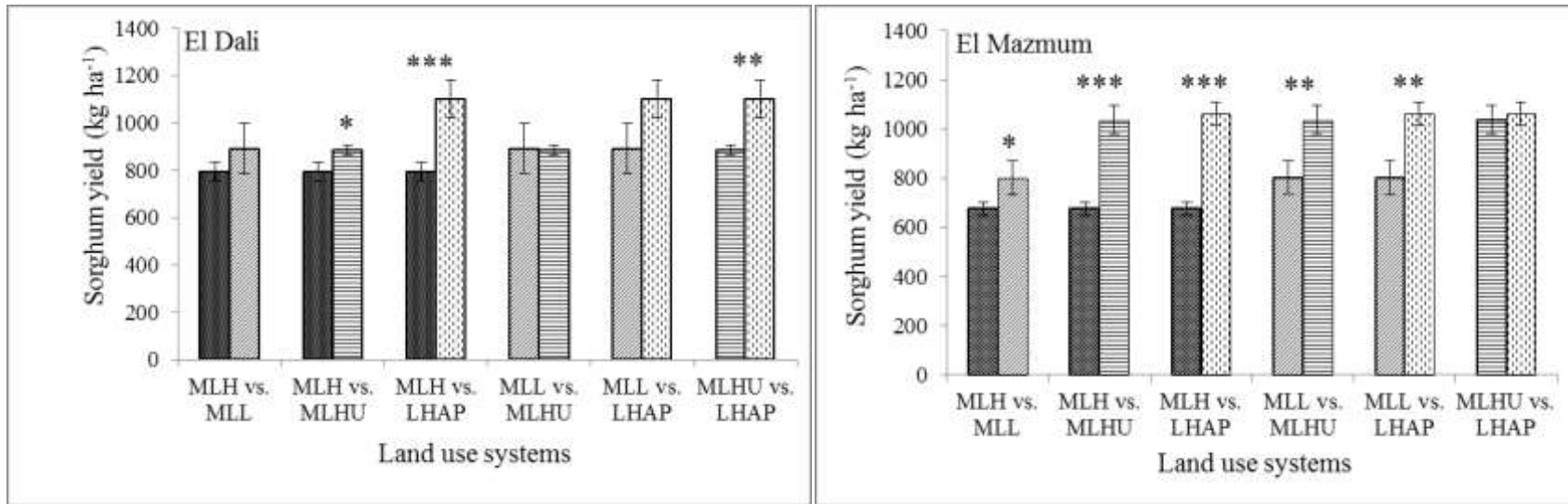
On average, from 2001 to 2010 and at both sites, the highest yields of sorghum and millet were consistently obtained by farmers growing their crops in agroforestry parkland systems (LHAP), and the lowest yields of same crops by leaseholderhouseholds in a monoculture system (MLH) (Table 4). The same trend was also true for sesame, except for the case of El Mazmum where a slightly higher yield was attained in monoculture with herbicide use (MLHU). These differences could not, however, be statistically confirmed.

Table 4 Variation in land holding size and 2001-2010 average crop yields (kg ha⁻¹) between El Dali and El Mazmum study sites in Sennar state, Sudan, for sorghum, pearl millet and sesame in different land use systems (see Table 2 for numbers of households surveyed and Table 3 for land use system codes).

Crop	Land use system	Land holding size (ha)						Crop yield(kg ha ⁻¹)						Difference in crop yields		
		El Dali			El Mazmum			El Dali			El Mazmum			between two areas		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean±SD	Min	Max	Mean±SD	f value	df	MS
Sorghum	MLH	4	840	55	2	735	73 ^{NS}	324	1349	794±261	360	1133	676±201	6.835	1	367490.5**
	MLL	21	420	128	4	504	133 ^{NS}	324	1457	891±330	432	1296	802±254	0.549	1	45688.1 ^{NS}
	MLHU	8	8400	372	42	1680	375 ^{NS}	432	1241	886±169	701	1728	1038±251	8.957	1	324074.0**
	LHAP	17	16800	1256	17	4200	579 ^{NS}	756	2342	1101±373	432	1728	1063±292	0.191	1	19775.7 ^{NS}
Millet	MLH	4	840	55	2	735	73 ^{NS}	216	917	416±153	216	701	345±120	7.189	1	134747.3**
	MLL	21	420	128	4	504	133 ^{NS}	324	756	561±160	216	648	428±123	5.367	1	103607.4*
	MLHU	8	8400	372	42	1680	475 ^{NS}	216	917	544±159	377	648	502±92	1.149	1	24752.9 ^{NS}
	LHAP	17	16800	1256	17	4200	579 ^{NS}	216	1241	612±252	216	792	509±144	4.133	1	144376.1*
Sesame	MLH	4	840	55	2	735	73 ^{NS}	240	960	412±156	240	600	351±110	5.324	1	96251.6*
	MLL	21	420	128	4	504	133 ^{NS}	240	540	378±106	240	900	467±171	2.107	1	46354.3 ^{NS}
	MLHU	8	8400	372	42	1680	475 ^{NS}	240	960	431±134	360	720	520±110	6.721	1	111380.8**
	LHAP	17	16800	1256	17	4200	579 ^{NS}	240	1200	492±214	240	960	500±137	0.034	1	932.6 ^{NS}

(*) and (**) denote significance level at 0.05 and 0.01 respectively; NS denotes no significant difference. MS = mean square; df= degrees of freedom.

Results from a subsequent, more accurate analysis for comparing crop yields (i.e. the averages for the period from 2001 to 2010 and separately for the two sites) among the different land use systems is presented in Fig. 4. The independent-sample t-test showed significant differences (at $P \leq 0.05$) between monoculture (MLH) and agroforestry parkland systems (LHAP), with the latter practice resulting in higher yields. In contrast, sesame yields in El Dalishowed no significant difference when different land use systems were compared. Small, non-significant yield differences were generally found for all three crops when monoculture with herbicide use (MLHU) was compared with the agroforestry parkland system (LHAP), except for sorghum in El Dali where a significantly higher yield was obtained with the latter land use system (Table 4).



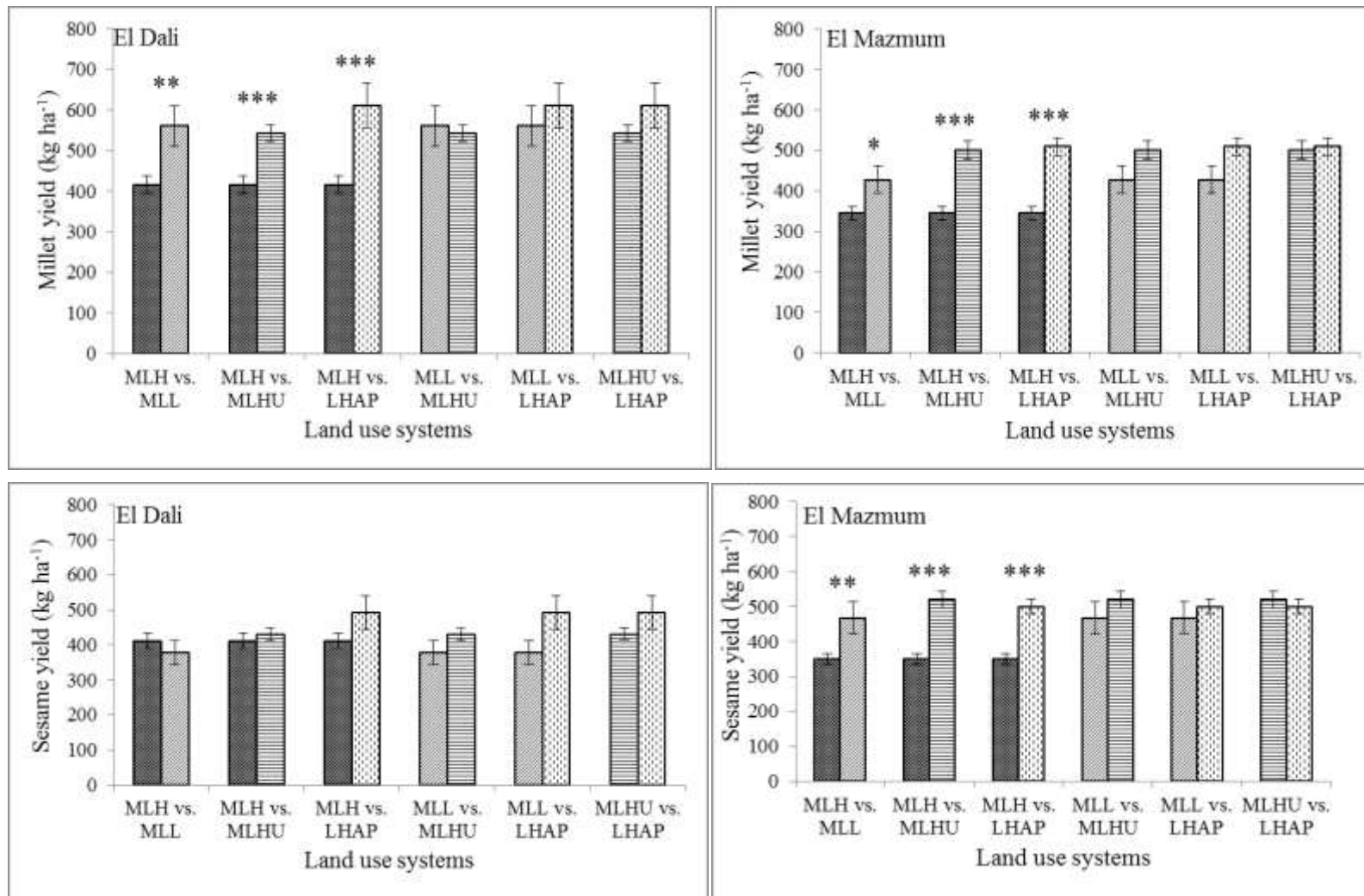


Fig. 4 Pairwise comparisons of average sorghum, millet and sesame yields (mean \pm SE kg/ha⁻¹) between different land use systems for the 2001-2010 period at the El Dali and El Mazmum study sites in Sennar State, Sudan. Explanations: MLH= monoculture by leaseholders, MLL= monoculture by landless farmers, MLHU= monoculture by leaseholders with herbicide use, and LHAP= leaseholders in agroforestry parklands. For number of respondents (N) in each land use system see Table 2.

Based on independent-sample t-test, the asterisks indicate statistically significant differences in pairwise comparisons of land use systems (*, $0.01 < p < 0.05$; **, $0.001 < p < 0.01$; ***, $p < 0.001$).

Cost-benefit analysis

A financial analysis was performed using Equations 2 and 3, based on the household income and cost data shown in Tables 5 and 6, respectively. Results (Table 7) indicate that all three crops, sorghum, millet and sesame, were consistently profitable irrespective of the land use system. Generally, and following the trend in crop yields, the highest net discounted return was consistently found in the agroforestry parkland system (LHAP); only in the case of sesame in El Mazmum monoculture with herbicide use (MLHU) a slightly higher value was again found.

Sensitivity analysis

At 20% annual discounting rate, millet and sesame remain profitable under different land uses. Similar trend follows for sorghum except for landless farmers in El Mazmum which breaks even at 18.1%. Again, the agroforestry parkland system (LHAP) proved to be most profitable compared to other land uses except for sesame in El Mazmum monoculture with herbicide use (MLHU).

It was obvious that sesame cultivation was not as much affected by the land use system as were the other two crops, sorghum and pearl millet. The benefit/cost ratio for sesame cultivation remained at a relatively high level and varied between 1.88 and 2.35 among all land use systems at the two sites. This can be compared to the same indicator for sorghum (varying between 1.00 and 1.69) and for pearl millet (1.08 to 2.77).

Table 5 Household income (USD ha⁻¹) from sorghum, millet and sesame in different land use systems in 2008, 2009 and 2010 at El Dali and El Mazmum study sites in Sennar state, Sudan. There were no differences in crop prices between the two areas. 1 USD = 2.6 SDG (exchange rate for Sudanese pounds 2008-2010). A sack measures 90 kg for sorghum and millet, and 100 kg for sesame. For land use system codes, see Table 3.

Crop type	Land use system	Household income								
		Crop yield and price in 2008			Crop yield and price in 2009			Crop yield and price in 2010		
		El Dali (kg ha ⁻¹)	El Mazmum (kg ha ⁻¹)	Both areas (USD sack ⁻¹)	El Dali (kg ha ⁻¹)	El Mazmum (kg ha ⁻¹)	Both areas (USD sack ⁻¹)	El Dali (kg ha ⁻¹)	El Mazmum (kg ha ⁻¹)	Both areas (USD sack ⁻¹)
Sorghum	MLH	561	432	23	540	450	25	540	495	27
	MLL	720	432	25	540	540	27	630	630	27
	MLHU	720	700	23	540	720	25	630	720	27
	LHAP	842	900	23	800	1020	25	820	1060	27
Millet	MLH	389	267	38.5	216	450	42	238	240	46
	MLL	600	292	42	292	350	46	475	450	46
	MLHU	600	312	38.5	312	348	42	436	450	46
	LHAP	630	312	38.5	450	350	42	540	450	46
Sesame	MLH	446	272	115.5	380	360	135	360	375	154
	MLL	400	360	115.5	360	411	135	312	427	154
	MLHU	456	400	115.5	400	427	135	346	540	154
	LHAP	540	400	115.5	540	400	135	480	540	154

Table 6 Costs of farm operations and inputs (USDha⁻¹) for cultivating and harvesting sorghum, pearl millet and sesame, in 2008, 2009 and 2010, at El Dali and El Mazmum study sites in Sennar state, Sudan.

Field input*	Description	Household cost		
		2008	2009	2010
Land preparation	Ploughing work and fuel, including driver incentive and tractor rent.	23	23	28
Seeds	For 2.5 kg of seeds used to plant one hectare:			
	Sorghum	1	1	1
	Millet	2	2	2
	Sesame	4	4	5
Weeding	Removal of detrimental weeds to avoid competition with crops.	69	69	74
Rental of public land	Fees annually paid to government.	3	3	4
Security	Guards for protecting crops and trees. ???	1	1	1
Empty sacks	Sack capacity is 90 kg for sorghum and millet, 100 kg for sesame.	2	2	3
Land rent per ha	Landless farmers rent the land to cultivate crops.	23	23	28
Herbicides	Herbicides are used instead of manual weeding.	74	74	92
		Manual harvesting cost		
Harvesting				
Sorghum	Cost of harvesting one sack (90 kg)	3(4)**	3(4)**	4(5)**
Millet	Cost of harvesting one sack (90 kg)	4	4	6
Sesame	Cost of harvesting one sack (100 kg)	31	31	38

Notes:

* No differences were found in the field input and harvesting costs between El Dali and El Mazmum the two studied sites.

** The price shown in parentheses is the cost of harvesting sorghum when farmers at both sites used harvesting machinery.

Table 7 Financial analysis (USD\$ha⁻¹) of sorghum, millet and sesame grown in different land use systems at El Dali and El Mazmum study sites in Sennar state, Sudan. For land use system codes, see Table 3.

Crop	Indicators of land use performance	El Dali				El Mazmum			
		MLH	MLL	MLHU	LHAP	MLH	MLL	MLHU	LHAP
Sorghum	Total discounted costs	319.7	389.5	354.9	362.4	290.9	370.4	367.8	389.8
	Total discounted benefits	362.9	442.2	418.4	544.3	303.9	371.7	473.0	657.5
	NPV _{12%}	43.2	52.8	63.5	181.9	13.3	1.3	105.2	267.8
	B/C ratio _{12%}	1.12	1.14	1.19	1.50	1.04	1.00	1.29	1.69
Millet	Total discounted costs	291.7	376.3	344.9	340.7	300	358.9	330.4	308.8
	Total discounted benefits	315.5	541.8	489.8	604.5	356.6	430.4	411.2	411.5
	NPV _{12%}	23.7	165.5	144.9	263.8	56.6	71.5	80.8	102.6
	B/C ratio _{12%}	1.08	1.44	1.42	2.77	1.19	1.20	1.24	1.33
Sesame	Total discounted costs	586.9	607.8	624.1	673.5	557.4	637.0	649.3	622.3
	Total discounted benefits	1263.5	1141.9	1279.9	1580.2	1079.0	1281.7	1467.2	1434.9
	NPV _{12%}	676.6	534.1	655.8	906.7	521.6	644.7	817.9	812.6
	B/C ratio _{12%}	2.15	1.88	2.05	2.35	1.94	2.01	2.31	2.31

Discussion

Socioeconomic characteristics of households

Our study confirms that cultivated land was commonly managed by men, either the male household head or one of his sons. There was considerable variation in the age and educational background of these farmers. At both of our study sites their age mostly exceeded fifty years, which also meant that they had profound experience of agricultural activities. This result is in agreement with the findings by Adam et al. (2015), who studied land use conflicts in the same area and also found most of the farmers to be at least fifty years old. They also concluded that the occurrence of female farmer household heads was infrequent (only found in 10% of the cases).

Farming system practices and crop yields

In our comparison of crop yields among the four different land use systems, the lowest yields per unit of land area for all three crops studied were generally found in monoculture systems without herbicide use, regardless of whether they were managed by leaseholders or landless farmers (Table 4). An exception was found in the case of sesame, where yields were not as much affected by land use type.

In earlier studies on monoculture system in the neighbouring Gadarif State (cf. Fig.1), Sulieman (2009) found that the average yields of sorghum and sesame since the 2000s have been 780 and 432 kg/ha, compared to 1920 and 1056 kg/ha, respectively, during the 1960s. For the entire farming area in Sudan the average yields of major crops from 2002 to 2007 was estimated as follows: sorghum 714 kg/ha, millet 428 kg/ha and sesame 357 kg/ha (Ahmed et al. 2012). In 2013, the average yields of sorghum, millet and sesame for the total cultivation area in the country were estimated at 633, 393 and 259 kg/ha, respectively (CBOS 2013). All these findings show that the monoculture farm productivity of the major agricultural crops in Sudan was manifestly higher in the past as compared to recent years.

The exclusion of support from agricultural farming inputs (e.g. fertilisers) in Sudan seems to have been another underlying factor behind the variability in crop yields and low outputs and financial returns (Ahmed et al. 2012). Our study also suggests that herbicides should be made available in the local market timely and at a price affordable to farmers, since they contribute to higher yields and net incomes, as indicated with the present high yield of sesame in El Mazmum.

In our two study areas it was found that all three studied crops showed the highest yields in the parkland agroforestry system where acacia trees were irregularly distributed over the farm. However, as mentioned above, in sesame the yield variation was generally smaller among the different land use systems and parkland agroforestry even resulted in a slightly lower average yield than monocropping with herbicide use at the El Mazmum site (cf. Fig. 4, Table 4).

A positive effect of intercropping with trees on yields in our study (as compared to some contrasting results discussed below) could have been due to the fact that acacia trees found in the cultivated parklands seemed to be mature and irregularly distributed with varying densities, as mentioned earlier. Hence, the trees were presumably not heavily competing with agricultural crops for soil water or nutrients.

In our work, in agroforestry parkland systems, sesame proved to be financially the most attractive crop in El Dali, as it showed the highest discounted net returns (Table 7). Similar results were found in an investigation by Fadl and El Sheikh (2010) in which the NPV of sesame crop was higher (387 SDG ha⁻¹ or 194 USD ha⁻¹, using the 2010 exchange rate) when intercropped with *A. senegal* than when planted alone (205 SDG ha⁻¹ or 103 USD ha⁻¹).

Fadl and Ahmed (2015) recently studied farmers' perceptions of agroforestry systems in South Kordofan state, Sudan. They found that farmers generally preferred growing their crops with trees and the yields of groundnut and sorghum integrated with trees such as *A. senegal* (a local dominant tree species) were higher than those obtained in a monoculture system.

In India, pearl millet in intercropping with planted 20-year-old *Prosopis cineraria* trees has been found to attain higher returns than grain monoculture cropping (Kaushik and Kumar 2003).

In earlier studies conducted by Gaafar et al. (2006) on sandy soils of North Kordofan State in central Sudan, sorghum intercropped with six-year-old planted *A. senegal* trees at a density of 266 trees ha⁻¹ showed a decrease in grain yield of 19%, as compared to pure crop cultivation. At a density of 433 trees ha⁻¹, the yield decrease compared to monocropping was 44%. They also found significant correlation between the soil water content and grain yield, which suggested root competition between trees and agricultural crops in the mixed system.

In the same area, Fadl and El Sheikh (2010) also confirmed that a higher yield (in this case, for sesame, groundnut and karkadeh, *Hibiscus sabdariffa*) was obtained with a lower tree density and this was most likely related to weaker competition between the trees and the agricultural crop for soil water.

In studies conducted by Raddad and Luukkanen (2007) on clay soils of the Blue Nile region of Sudan sorghum yields showed no statistically significant differences between grain monocropping and agroforestry systems with trees planted at 5 x 5 m or 10 x 10 m spacing; however, the highest average grain yield for the four years of observations was recorded in the agroforestry system with trees at 10 x 10 m spacing.

In China, Yin and He (1997) demonstrated that apart from tree density, also the age of trees can have a significant effect on crops. In their investigations, fast-growing *Paulownia elongate* trees, planted with 5 x 6 m spacing (333 trees ha⁻¹), had little effect on maize yields during the first three years of intercropping, after which the yields started to decline sharply and equaled zero from the ninth year onwards. In the ninth year, tree densities of 200, 100 and 50 trees ha⁻¹ gave maize yield corresponding to 31%, 61% and 96% of the monocropping control, respectively.

The choice of tree species in an agroforestry system seems to have a distinct effect on agricultural crop production. In studies conducted by Mubarak et al. (2012) on sandy soils in South Kordofan state in Sudan, pearl millet was cultivated adjacent to *A. senegal*, *Balanites aegyptiaca*, or *Azadirachta indica* trees. Results showed the lowest yield of 111 kg ha⁻¹, in association with *A. senegal*, compared to 175 and 173 kg ha⁻¹ with *B. Aegyptiaca* and *A. indica*, respectively; this is in contrast to the general assumption of leguminous trees having particularly beneficial effects on agricultural crops.

Alongside with similar other studies (e.g. Duguma and Hager 2011; Kidanu et al. 2004); Lisanevork and Michelson (1993) have shown a negative impact of trees on crops in agroforestry systems, especially in relation to

soil fertility and soil moisture. Obviously, more studies are needed for clarifying the effect of trees on crop yields in dryland agroforestry systems with different soil types, tree species, spacing regimes and accompanying crops.

Challenges in dryland agroforestry

In the present study, agricultural crops integrated with acacia trees growing naturally on farmland proved to be the most profitable land use practice for households, even though only 21% of the farmers at El Dali and 42% of those at El Mazmum were engaged in this system.

In agroforestry parklands, as in agroforestry systems in general, trees can positively affect the agricultural crops, due to their ecological roles in restoring the soil fertility and by providing favourable microclimate conditions (Nair and Garrity 2012). However, in the two specific areas presently studied, farmers' perceptions of natural trees on agricultural land assumed them as a liability, i.e. potentially a reason for government authorities to evict them from their holdings, because of the fact that forest land in Sudan is generally considered to be owned by the state.

In fact, the land tenure regime has been concluded to be the most decisive factor in Sudan leading to the exhaustion of natural resources by uncontrolled human activities (Ahmed et al. 2012). According to Elhadary (2010), the Sudanese government has up to the present time had little interest to take further action for solving land tenure and land right problems; the same author also concluded that land tenure is strongly related to challenges that African countries encounter in poverty alleviation and build-up of security in rural communities. Thus strengthening of land tenure systems in sub-Saharan Africa could also improve crop yields and the economic situation of smallholder households in general, but conditions vary in different countries and must be specifically considered (cf. Namubiru-Mwaura and Place 2013).

In the present investigation, within the same land use system some crop yields showed significant differences between the two adjacent study areas (Table 4). This could stem from spatial variability of rainfall during the ten years of crop cultivation now studied (Fig. 2). In a region corresponding to our study area (Kassala state in the eastern clay plains of Sudan), Larsson (1996) analysed the relationships between rainfall and crop yields of sorghum, millet and sesame from 1960 to 1990. He found that as the rainfall decreases, the yield also decreases, and concluded that the annual yields of these three crops are mainly related to climate as measured by the rainfall. Obviously, more research is needed on the effect of local variations in rainfall in a given year.

Conclusions

The present study suggests that among the four land use systems analysed, the agroforestry parkland seems to offer economically the best alternative for profitable farming. This is especially due to the fact that sorghum, the main local crop for food security, showed the highest yields when this system was used. The cash crops now analysed, sesame and pearl millet, also performed well in the agroforestry system, which gives further support for its use.

Growing sesame seems to be a financially attractive activity, as evidenced by the highest net discounted returns now found in this particular crop among the three different ones studied.

Despite the fact that the agroforestry parkland system, which integrates natural acacia trees with agricultural crops on the same piece of land, proved to be potentially the most feasible system for securing livelihoods and income

generation for the households, only few farmers seemed to be willing to adopt it. This was due to the fact that trees on farmland pose land tenure problems that have not yet been overcome.

There was a distinct fear among the farmers that agroforestry parklands could any time be acquired by the government if considered to be part of the government forest estate. Moreover, agroforestry parkland can be secured for an individual farmer's use only for a fixed contract period (varying between 10 and 25 years). The decision concerning a renewal of the contract for a new period remains in the hands of the government. This situation also seems to lead most farmers to move away from planting trees, for instance acacias which also are valuable for gum tapping, on their farms.

Our study suggests that, in order to increase the productivity of staple crops and to improve the income generation in Sennar state, the government should more actively promote a reform of land use policies and specifically address the tree tenure problem. There should be a greater security for tree ownership in order to encourage farmers to adopt the agroforestry parkland system by retaining the existing trees (which mostly consist of acacias) and planting additional ones.

Farmers now engaged in monoculture cropping should be supported in incorporating acacias with agricultural crops on their farms in order to increase the food production as well as the individual cash income generation. Apart from improving the soil properties on farms, trees would then provide economically valuable products.

In fact, several fertiliser-tree regimes, for instance, the *Faidherbia albida* system, contribute to a higher soil nutrient level through their biomass. The decrease in the demand for commercial fertiliser could be as high as 75%, while a significant increase is found in the crop yield (Akinnifesi et al. 2010).

Weed control with herbicides is a potential tool for increased agricultural production. In our study this practice was only used by some more affluent households, which already had been able to increase their crop productivity by applying it. Proper instructions on herbicide use should be disseminated to farmers. New policies should also contribute to improving the availability of herbicides, either through actions by agricultural unions or by agricultural banks providing suitable loans.

Present results on the benefits of trees for dryland farming are in agreement with earlier recommendations, especially given by international agricultural research organizations such as the World Agroforestry Centre (ICRAF), which invite more attention to be given to the use of nitrogen-fixing trees such as acacias as a tool for soil improvement. This practice would gradually lead to improved crop production and be especially important in cases like Sennar state in Sudan, where the availability or cost of mineral fertilizers commonly still restrict their use.

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