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Research Article

Nutrient Balances as Indicators of Sustainability in *acacia senegal* Land use Systems in the Semi-arid Zone of North Kordofan, Sudan

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Abstract

The objectives of this study were: (1) to assess nutrient flows and balances at land management systems and cropping seasons levels, and (2) to determine rate of nutrient depletion. The study was conducted in dry lands of Northern Kordofan, Sudan, at El Demokeya Forest Reserve (lat.13° 16′ N; long. 30° 29′ E, and alt. 560 m), over three cropping seasons (2002, 2003 and 2004). Flows and balances of organic carbon (OC), nitrogen (N), phosphorous (P) and potassium (K) in pure and intercropped sorghum, roselle and grasses with Acacia senegal at low- and high-tree density (LD 266 and HD 433 trees ha^{-1}, respectively) were investigated. Sources of nutrient inflows were organic matter (OM) from trees, gum Arabic, crop roots, atmospheric deposition, and N_2 fixation. Outflows were harvested products, crop residues, leaching, gaseous losses and wind erosion. Nutrient balances were positive in grass systems, but negative in pure sorghum and roselle. Large variations exist between inter cropped sorghum and roselle systems. Nutrient balances were positive during the poor cropping season (2002), while negative during the good season (2003). Nutrient depletion was severe for all studied nutrients in pure sorghum and roselle, but P depletion was remarkably more severe in roselle systems. For all systems, P availability is the major determinant of sustainability. The study demonstrated that OM was essential for positive nutrient balances. Hence, intercropping is considered as an appropriate option to enhance soil fertility. Ways for adjusting the negative balances in the context of sustainability were suggested.

Keywords*:* Organic carbon; Nutrient depletion; Sustainability; cropping seasons; Gum Arabic

INTRODUCTION

Land degradation, particularly in the drylands of the world, is forcing the international community to search for alternative sustainable production systems. Soil degradation in the drylands is a key factor affecting the sustainability of agricultural systems (Young, 2000). It is a complex process with physical, chemical and biological dimensions. Nutrient depletion is one of the most important chemical processes involved in soil degradation. Since soil nutrient supply is vitally important for crop production, nutrient depletion has major implications for the sustainability of agricultural systems and future food supplies.

Soil nutrient depletion can be measured by determining the amount of nutrients removed from the soil as a proportion of the nutrient stock in the soil (Stoorvogel and Smaling 1990; Wortmann and Kaizzi, 1998). Smaling et al. (1996) have suggested that nutrient budgets and nutrient stocks are quantifiable indicators of agricultural sustainability and have used this information to classify agro-ecosystems. Subsequently, nutrient balances have been proposed as an indicator for assessing land quality (Pieri, 1992).

Nutrient balance, which is the difference between the sum of the nutrient entering and leaving a system, respectively, is a method commonly used for assessing the sustainability of a land use system (Stoorvogel and Smaling, 1990; Scoones and Toulmin, 1998). Use of nutrient balance is one of the ways to define the degraded state of a system and provides an early indicator for intervention. This requires an understanding of the major interactions between plants, soils, and environment.

This understanding will enable the development of scientifically sound assessment of nutrient status of these systems and will help advocate acceptable interventions that will improve resource management. Using diverse nutrient balance models and approaches, soil degradation resulting from nutrient depletion in Sub-Saharan and other parts of Africa has been documented at various scales including regional, district, landscape, village, farm and plots levels (Stoorvogel and Smaling, 1990; Van der Pol, 1992; Smaling et al., 1993, Stoorvogel et al., 1993, Krogh, 1997; Smaling, 1998; Lynam, et al., 1998, Ramisch, 1999).

Soil degradation due to nutrient depletion can be found all over the Sudan, but is largely critical in the rain fed agricultural systems in the arid and semi-arid parts of Western Sudan (Ayoub, 1998). Nutrient depletion in these systems has been identified as one of the major biophysical constraints to food security and economic development in the rural areas of Kordofan and Darfur regions (Ayoub, 1998). In semi-arid Kordofan, the use of gum-gardens (bush-fallow with *Acacia senegal*) has been a traditional farming system for crop production and soil improvement while simultaneously producing gum Arabic and fuel wood, fodder and other non-timber products (El Huri, 1986; El Tahir et al., 2009). In a gum-garden farm the land is rotated between agricultural crops (3-5 years) and trees (15-20 years). Over the fallow period, trees are tapped for gum Arabic that can produce income during the less intense winter season. Once gum production starts to decline, the trees are felled and the area cultivated again with renewed productivity. Over the years, this traditional agroforestry system had ensured optimum and sustainable utilization of the natural resource base, because both gum production and crop cultivation form the main production components of the system (El Huri, 1986). Moreover, the tree fallow were of sufficient duration to restore soil fertility to the extent that it can sustain many years of subsequent cropping (Deans et al., 1999) that ensured socioeconomic and environmental sustainability (Elmqvist et al., 2005).

In the dry lands of North Kordofan, the sustainability of *Acacia senegal*-based systems is a concern for the welfare of the population in this relatively poor area of the country. Poor soil fertility, erratic rainfall and low inputs are seen as major causes of these problems. In this context, nutrient balance analyses are seen as a powerful tool for the assessment of critical components of the sustainability of these systems. In arable farming, nutrients will generally be lost to crop and livestock products and there will be a need to balance these losses with inputs in order to maintain the nutrient resource capital of the farm (Sanchez and Palm, 1997). Positive nutrient balance in the soil occurs when nutrient inputs are greater than the nutrients removed from the soil and the reverse is true for negative balance (Sanchez and Palm, 1997; Khanna, 1998). Positive balances could indicate that farming systems are inefficient, and in the extreme may be polluting the environment whereas negative balances could well indicate that soils are being depleted and that farming systems are not sustainable over the long term (Gruhn et al., 2000). In this case nutrients have to be replenished to maintain agricultural output and soil fertility into the future (Sanchez and Palm, 1997).

Soil nutrient balances may be computed at different scales, starting from the plant level and moving through the plot, farm, watershed, village, and district, national, regional, and international levels (Stoorvogel et al., 1993). The most common scale used by soil scientists is the household level (farm scale) (e.g. Wortmann and Kaizzi, 1998; de Jager et al., 2001), as this is an important level for storing and transferring nutrients, as well as making farm management decisions (Defoer et al., 2000). The time interval commonly used for computing rates of nutrient flow is one year, because this period completes the seasonal and crop production cycles (Defoer et al., 2000).

The objectives of this study were:

(1) To assess nutrient flows and balances at land management systems (LMS) and cropping seasons levels, and
(2) To relate average nutrient balances to baseline nutrient stocks (2002) to determine rate of nutrient depletion.

Materials and Methods

Research Site

The study was conducted at El Demokeya Forest Reserve (lat.13° 16′ *N*; long. 30° 29′ *E*, and alt. 560 m), located at 31 km east of El Obeid town, North Kordofan State. The climate of the area is semi-arid characterized by a very erratic rainfall. Rainfall records in the study area were: 86, 324 and 196 mm, during 2002, 2003 and 2004 rainy seasons, respectively. The long-term average annual rainfall is 358 mm, and it occurs from July to September. The mean relative humidity is 34%, and it reaches to a maximum of 60% in the wet season. The mean annual evaporation is 15.5 mm day^{-1} and increases to 20 mm day^{-1} in the hot summer months (Ballal, 2004). Mean daily temperatures are about 27 °C, but they can rise as high as 46 °C during the hot summer months (May-June). The soils of the site are characterized as Cambric Arenosols mainly Aeolian deposits (FAO, 1995). They have very poor functional characteristics viz: clay, mineral elements, OM, CEC and water holding capacity (El Tahir, et al., 2009). Their OM content of the upper 10 cm is about 4970 kg C ha^{-1} (Olsson and Ardö, 2002). The available water of these soils is about 16% and the infiltration rate is 6.0 mm min^{-1}, indicating very high porosity and virtually non occurrence of surface runoff (Gaafar, 2005).

Experimental Design and Layout

This study is a complement to a previous long-term experiment (LTE) established in early May, 1999 in a six years old *A. senegal* plantation. Its objective was to determine the interaction between trees and field crops, using gum and agricultural crop yields and physiological characteristics as criteria (Gaafar, 2005). The experiment consisted of 27 plots of 20 m x 30 m, established side-by-side with 10 m between plots in either direction. The plots were arranged using a randomized complete block design (RCBD) with three replications. Two densities of *A. senegal* were chosen, which were 16 and 26 trees plot^{-1}, corresponding to 266 trees ha^{-1} and 433 trees ha^{-1} and referred to as low- (LD) and high-density (HD), respectively. Trees in each plot were randomly thinned when appropriate to attain the desired tree density, and the tree spacing ranged between 6 and 8 m. Sorghum (S) *Sorghum bicolor* (L.) Moench, roselle (R) *Hibiscus sabdariffa* L and grass (G) were used as intercropping components with *A. senegal*. Hence, the different combinations of treatments were: HD+S; HD+R; HD+G; LD+S; LD+R; LD+G, pure sorghum (PS); pure roselle (PR) and pure grass (PG).
Sorghum and roselle were sown in pits at the onset of the rainy seasons on 15th of June 2002, 20th of July, 2003 and 18th of July 2004, using a traditional hand hoe. After two weeks from sowing, crops were thinned to two plants per hole with resulting densities of 0.75x0.35m and 0.75x0.25m for sorghum and roselle, respectively. Further, empty gaps were re-sown as necessary and weeds were removed in the same time. Zinc phosphate was applied for rat control and general protection was assured by thorn fencing.

Data Collection and Analysis

Field measurements included soil sampling for determining physical and chemical properties. The biomass and yields considered in this study were:
(1) *Acacia senegal* leaf litter,
(2) gum Arabic,
(3) Sorghum grains and residues,
(4) Roselle calyx, seeds and residues,
(5) Grass aboveground parts, and
(6) Roots biomass from trees, crops and grasses.

Tree Litter, Fine Roots Biomass and Gum yield

The model (ROTATE) estimating the nitrogen budget in the *A. senegal-sorghum bicolor* system during the tree and crop phases for fallow areas (Robertson, 1994) was used to determine nutrient inputs in OM from trees. The model simulated the expected patterns of increases in old (recalcitrant) soil organic N during tree rotations and their decreases under continuous cropping. Adopting this model, the study assumes that the nutrient contribution of *Acacia senegal* through OM is mainly from leaves litter and fine roots (<2 mm). Furthermore, all leaves and fine roots were assumed to have been shed each year after the end of the growing season, and that considerable amounts of nutrients in both of them will be available for plant uptake (Bernhardt-Reversat, 1982).

Tree litter was determined by trays (each of 0.5 m^2) placed under the canopies of three trees (small, medium and large) at 1 m, from the tree trunk in all plots with trees. The litter was collected every two weeks from early June (flush time) to the end of March (end of litter fall). Samples were weighed and kept dry until analysis. The average amount of nutrients accumulated in the litter was estimated by multiplying dry matter by percentage nutrient content; and the total amount of nutrients per plot was obtained by multiplying the average nutrient content of three sampled trees by number of trees in each plot, and then extrapolated to kg ha^{-1}.

Fine root biomass was estimated by a regression equation developed by Deans et al. (1999) which shows a linear relationship between root biomass and the stem cross-sectional area (CSA) at 0.30 m height. Tree diameters in each plot were measured and stratified into three size-classes (small, medium and large) and CSA (in mm^2) of the median diameter was subsequently used to compute fine root biomass per tree, by the equation:

$$Y_{FR} = 23.4 \times CSA^{0.512} \qquad r^2 = 0.80 \qquad (1)$$

Where: Y_{FR} is the fine root biomass (g) and; CSA is the tree cross-sectional area (mm^2).

Total fine-root biomass per plot was determined by multiplying the average dry matter per tree by the total number of trees in each plot. These in turn are extrapolated to a per hectare basis to calculate nutrient inputs of the tree-based systems.
Gum Arabic yield was estimated from 5 trees per plot. Some braches are usually tapped on about the 15th of October, and gum harvesting normally commences after 45 days from tapping and the crop collection continues until May (Ballal, 2004). Collected gum was weighed and kept dry for analysis of its nutrient content.

Above- and below ground Biomass of Crops and Grasses

Biomass of sorghum, roselle and grasses in intercropped plots was measured in four quadrants demarcated in each plot, two under tree canopy and two in the open (interspaces). In pure crop plots, five quadrants were demarcated in each plot, in the middle and at the corners. Sorghum and roselle sampling was carried out at harvest (October), and that of grasses was carried out in September at the peak of standing biomass. All plants within each quadrant were cut at the ground level. Sorghum yield was separated into heads and residues (leaves and stems) while roselle yield was separated into capsules; calyx; seeds and residues. Fresh and dry (in an oven at 70℃ for 48 hr) weights of the crop products and biomass were determined and stored for nutrient analysis.
Root biomass of sorghum and roselle was estimated by assuming a root to shoot ratio (R/S) of 0.1 using the formula developed by (Jackson et al., 1996), as follows:

$$Y_R = Y \times 0.1 \quad (2)$$

Where: Y_R is the root biomass and; Y is the total aboveground biomass (residues plus grain yield).

In this study, grasses occur under trees, between trees in plots with *A. senegal* and in sole grass plots. Grouzis and Akpo (1997) found that root to shoot (R/S) ratios for grasses under semi-arid conditions were 1.6 under canopy and 4.0 in the open (interspaces). These ratios were used to calculate grass root biomass, as follows:

$$R_{BO} = 4.0 \times B_{Ag} \quad (3)$$

$$R_{BU} = 1.6 \times B_{Ag} \quad (4)$$

Where: R_{BO} is the root biomass in the open space; R_{BU} is the root biomass under tree canopy and; B_{Ag} is the total aboveground biomass.

Plant Nutrient Analyses

Plant nutrient analyses were undertaken at the Animal Nutrition Laboratory at the El Obeid Agricultural Research Station. Dry samples of trees, crops and grass were ground sieved to 2 mm mesh size and analyzed for nitrogen (N) phosphorus (P), and potassium (K). All chemical analyses were carried out according to the procedures described by Allen et al. (1989): Nitrogen content was estimated by micro-kjeldahl method; P was measured calorimetrically using spectrophotometer (Hitachi V-3300) according the molybdenum blue method; K was determined by flame-emission photometry and OC was determined a combustion analyzer (Vario EL III, CHNOS Elementer, Germany).

Nutrient Balance

The tool used to assess nutrient flows and balances in this study is the nutrient balance model developed by Stoorvogel and Smaling (1990). The model determines net surplus or deficits of nutrients by measuring and summing the input and output flows of resources from a given plot in a given period. The model comprises five inputs and five outputs. The inputs are: mineral fertilizers (IN1); organic manure (IN2); atmospheric deposition (IN3); biological N_2 fixation (IN4) and sedimentation (IN5). The outputs are: harvested product (OUT1); crop residues (OUT2); leaching (OUT3); gaseous losses (OUT4) and erosion (OUT5). In the study area there were no application of inorganic fertilizers (IN1), animal manure (IN2) and irrigation or flooding (IN5), therefore these parameters were not incorporated in the nutrient balances.

Quantification of Nutrient Flows

The nutrient flows and balances were calculated from a combination of three methods:
(1) direct field measurements and laboratory analysis;
(2) environmentally determined parameters which were calculated from appropriate secondary literature sources (Stoorvogel and Smaling, 1990; Herrmann et al., 1996; Khair El Seid, 1997; Ramisch, 1999; Deans et al., 1999) and (3) estimates based on mixtures of off-sites and/or transfer functions. The choice of the transfer functions was based on research by Stoorvogel and Smaling (1990) who calculated nutrient balances for Sub-Saharan Africa. For simplicity, a step-wise approach has been adopted (Smaling and Fresco, 1993), where the differences between inputs and outputs were calculated at the plot level and then standardized to kg ha^{-1}.

Nutrient Inflows and Pathways

The major inflow pathways quantified were: plants OM (IN1); atmospheric deposition (IN2) consisted of dry (IN2a) and wet (IN2b), and biological N_2 fixation (IN3) consisted of symbiotic (IN3a) and non-symbiotic (IN3b).

Atmospheric Deposition (IN2)

Fine soil particles (dust) input was estimated from values found by Herrmann et al. (1996) and Ramisch (1999) in the Sahel region and according to these authors dust carried by wind can contribute up to 3 kg N ha^{-1} yr^{-1}, 1 kg P ha^{-1} yr^{-1} and 15 kg K ha^{-1} yr^{-1}.

Wet deposition by rainfall was estimated by using the regression equations derived by Stoorvogel and Smaling (1990) for sites with low rainfall in Sub-Saharan Africa, as follows:

$$\text{IN 3b (N)} = 0.14 \times \sqrt{RF} \quad (5)$$

$$\text{IN 3b } (P_2O_5) = 0.053 \times \sqrt{RF} \quad (6)$$

$$\text{IN 3b } (K_2O) = 0.11 \times \sqrt{RF} \quad (7)$$

Where: IN3b is the nutrient content in kg ha^{-1} yr^{-1} and; $\sqrt{RF}$ is the square root of rainfall in mm yr^{-1}.

The amounts of daily rainfall during the study period were recorded using rain gauges installed at the experimental site. Total rainfall was 86, 324 and 195 mm during 2002, 2003 and 2004, respectively.

Biological N_2 fixation (IN3)

In the study, two sources of biological N_2 fixation were considered, namely, symbiotic (IN3a) and non-symbiotic (IN3b). Quantification of biological N_2 fixation is controversial and difficult to achieve in these areas due to shortage of moisture, low OM and soil nutrients and poor biological activity (Stoorvogel and Smaling, 1990; Mobbs and Cannell, 1995; Boffa, 1999). Nevertheless, taking all the above into consideration, and given the research site conditions (semi-arid sandy soils of low mineral fertility), symbiotic N_2 fixation (IN3a) by *A. Senegal* was estimated as 30% of the total N uptake in the aboveground biomass (Ballal, 1992) and non-symbiotic (IN3b) N_2 fixation was taken as 3 kg N $ha^{-1}yr^{-1}$.

Output flows and Pathways

The major outflow pathways quantified were crop products (OUT1), crop residues (OUT 2), leaching (OUT 3), gaseous losses (OUT4) and wind erosion (OUT 5).

Crop Products (OUT1)

Crop products comprise of sorghum grains (OUT1a), roselle calyces and seeds (OUT 1b) and gum Arabic (OUT1c). Nutrients removal in this pathway was quantified by multiplying dry matter by nutrients concentrations (Table 2) using the formula developed by Stoorvogel and Smaling (1990) as:

$$\text{OUT 1} = \text{nutrient content (\%)} \times \text{crop products (kg ha}^{-1}) \quad (8)$$

Where: OUT1 is the total dry matter (kg ha^{-1}) outflows.

The concentrations of N and K in gum Arabic (OUT1c) were estimated based on Karamalla et al. (1998). The authors estimated values from 0.34 to 0.38% for N and from 0.032 to 0.044% for K. In this analysis, mean values of 0.36% and 0.038% for N and K were used. No data available for specific values of P in gum Arabic hence this was excluded from the analysis.

Crop Residues (OUT2)

Crop residues were comprised of sorghum stover (OUT 2a), roselle stover (OUT 2b), and aboveground biomass of grass (OUT 2c). Removal of nutrients in these pathways was quantified by using equation (8).

Leaching (OUT3)

Given the sandy characteristics of the soil at the research site, leaching is a significant loss mechanism for N and K. Since there were no available data on leaching in the study area, transfer functions derived by Stoorvogel and Smaling (1990) for Sub-Saharan Africa were used. These transfer functions incorporate rainfall, soil texture (clay content), soil N and application of fertilizer and organic manure in regression equations for leaching (OUT3), as follows:

$$(Nl) = 2.3 + (0.0021 + 0.0007 \times F) \times R + 0.3 \times (IN\ 1 + IN2) - 0.1 \times UN \quad (9)$$

$$(K_2O) = 0.6 + (0.0011 + 0.002 \times F) \times R + 0.5 \times (IN1 + IN2) - 0.1 \times UK \quad (10)$$

where: (Nl) is the amount of leached nitrogen (kg ha^{-1}); (K_2O) is the amount of leached potassium (kg ha^{-1}); F is soil fertility class (1 = low, 2 = moderate, 3 = high); R is the rainfall (mm); IN1 is inorganic fertilizers (kg ha^{-1} yr^{-1}); IN2 is organic fertilizer (kg ha^{-1} yr^{-1}); UN is the total nitrogen uptake (kg ha^{-1} yr^{-1}) and; UK is the total potassium uptake (kg ha^{-1} yr^{-1}).

In this study, however, it was assumed that the soils of the study area have low fertility (F = 1) and IN1 and IN2 equaled to zero. Also, it was assumed that leaching occurs only in plots with pure crops, based on the evidence that trees reduce nutrient leaching and form a “safety net” under the root zone of annual crops and are able to lessen nutrient leaching in comparison to pure crops (Van Noordwijk and Hairiah, 2000). Also, trees are able to mobilize nutrients from the sub-soil and return them to the topsoil making them available for annual crops (Buresh and Tian, 1998).

Gaseous Losses (OUT 4)

The main sources of gaseous N losses are volatilization of ammonia, burning and de-nitrification. Volatilization is generally recognized as negligible in cultivated fields with highly-weathered acidic soils in east Africa. Therefore, gaseous losses through volatilization were not considered important as soils of the study site is not alkaline (pH=7.4). In the study area, crop residue is used intensively as feed in the field. Therefore, N losses through burning were assumed to be negligible. De-nitrification was considered to be an important process through which gases are lost in the study site. Since, there is no quantitative information available on de-nitrification within the research site or comparable sites, N losses through de-nitrification were estimated using a transfer function derived by Stoorvogel and Smaling (1990). The authors derived multiple regression equations for OUT4 using the generally accepted determinants of rainfall, soil texture (clay content), soil N and application of fertilizer and organic manure as:

$$N_d = (N_s + N_f) \times (-9.4 + 0.13 \times C\% + 0.01 \times P) \quad (11)$$

Where: N_d is N losses through de-nitrification (kg $ha^{-1}yr^{-1}$), N_s is mineralizable N in the upper 0.3 m soil profile, N_f is mineral or organic fertilizer (kg $ha^{-1}yr^{-1}$), $C\%$ is soil clay content in the upper 0.3 m soil profile, P is the mean annual precipitation (mm).

Since, there was no application of inorganic fertilizer or manure in the study site the value of N_f in this equation equal to zero.

Soil Erosion (OUT 5)

The soils of the study site have high water infiltration rates (6.0 mm $min.^{-1}$) with no surface run-off (Gaafar, 2005), thus only wind erosion was accounted for in this study. Values of soil erosion losses by wind on the site were taken from Khair El Seid (1998) who assessed soil erosion losses by wind on the site and found that amounts of soil exported were about: 15.4 and 0.2 tons ha^{-1} yr^{-1} from bare soils and grass fallow, respectively. The estimated contents of OC, N, P and K in the eroded soil were 3%, 0.05%, 0.02%, and 0.05%, respectively.

Nutrient Depletion

Nutrient depletion under the different LMS was obtained by relating nutrient balances in 2004 to soil nutrient stocks obtained in June, 2002 for the top 0.3 m of soil before conducting this experiment.

Data Analysis

The final data for all treatments was subject to analysis of variance (ANOVA) (Gomez and Gomez, 1984) across years to determine the effects of LMS, cropping seasons and their interactions on studied nutrients inputs, outputs and balances. Data were analyzed using the JMP (3.2.3) statistical software program by SAS Institute Inc. (SAS, 1995). Treatment means were separated using Turkey-Kramer Honestly Significant Differences (HSD) at $P \leq 0.05$. Finally, the change (gains or losses) in soil nutrients stocks after three cropping seasons was determined by obtaining the difference between soil nutrient stocks in 2002 and the final nutrient balances in 2004 for the LMS to determine soil nutrient depletion.

RESULTS

3.1 Yields, Biomass and Nutrient Concentrations in Plants Tissues

The highest overall inputs as OM were in the tree-based systems, which ranged from 6.7 t ha^{-1} in HD+G to 3.7 t ha^{-1} in LD+R, and the lowest inputs were pure crops or grass (Table 1). Pure grass inputs exceeded those in PS and PR by 2.5 and 4.4 folds, respectively. Interestingly, the average root biomass input in pure grass and crop systems were: 938.7 t ha^{-1} in PG, 358.7 t ha^{-1} in PS and 245 t ha^{-1} in PR. The order of inputs season-wise was: season 2004 > season 2003 > season 2002.

The highest exports were from sorghum-based systems whether pure or intercropped, followed roselle-based and then grass-based systems (Table 1). Tree contribution in biomass exports, as gum Arabic, was minimal and accounted only for 179 t ha^{-1}. The average exports in crop yields or grass cuttings were: 1794.8, 1290.7 and 465.7 t ha^{-1} for sorghum, roselle and grass, respectively. Biomass exports through seasonal harvesting were highest in season 2003 followed by 2004 and then 2002. Nutrients concentrations in dry matter (dry weight) in trees leaves and fine roots, crop products, residues, grasses and other pathways designated as inputs and output sources, were presented in (Table 2).

Nutrient Flows and Pathways

Nutrient Flows at LMS Levels

Nutrient inflows and outflows and the percentage contribution (in parenthesis) of the different pathways for OC, N, P and K in LMS over the three cropping seasons are shown in Tables 3, 4, 5 and 6, respectively. Generally, all the inflows and outflows of the measured nutrients were significantly ($P \leq 0.001$) affected by the LMS. Overall, the highest OC inflows were in intercropped systems and the lowest were in pure crops. Among the intercropped systems, OC inflows were higher in systems at HD than in LD. No significant ($P \leq 0.05$) differences between pure sorghum and pure roselle (PS=PR) were found, but pure grasses had significantly higher OC inflows (Table 3). Organic carbon outflows were highest in PS than in PR and PG. There were no significant ($P \leq 0.05$) differences in OC outflows between either systems of roselle and grass.

Nitrogen inflows were higher in inter cropped than in pure cropped systems. Within the intercropped systems, higher N inflows were found in sorghum and roselle at HD (Table 4). For pure crops, N inflows were very low and were not significantly ($P \leq 0.05$) different. Nitrogen outflows were higher in sorghum and roselle systems than in grass systems. However, there were no significant differences in outflows between sorghum and roselle systems; but comparatively N outflows in roselle were higher than in sorghum. In pure roselle and sorghum, N outflows were significantly ($P \leq 0.001$) higher than in pure grass. Nitrogen outflows in grass systems, whether pure or combined with trees, were low and were not significantly different between them.

Phosphorous inflows were significantly ($P \leq 0.001$) higher in intercropped systems than pure crops (Table 5). For intercropped systems the highest inflows were in systems at HD. Overall, all roselle systems had the highest P outflows compared to sorghum systems and the lowest were grass systems, averaging to only 1 kg ha^{-1} yr^{-1}.

Potassium inflows and outflows were significantly ($P \leq 0.001$) higher in intercropped than pure crops (Table 6). Overall, among systems, K inflows were higher in intercropped at HD. Intercropped roselle systems had significantly higher K outflows compared to other systems; K outflows in the grass systems were low and were not significantly different them (Table 6).

Nutrient Flows at Cropping Season's Levels

The effects of cropping seasons on nutrients inflows were significant ($P \leq 0.05$) for OC, but not significant ($P \leq 0.05$) for N, P and K (Fig.1a-d). Overall, inflows were higher in the second season (2003) than in the first and third seasons.

Table1. Means of dry biomass (kg ha^{-1}) in trees, crop products, crop residues, and grasses designated as inputs and output sources at land management systems and cropping season levels at El Demokeya Research Site, North Kordofan, Sudan, (combined for 3 cropping seasons, n=3)

Nutrient pathways	Land management systems •									Cropping seasons		
	HD+S	LDS+S	PS	HD+G	LD+G	PG	HD+R	LD+R	PR	2002	2003	2004
Inputs												
Tree litter & fine roots	5 900	3 977	-	5 645	4 196	-	6 183	3 449	-	3 542	4 004	3 780
Grass roots	-	-	-	1 041	810	965	-	-	-	820	1 054	942
Sorghum roots	312	391	373	-	-	-	-	-	-	0	718	7 179
Roselle roots	-	-	-	-	-	-	276	240	220	24	455	257
Total inputs	6 212	4 367	373	6 685	5 006	965	6 460	3 690	220	844	2 227	8 378
Outputs												
Sorghum grain	208	286	233	-	-	-	-	-	-	-	484	242
Sorghum stover	2 917	3 625	3 500	-	-	-	-	-	-	-	6 694	3 347
Roselle seed/calyx	-	-	-	-	-	-	630	600	516	109	991	384
Roselle stover	-	-	-	-	-	-	2408	2112	1478	130	3 556	2 191
Grass shoots	-	-	-	650	506	241	-	-	-	414	507	476
Gum Arabic	217	125	-	212	130	-	208	184	-	208	210	163
Total Outputs •	3 125	3 911	3 733	650	506	241	3 038	2 712	1 994	681	12 442	6 803

• HD and LD denote 433 and 266 tree ha^{-1}, R, S and G denotes roselle, sorghum and Grass; P denotes pure crop.

Table2. Nutrients concentrations in dry matter (dry weight) in trees leaves and fine roots, crop products, residues, grasses and other pathways designated as inputs and output sources at El Demokeya Research Site, North Kordofan, Sudan

Nutrients pathways	**Nutrients concentrations****			
Inputs	OC [a]	N	P	K
Tree leaves biomass (%)	50	4.46	0.17	1.40
Tree fine roots (%)	50	1.70	0.07	0.21
Grass roots (%)	50	0.20	0.20	0.83
Sorghum roots (%)	50	1.31	0.08	0.37
Roselle roots (%)	50	1.04	0.10	1.50
Dry deposition (kg ha^{-1})	Na	3.0	1.0	15.5
Wet deposition (kg ha^{-1}) [b]	-			
First seasn (2002)	Na	1.29	0.49	1.01
Second season (2003)	Na	2.52	0.95	1.98
Third season (2004)	Na	1.95	0.74	1.54
Symbiotic N_2 fixation (kg $ha^{-1}yr^{-1}$)	Na	15	Na	Na
Non-symbiotic N_2 fixation (kg $ha^{-1}yr^{-1}$)	Na	3.0	Na	Na
Outputs				
Gum Arabic (%)	Na	0.36	Na	0.04
Sorghum Grain (%)	50	2.04	0.35	0.39
Sorghum stover (%)	50	1.26	0.32	1.4
Roselle Calyx (%)	50	0.30	0.57	1.20
Roselle Seeds (%)	50	3.86	0.6	7.0
Roselle stover (%)	50	1.92	1.3	1.6
Grass shoot (%)	50	0.72	0.2	1.5
Leaching under Pure sorghum (kg ha^{-1})	Na	1.5	1.0	16.0
Leaching under Pure Roselle (kg ha^{-1})	Na	7.0	1.0	16.0
Concentrations in eroded soils (%) [c]	3.0	0.05	0.02	0.05

a Assumed organic carbon in all plant biomass was 50% of total dry matter (kg), b Transfer function for N is $0.14\sqrt{R}$, for P is $0.053\sqrt{R}$, and for K is $0.11\sqrt{R}$; R is the annual rainfall; c the amounts of eroded soils estimated as 14500 kg ha^{-1} on bare soils, and 200 kg ha^{-1} on grass fallow. Na denotes not applicable. ** Concentrations are average of three seasons

The outflows of studied nutrients were significantly ($P \leq 0.001$) higher in the second and the third seasons than for the first season.

The interaction between LMS and cropping seasons on the inflows of OC, N, P and K were not significant ($P \leq 0.05$), but there were tendencies for higher inflows for intercropped systems at HD in the second and the third seasons. By contrast, the interaction effects on the outflows (Fig. 2a-d) were highly significant ($P \leq 0.001$) for OC, P, N and K. Generally, the outflows were significantly higher in all LMS in the second season (2003).

Table3. Organic carbon inputs, outputs flows and balances (kg $ha^{-1}yr^{-1}$), main pathways and balances for the different land management systems over three cropping seasons (2002-2004) at El Demokeya Research site, North Kordofan, Sudan

Nutrients pathways		Land Management Systems•								
		HD+S	LD+S	PS	HD+G	LD+G	PG	HD+R	LD+R	PR
Code†	Inputs									
IN 2a	Tree (OM)	2 950 (91)	1 988(95)	-	2 822 (84)	2 098 (84)	-	3 092 (96)	1 725 (93)	-
IN 2b	Grass roots	-	-	-	325(16)	253(16)	483 (100)	-	-	-
IN 2c	Sorghum roots	156 (9)	196 (5)	187 (100)	-	-	-	-	-	-
IN 2d	Roselle roots	-	-	-	-	-	-	138 (4)	120 (7)	110 (100)
	Total Inputs [a]	3 106 b	2 184 d	187 g	3 342 a	2 503 c	483 f	3 230 ab	1 845 e	110 g
	SE	*87.1****								
	Outputs									
Out 1a	Sorghum grain	104 (7)	143 (7)	116 (5)	-	-	-	-	-	-
Out 2a	Sorghum stover	1 458(93)	1 813(93)	1 750 (75)	-	-	-	-	-	-
Out 1b	Roselle seed/calyx	-	-	-	-	-	-	315 (22)	300 (22)	258 (18)
Out 2b	Roselle stover	-	-	-	-	-	-	1 204 (78)	1 056 (78)	739 (51)
Out 2c	Grass shoots	-	-	-	325 (100)	253 (100)	127 (100)	-	-	-
Out 3	Erosion	-	-	462(20)	-	-	6	-	-	462(31)
	Total Outputs [a]	1 562 c	1 956 b	2 328 a	325 d	253 d	127 d	1 519 c	1 356 c	1 459 c
	SE	*145.5****								
	Balance	1 544 c	228 e	-2142 g	3 017 a	2 250 b	356 de	1 771 c	489 d	-1 349 f
	SE	*155.7****								

•Means followed by the same letter(s) in the same row are not significantly different at the 5% level, according to Tukey-Kramer Honestly Significant Differences (HSD). *** denotes significant at P≤0.001. Numbers in parenthesis indicate % contribution of pathways to nutrient flows relative to total. HD and LD denote 433 and 266 tree ha^{-1}; R, S and G denote roselle, sorghum and Grass, respectively; P denotes pure crop

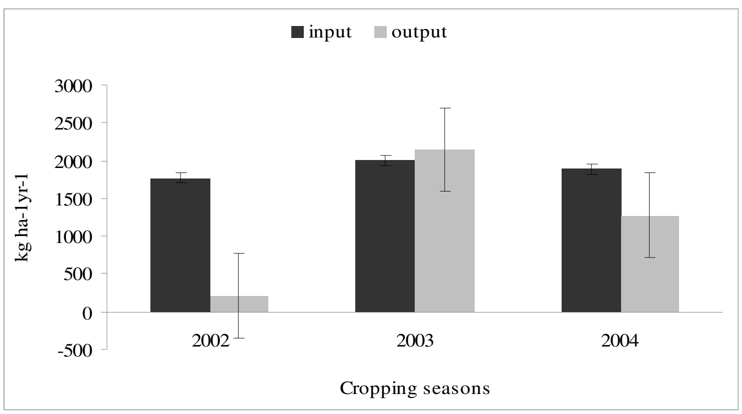

Figure1a. Effects of cropping seasons on nutrient input and outputs (Organic carbon)

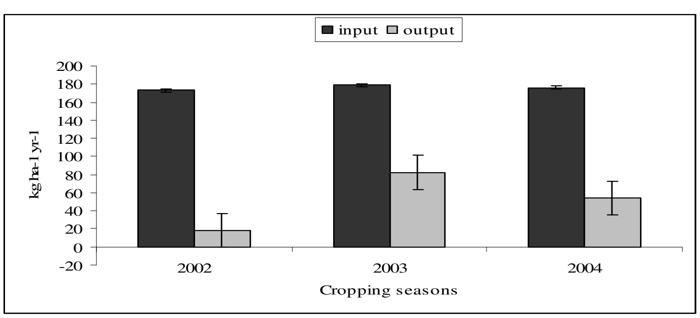

Figure1b. Effects of cropping seasons on nutrient input and outputs (Nitrogen)

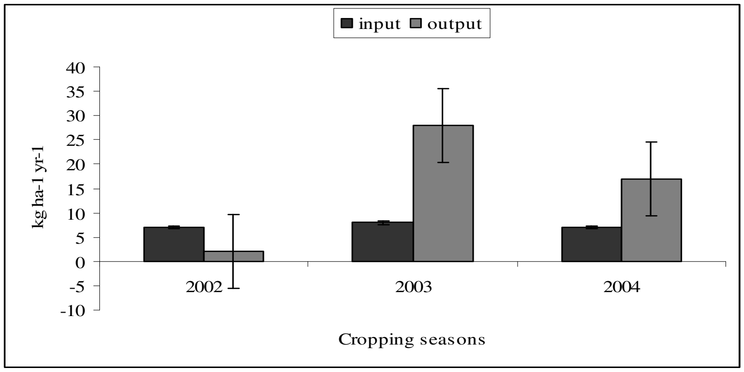

Figure1c. Effects of cropping seasons on nutrient input and outputs (Phosphorous)

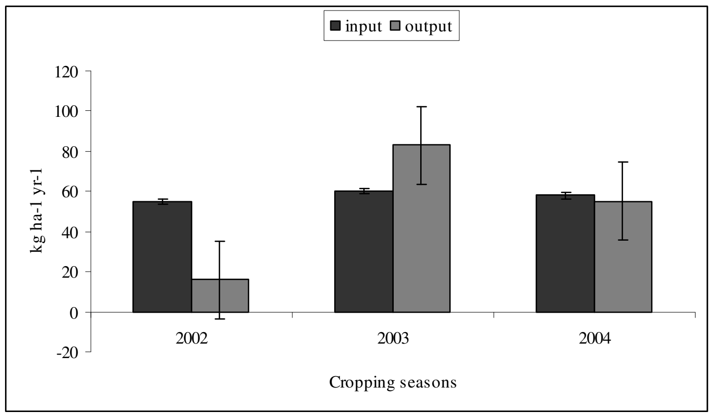

Figure1d. Effects of cropping seasons on nutrient input and outputs (Potassium)

Table4. Nitrogen inputs and outputs flows (kg $ha^{-1}yr^{-1}$), main pathways and balances for the different land management systems over three cropping seasons (2002-2004) at EL Demokeya Research Site, North Kordofan, Sudan

Nutrients pathways		**Land Management Systems•**								
		HD+S	LD+S	PS	HD+G	LD+G	PG	HD+R	LD+R	PR
Code†	Inputs									
IN2a	Tree OM	268 (86)	182 (85)	-	256 (86)	193 (87)	-	282 (86)	156 (84)	-
IN2b	Grass roots	-	-	-	2 (1)	2 (1)	2 (20)	-	-	-
IN2c	Sorghum roots	4 (1)	5 (2)	5 (38)	-	-	-	-	-	-
IN2c	Roselle roots	-	-	-	-	-	-	3 (1)	3 (1)	2 (20)
IN3a	Dry deposition	3 (1)	3 (1)	3 (23)	3 (2)	3 (2)	3 (30)	3 (1)	3(1)	3 (30)
IN3b	Wet Deposition	2 (1)	2 (1)	2 (16)	2 (1)	2 (1)	2 (20)	2 (1)	2 (1)	2 (20)
IN4a	Non-symbiotic N	3 (1)	3.0	3 (23)	3 (2)	3 (2)	3 (30)	3 (1)	3 (1)	3 (30)
IN4b	Symbiotic N	32 (10)	19 (10)	0	32 (9)	19 (7)	0	32 (10)	19(10)	-
	Total Inputs [a]	312 a	215 c	13 e	298 b	222 c	10 e	325 a	186 d	10 e
	SE	*8.6****								
	Outputs									
Out1a	Sorghum grain	4 (7)	6 (9)	5 (7)	-	-	-	-	-	-
Out2a	Sorghum stover	37 (65)	46 (70)	44 (66)	-	-	-	-	-	-
Out1b	Roselle seed/calyx	-	-	-	-	-	-	19 (23)	21 (28)	10 (16)
Out2b	Roselle stover	-	-	-	-	-	-	45 (55)	35 (47)	31 (51)
Out2c	Grass shoots	-	-	-	5 (28)	4 (24)	2 (15)	-	-	-
Out1c	Gum Arabic	1 (2)	0.4	-	1 (6)	1 (6)	-	1 (1)	1 (1)	-
Out3	Leaching	2 (4)	2 (3)	3 (4)	-	-	1 (8)	5 (6)	5 (7)	5 (8)
Out4	Erosion	-	-	8 (12)	-	-	0	-	-	8 (13)
Out5	Gaseous N	12 (21)	12 (18)	8 (12)	12 (66)	12 (71)	10 (77)	12 (15)	12 (16)	7 (11)
	Total Outputs [a]	57 a	66 a	67 a	18 b	17 b	13 c	82 a	74 a	61 a
	SE	*4.84****								
	Balance	255 a	149 b	-54 bc	280 a	204 ab	-3 d	243 a	112 c	-51 c
	SE	*9.51****								

• Means followed by the same letter (s) in the same row are not significantly different at the 5% level, according to Tukey-Kramer Honestly Significant Differences (HSD). *** denotes significant at $P \leq 0.001$. Numbers in parenthesis indicate % contribution of pathways to nutrient flows relative to total. HD and LD denote 433 and 266 tree ha^{-1}; R, S and G denote roselle, sorghum and Grass, respectively; P denotes pure crop

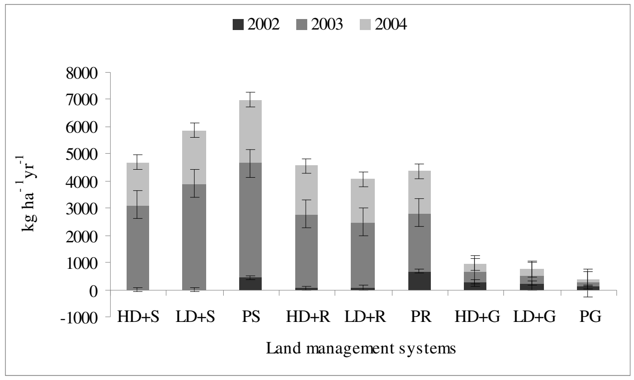

Figure2a. Interaction effects of LMS and cropping seasons on nutrients outflows (Organic carbon)

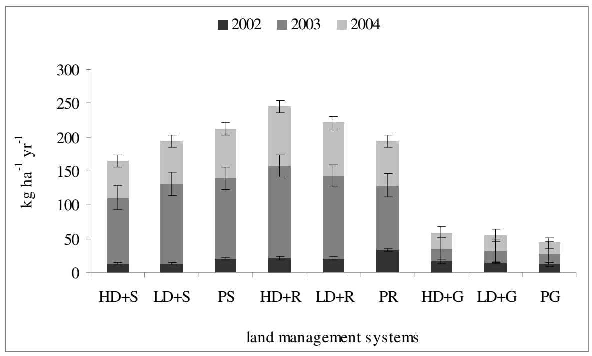

Figure2b. Interaction effects of LMS and cropping seasons on nutrients outflows (Nitrogen)

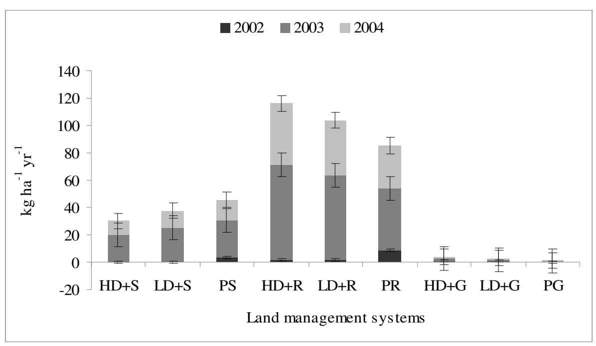

Figure2c. Interaction effects of LMS and cropping seasons on nutrients outflows (Phosphorous)

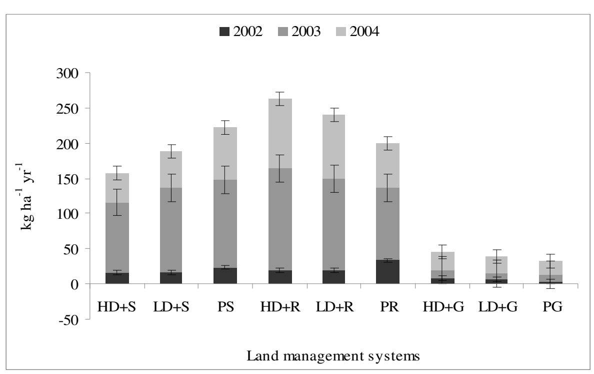

Figure2c. Interaction effects of LMS and cropping seasons on nutrients outflows (Potassium)

Table5. Phosphorous inputs and outputs flows (kg $ha^{-1}yr^{-1}$), main pathways and balances for the different land management systems over three cropping seasons (2002-2004) at EL Demokeya Research Site, North Kordofan, Sudan

Nutrients Pathways		**Land Management Systems•**								
Code†	Inputs	HD+S	LD+S	PS	HD+G	LD+G	PG	HD+R	LD+R	PR
IN2a	Tree OM	9 (84)	6 (76)	-	8 (67)	6 (61)	-	9 (82)	5 (71)	-
IN2b	Grass roots	-	-	-	2 (18)	2 (20)	2 (55)	-	-	-
IN2c	Sorghum roots	0.3 (2)	0.3 (4)	0.3 (16)	-	-	-	-	-	-
IN2c	Roselle roots	-	-	-	-	-	-	0.3 (3)	0.2 (4)	0.2 (12)
IN3a	Dry deposition	1 (8)	1.0 (13)	1 (50)	1 (10)	1 (12)	1 (26)	1 (9)	1 (14)	1 (53)
IN3b	Wet Deposition	1 (6)	1(9)	1 (34)	1 (6)	1 (7)	1 (19)	1 (6)	1 (10)	1 (35)
	Total Inputs [a]	11 b	8 d	2 g	12 a	10 c	4 f	11b	7 e	2 g
	SE	*0.3****								
	Outputs									
Out1a	Sorghum grain	1 (7)	1 (8)	1 (4)	-	-	-	-	-	-
Out2a	Sorghum stover	9 (93)	12 (92)	11 (75)	-	-	-	-	-	-
Out1b	Roselle seed/calyx	-	-	-	-	-	-	4 (11)	4 (12)	3 (11)
Out2b	Roselle stover	-	-	-	-	-	-	31 (89)	27 (88)	19 (78)
Out2c	Grass shoots	-	-	-	1 (100)	1(100)	1 (100)	-	-	-
Out 3	Erosion	-	-	3 (21)	-	-	-	-	-	3 (11)
	Total Outputs [a]	10 e	13 de	15 d	1 f	1 f	1 f	35 a	31 b	25 c
	SE	*2.5****								
	Balance	1 b	-5 c	-13 d	11 a	9 a	3 b	-24 e	-24 e	-24 e
	SE	*2.5****								

•Means followed by the same letter (s) in the same row are not significantly different at the 5% level, according to Tukey-Kramer Honestly Significant Differences (HSD). *** denotes significant at P≤0.001. Numbers in parenthesis indicate % contribution of pathways to nutrient flows relative to total. HD and LD denote 433 and 266 tree ha^{-1}; R, S and G denote roselle, sorghum and Grass, respectively; P denotes pure crop

Table6. Potassium inputs and outputs flows (kg $ha^{-1}yr^{-1}$) and main pathways for the different land management systems over three cropping seasons (2002-2004) at EL Demokeya Research Site, North Kordofan, Sudan

Nutrients pathways		**Land Management systems•**								
Code†	Inputs	HD+S	LD+S	PS	HD+G	LD+G	PG	HD+R	LD+R	PR
IN2a	Tree OM	66 (78)	45 (72)	-	63 (71)	48 (67)	0	70 (77)	39 (64)	-
IN2b	Grass roots	-	0	-	9 (10)	7 (10)	8 (32)	-	-	-
IN2c	Sorghum roots	1 (1)	1 (1)	1 (8)	-	-	-	-	-	-
IN2d	Roselle roots	-	-	-	-	-	-	4 (5)	4 (7)	3 (13)
IN3a	Dry deposition	15 (18)	15 (24)	15 (83)	15 (17)	15(21)	15(60)	15 (16)	15(25)	15(75)
IN3b	Wet Deposition	2 (3)	2 (3)	2 (11)	2 (2)	2 (2)	2 (8)	2 (2)	2 (4)	2 (12)
	Total Inputs	85 b	63 d	18 f	89 a	72 c	25 e	91 a	60 d	20 f
	SE	*2.2****								
	Outputs									
Out1a	Sorghum grain	1 (2)	1 (2)	1 (1)	-	-	-	-	-	-
Out2a	Sorghum stover	41 (78)	51 (80)	49 (67)	-	-	-	-	-	-
Out1b	Roselle seed/calyx	-	-	-	-	-	-	33 (37)	30 (37)	23 (34)
Out2b	Roselle stover	-	-	-	-	-	-	39 (44)	34 (43)	24 (35)
Out2c	Gum Arabic [a]	0.1	0.1	0	0.1	0.1	-	0.1	0.1	0
Out2d	Grass shoots	0	0	0	10 (67)	8 (57)	4 (33)	0	0	0
Out3	Leaching	11 (20)	11 (18)	16 (21)	5 (33)	6 (43)	7 (58)	16 (18)	16 (20)	12 (19)
Out4	Erosion	-	-	8 (11)	-	-	1 (9)	-	-	8 (12)
	Total Outputs	53 e	63 d	74 bc	15 f	14 f	12 f	88 a	80 ab	67 cd
	SE	*5.5****								
	Balance	32 c	0 e	-56 h	74 a	58 b	13 d	3 e	-20 f	-47 g
	SE	*5.5****								

• Means followed by the same letter (s) in the same row are not significantly different at the 5% level, according to Turkeys mean Separations. *** denotes significant at P≤0.001. Numbers in parenthesis indicate % contribution of pathways to nutrient flows relative to total. HD and LD denote 433 and 266 tree ha^{-1}; R, S and G denote roselle, sorghum and Grass, respectively; P denotes pure crop. [a] Gum outputs are less than 1 kg ha^{-1}

Nutrient Balances

Nutrient Balances at LMS Levels

The balances for OC, N, P and K were significantly (P≤ 0.001) affected by LMS. Overall, OC balances were (Table 3) positive for all intercropped systems irrespective of crop types and tree density. Nevertheless, the balances were higher in systems at HD than for LD, but the highest were in intercropped grass systems. In pure systems, OC balances were positive for PG, but negative for PS and PR. Nitrogen balances (Table 4) were positive in intercropped and negative in pure crops. For intercropped systems, higher positive balances were in systems at HD than LD. For pure crop systems, higher negative balances were in PR and PS than PG. Phosphorous balances (Table 5) were negative in all roselle systems with almost equal amounts (-24 kg ha^{-1} yr^{-1}). In sorghum systems, P balances were positive in HD+S, negative in LD+S and PS. All grass systems had positive balances. Potassium balances (Table 6) were negative in PS, PR and roselle at LD; positive in roselle and sorghum at HD and neutral in sorghum at LD. All grass systems had positive K balances.

Nutrient Balances at Cropping Season Levels

Nutrient balances were significantly (P ≤ 0.001) different among cropping seasons (Fig.3a and 3b). Balances for each individual nutrient showed diverse patterns. Balances of OC were positive in the first and the third season and negative in the second season. For N, balances were positive for three seasons but the lowest were found in the second season. Phosphorus balances were positive in the first season, but negative in the second and the third seasons. Potassium balances were positive in the first and the third seasons, but negative in the second season.

The interactions between LMS and cropping seasons on nutrient balances were highly significant (P ≤ 0.001) for OC (Figure 4a), N (Figure 4b), P (Figure 4c) and K (Figure 4d). Nitrogen had positive balances in the three seasons, but OC, P and K balances showed inconsistent patterns among the intercropped systems. Balances of OC, P, and K were positive in the first and the third seasons. In the second season, balances of OC were positive, while those of P and K were negative. For sorghum at LD, balances of OC were positive in the first and the third seasons, but negative in the second. Balances of P and K were positive in the first season, but negative in the second and the third seasons. For roselle at HD, balances of OC were positive in the three seasons. For roselle at LD, balances of OC were positive in the first and the second seasons, but negative in the third season. However, for roselle at HD and LD balances of P and K were positive in the first season, but negative in the second and the third season. Balances of OC, N, P and K in pure crop systems were negative in the three seasons, and the highest balances of all occurred in the second season (2003). However, PG had positive balances for OC, P and K, in the three seasons. Generally, in all systems, balances of nutrients in the second season were higher than in the first and third seasons.

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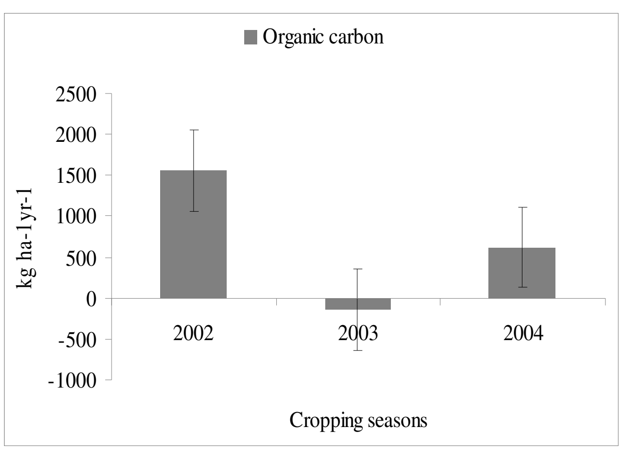

Figure3a. Effects of cropping seasons on balances of OC, N, P, and K (kg ha^{-1} yr^{-1}) (Organic carbon)

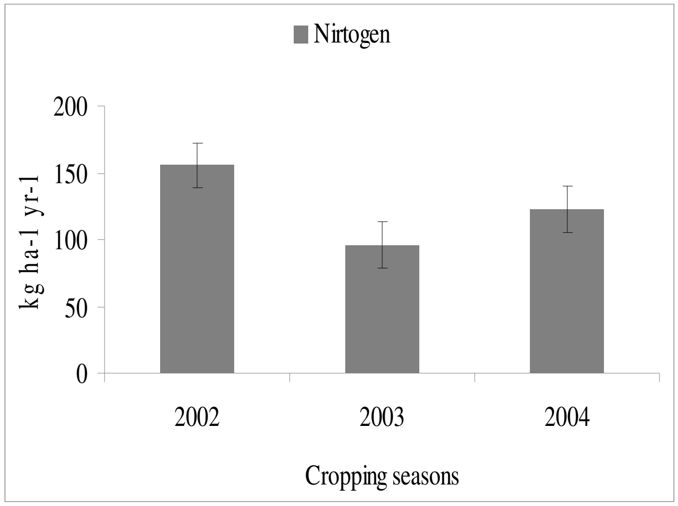

Figure3b. Effects of cropping seasons on balances of OC, N, P, and K (kg ha^{-1} yr^{-1}) (Nitrogen)

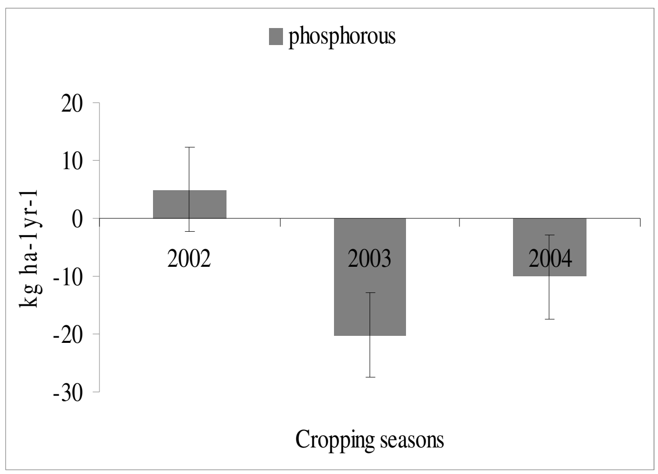

Figure3c. Effects of cropping seasons on balances of OC, N, P, and K (kg ha^{-1} yr^{-1}) (Phosphorous)

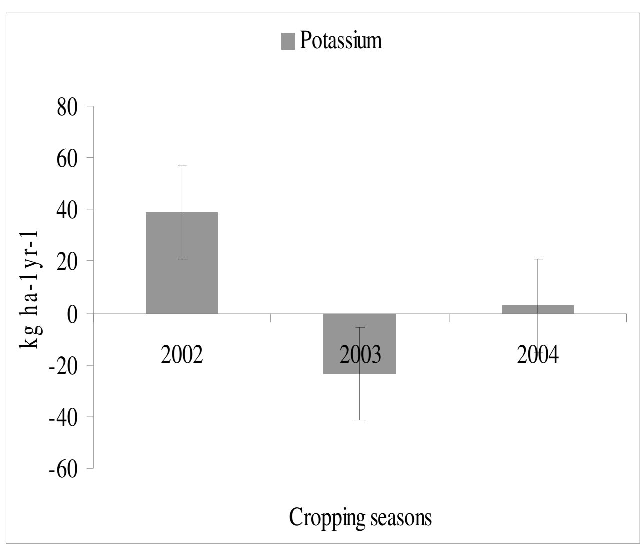

Figure3d. Effects of cropping seasons on balances of OC, N, P, and K (kg ha^{-1} yr^{-1}) (Potassium)

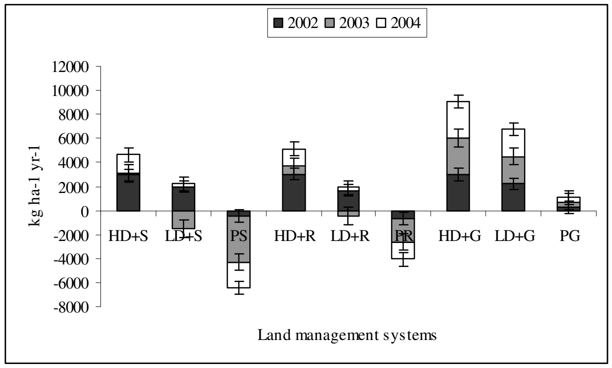

Figure4a. Interaction LMS and Cropping Seasons on balances (Organic carbon)

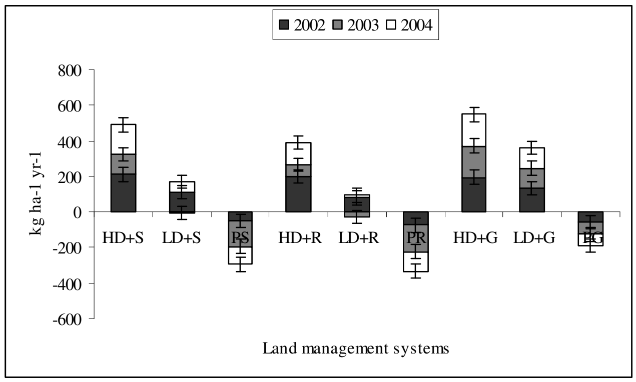

Figure4b. Interaction LMS and Cropping Seasons on balances (Nitrogen)

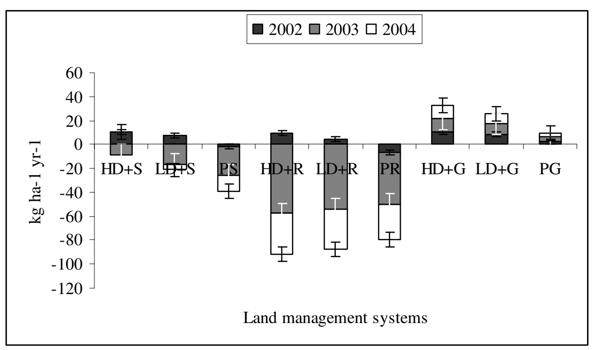

Figure4c. Interaction LMS and Cropping Seasons on balances (Phosphorous)

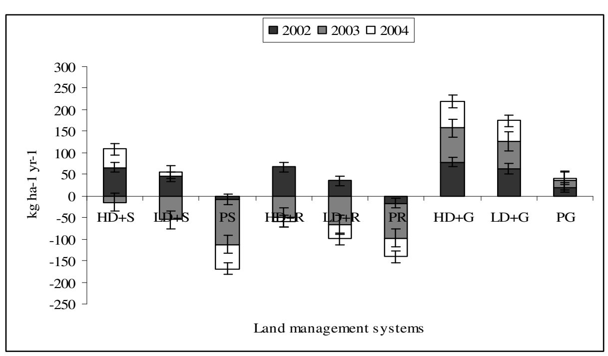

Figure4d. Interaction LMS and Cropping Seasons on balances (Potassium)

Nutrient Depletion

Table 7 shows changes in soil nutrient stocks (June 2002) for OC, N, P and K calculated relative to nutrient balances (June, 2004). Organic carbon, N, P and K were depleted by -49, -10, -130 and -21% in PS, respectively, and by -29, -8, -209 and -20% in PR, respectively. In pure grass, N depletion was neutral. In intercropped systems, the rate depletion for a particular nutrient was variable among and within the systems. However, the stocks of phosphorous were severely mined for inter cropped roselle systems and sorghum at LD.

Table7. Nutrient stocks (in June 2002) of OC, N, P and K at topsoil (0.3 m depth), nutrient balances (2004), and relative gains and losses under land management systems at El Demokeya Research Forest, North Kordofan Sudan

LMS	Stocks (kg ha^{-1}) in June, 2002**				Balances (kg ha^{-1}) in 2004				% depletion of stocks			
	OC	N	P	K	OC	N	P	K	OC	N	P	K
HD +S	4029	921	11	252	1544	255	1	32	38	28	9	13
LD +S	4633	855	12	248	228	149	-5	0	5	17	-42	0
PS	4387	548	10	261	-2142	-54	-13	-56	-49	-10	-130	-21
HD +R	4342	1035	11	244	1711	243	-24	3	39	23	-218	1
LD +R	5101	880	12	257	489	112	-24	-20	10	13	-200	-8
PR	4677	668	11	230	-1349	-51	-23	-47	-29	-8	-209	-20
HD +G	3862	893	11	248	3017	280	11	74	78	31	100	30
LD +G	4732	881	12	283	2250	204	9	58	48	23	75	20
PG	5396	700	12	226	356	-3	3	13	7	0	25	6

LMS: land management systems. HD and LD denote 433 and 266 tree ha^{-1}; R, S and G denote roselle, sorghum and Grass, respectively; P denotes pure crop

DISCUSSION

Nutrient flows and balances at lms levels

Organic Carbon

Organic carbon inflows were appreciably higher in all intercropped systems irrespective of tree density compared to pure crops. This could be attributed to high OM inputs from tree biomass. This pathway accounted for 84%, 93% and 94.5% of the total OC inflows in grass, sorghum and roselle systems, respectively (Table 3). A striking aspect is the overall low import of OC from plant roots of PR and PS compared to that of PG. The low inputs from root system in sorghum could be attributed to absence of root biomass due to crop failure in the first season (2002). For roselle could be due to poor growth and low yields in the same season. Root systems are primarily a pool of OC (Jackson et al., 1996), but their contribution to OC inflow is controlled by plant growth (photosynthesis), climatic (CO_2 uptake) and soil conditions (Elberling et al., 2003). Generally, OC outflows were significantly higher in sorghum systems than for roselle and grass systems (Table 3). Since we used the same concentrations (50%) to estimate OC in tissues of crops and grass, the differences in outflows among and within systems could be ascribed to differences in the amounts of harvest exports. This is evident from the larger dry weight biomass produced by sorghum systems compared to roselle and grass systems (Table 1).

The results showed that OC balances were negative in PS and PR. This is likely due to larger biomass exports and minimal import from roots and other pathways. Generally, a large body of literature emphasizes that much of the loss of soil organic carbon (SOC) under pure crop cultivation can be attributed to reduced inputs of OM, increased decomposability of crop residues and tillage effects that reduce the amount of physical protection to decomposition (Juo et al., 1995; Masse et al., 2004). In contrast to pure cropping, all intercropped systems showed positive OC balances and the highest were in grass systems (Table 3). High positive balances in grass systems could be ascribed to high OM inputs from trees and minimal exports in the form of aboveground biomass. This result agrees with Ardö and Olsson (2003) who found that in low-input subsistence agro-ecosystems in the semi-arid sandy soils in North Kordofan cropland and grass fallow decrease SOC by 9.4 and 8.4 kg ha^{-1}yr^{-1}, respectively, while savanna (trees with grass) increases SOC by 7.5 kg ha^{-1} yr^{-1}.

Nitrogen

In this study, nitrogen inputs were mainly from OM in tree leaf litter and roots, grasses and crops roots, atmospheric deposition, and nitrogen fixation. Overall, except OM input from trees the contributions of other pathways were insignificant. The larger N inflows in intercropped systems compared to pure crops, emphasize the crucial role of trees in ameliorating soil fertility and N budgets (Prinsley and Swift, 1994; Buresh and Tian, 1998). The tree component in this study was one of the most important N input pathways.

The contribution of this pathway for inter cropped systems accounted for 95% of the total N inputs, of which 85% as OM and 10% as biological N_2 fixation (Table 4). As expected, N inflows in pure crops were very low because the main pathways were crop roots, atmospheric deposition and non-symbiotic N_2 fixation. The contribution of these pathways to the N budget was insignificant, not only in pure crops, but also in intercropped systems (Table 4).

The significantly higher N outflows in roselle and sorghum systems compared with grass systems could be due to the larger biomass (Table 1) and higher N concentrations in the dry matter of roselle and sorghum yield components (calyces, seeds, grains and stover) that were exported out of these systems. The analysis of nutrient concentrations in crop products showed that sum of N contents in roselle and sorghum yield components were considerably higher than for grass (Table 2). Nitrogen contents were 6.8%, 3.3%, and 0.72%, for roselle, sorghum and grass, respectively. Nitrogen outflows due to gum Arabic were insignificant in all tree-based systems (0.4 to 1.1 kg ha^{-1} yr^{-1}). Gum Arabic contribution to total outputs ranged from 1% to 2% in intercropped sorghum and roselle and about 10% to 17% in tree-grass systems (Table 4). This could partly be due to low concentrations of N in the gum (0.36%) and partly to low yields, which ranged from 125 to 217 kg ha^{-1} yr^{-1}.

The significant differences in N balances between HD and LD intercropped systems indicate the significance of tree density as a major source of nutrient supply. Generally, positive N balances in intercropped systems could result from the large amount of OM and subsequently high rate of decomposition, compared with pure crops (Table 1). The increased rates of mineralization were due to ample supply of readily mineralizable soil organic matter (SOM) from *A. Senegal* plantations. Effectively, N surpluses obtained in this study exceeded 40 kg N ha^{-1} which is considered to be acceptable for agricultural production in most countries (Sanchez and Palm, 1997) and has greater implications on sustainability of tree-based systems. Conversely, negative N balances in pure systems could be due to high exports in crop harvest which was not compensated by inputs, which conforms to results obtained from West African Sahel (Buerkert and Hiernaux, 1998; Krogh, 1997).

Phosphorus

Results from this study showed that there were significantly higher P flows into intercropped systems at HD. The contribution of this pathway to P supply ranged from 76 to 84% in intercropped sorghum, 61 to 67% in grass systems and 71 to 82% in roselle systems. The contribution of plant roots and atmospheric deposition to P inflows in all systems were minimal. Overall, the low P inflows under all systems (Table 5) could be attributed to the intrinsic low soil fertility of the research site, as it is the case of all tropical drylands soils which are deficient or have low phosphorous content (Palm, 1995).

The main loss pathways for P in agro-ecosystems are crop products, crop residues and soil erosion (Sanchez and Palm, 1997). In the present study, these are the most serious loss pathways for P in all LMS. Amongst systems, mean P outflows were highest for roselle, intermediate in sorghum and lowest in grass systems. These differences could be attributed to dissimilarities in P uptake by the different crops. In intercropped roselle systems, P removed in stover accounted for 88 to 89% and that in products (in calyces plus seeds) accounted for 11 to 22%. Whereas, in PR about 76% was removed in stover, 12% in calyces plus seeds, and the remaining 12% by soil erosion. For intercropped sorghum systems, about 92% of P outflows were removed in stover and only 8% in grains. Whilst in PS about 74% were removed in stover, 5% in grains and 20% by erosion.

Phosphorus balances were highly negative in roselle systems at studied tree densities compared to sorghum. The significantly negative balances in roselle systems relative to sorghum could be due to high uptake and immobilization in roselle yield components. In fact P was found to be a basic constituent in all roselle tissue composition (Abdel Bagi et al., 2002). The authors found that P is accumulated in roselle calyces and significantly increases their citric acid, protein, anthocyanin and oxalate and also increases oil contents of the seeds. In this study, P concentrations in calyces and seeds were higher than those in sorghum grains (Table 2). Generally, however, negative P balances for intercropped systems could be due to very low soil P contents of the study site, which is typical for semi-arid drylands that are deficient in P. The positive P balances in grass systems could be due to minimal export of grass from the site (Table 5). In general, a reduction in labile P has been closely associated with SOM losses. Phosphorous is often the critical nutrient in agroforestry and other low external-input systems (Sanchez and Palm, 1997). In agroforestry systems trees cannot supply most of the required P for crops, hence, external sources of P from organic manure and inorganic fertilizers are required to equilibrate the balances (Palm, 1995; Sanchez and Palm, 1997; Buresh and Tian, 1998).

Potassium

Major sources of K inflows were OM from trees, crops and grass roots, and atmospheric deposition. The results showed that the highest K inflows were in intercropped systems at HD and the lowest were in pure crops. Since all systems had received the same amount of K inputs from atmospheric deposition, variations in K inflows could be attributed to dissimilarities in the amounts of OM and the element concentrations in trees and crop roots.

Potassium outflows were significantly higher in intercropped roselle systems compared with sorghum and grass systems. This could be attributed to the high concentrations of this element in roselle yield components, predominantly in calyces and seeds which amounted to 9.8% compared to 1.8% in sorghum and 1.5% in grass (Table 2). Calyces and seeds (Out1b) removed about 38% of total K from HD+R and LD+R, while sorghum grains (Out1a) removed about 2% and 1% of total K from intercropped and pure crop systems.

Potassium balances were positive for intercropped roselle and sorghum at HD with negative balances at LD. The highest balance differences were in roselle compared with sorghum; although total dry matter production was higher for sorghum than for roselle (Table 1). These differences could be attributed to differential uptake of K by the two crops and greater accumulation of K in harvested yield components of roselle. The positive K balances in grass systems compared with sorghum and roselle is likely to be due to low exports from grass systems.

Overall, in this study, nutrient balances were negative in pure crops. This result agrees with findings from low-input subsistence farming systems in Sub-Saharan Africa (Stoorvogel and Smaling, 1990; Krogh, 1997; Van den Boch et al., 1998; Wortmann and Kaizzi, 1998; Scoones and Toulmin, 1998; De Jager et al., 2001; Ardö and Olsson, 2003). Generally, the LMS under study could be regarded as low-input systems where the majority of nutrients inflow and outflow pathways are tied to either tree biomass, crop and grass products and residues, or a combination of them. Gum yield had insignificant contribution to outflows of both N and K in intercropped systems, due to the very low concentrations of these elements in gum.

Nutrient Flows and Balances at Cropping Seasons Levels

The significantly higher outflows of all nutrients during the second season (had ample rainfall) could be explained by the large export of biomass, soil erosion, leaching. Nutrient balances were significantly variable among cropping seasons (Fig.3). With exception of N which had positive balances, the other nutrients had negative balances in the second season (2003) signifying higher outflows through the harvest export. In this season, crop yields and biomass production were considerably higher compared to the first and the third seasons (Table 1). On the other hand, very low crop yield with consequent low removal of nutrients in harvested products could be the main cause of the positive balances in the first and the third seasons.

Generally, nutrient budgets can be affected by a complex interaction of factors such as soil management practices, livestock integration and water conservation (de Jager et al., 2001). Overall, in this study productivity differs considerably among and within LMS as a consequence of differences in crop types (sorghum, roselle and grasses), tree densities and cropping seasons. In this context, the nutrients removed per unit of yield are practically not the same in all LMS, indicating a very close relationship between yield and the amount of nutrients at the disposal of the crop in question. This is strongly supported by the highly significant interactions between LMS and cropping seasons. For example, balances for studied nutrients were negative in PS and PR roselle in the first season. During this season, yields of sorghum were nil and that of roselle were very low, due to very low amount of rainfall. However, under the same systems, highest negative balances were in the second season when rainfall was sufficient and high crop yield was obtained. Furthermore, the apparent differences between pure crops and intercropped systems could indicate that further growth and productivity of crops depend considerably on the increased consumption of nutrient inputs available within the particular systems and this could only be achieved with sufficient soil moisture (Kessler and Breman, 1995; Buresh and Tian, 1998).

Nutrient Depletion

The results showed that the stocks of OC, N, P and K in the topsoil (0.3 m) were severely depleted under pure sorghum and roselle which may indicate accelerated soil degradation. Conversely, in tree-based systems major differences exist between systems at high- and low-tree density for a particular element. The variation in gains and losses (Table 7) among and within systems for particular nutrient could be attributed to differences in existing soil stocks, inputs and outputs pathways. However, to a greater extend, in all LMS removal in OM is the major determinant of nutrient depletion. The effect of crop production on nutrients is highly diverse and is a function of soil type, crop type and management. In this study, the rates of depletion of OC in pure crops were within the ranges reported in the literature for similar period (3-5 years) of cultivation (Tiessen et al., 1998; Solomon et al., 2002).

The least depletion of OC and N in intercropped systems could be due to the beneficial effects of tree components on the soil chemical properties (Buresh and Tian, 1998). Trees produce more litter than crops and maintain a closed cycle of nutrients. Some of the litter produced is added to the SOM pool, and the remainder is mineralized releasing nutrients that are reabsorbed by the trees or crops (Mobbs and Cannell, 1995). Besides, losses of N from soil surface may be in part compensated by gains of N in the sub-soil or at very profound soil depths by root decay and exudates. Greater nitrate concentrations at about 0.3 m depths were found under *A. senegal* in sandy soil in Senegal (Deans et al., 1999).

Overall, pure sorghum and roselle are the most depleting systems for all nutrients under study. In contrast, intercropped grass systems were the least deleterious to all nutrients and intercropped sorghum and roselle fell at amid-way stage.

This highlights the essential function of the traditional *A. senegal* bush-fallow system for maintaining land sustainability in the semi-arid of the Sahel region. Thus, modern exploitation and introduction of new technologies for farming these drylands should not bypass or ignore the traditional practices and farmer experiences.

CONCLUSIONS

The nutrient balance model, employed in this study, succeeded in identifying the important nutrient flows, and can be used as a tool for nutrient management in the different LMS. Nutrient balances varied with diversification of LMS, and with seasonal variations. Moreover, all LMS can be regarded as low-input agricultural farming systems since they receive no applied inputs. Nutrient balance analysis indicated that the sustainability of pure cropping is threatened by large losses of all the studied nutrients. If this situation is sustained both P and K would be depleted in, and posing a threat to long-term productivity of the land. Hence, procedures to adjust these balances should be undertaken in order to improve land use sustainability. These would include returning and incorporating crop residues, practicing land tillage, application of animal and green manure, planting of leguminous crops and sensible use of micro-fertilization.

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