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Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda

A.O. Esilaba [a,*], P. Nyende [c], G. Nalukenge [a], J.B. Byalebeka [b], R.J. Delve [c], H. Ssali [b]

[a] Centro Internacional de Agricultura Tropical (CIAT), Kawanda, P.O. Box 6247, Kampala, Uganda
[b] National Agricultural Research Organisation (NARO), Kawanda Agricultural Research Institute, P.O. Box 7065, Kampala, Uganda
[c] Tropical Soil Biology and Fertility Institute of CIAT, P.O. Box 30592, Nairobi, Kenya

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Abstract

Resource flow models are useful tools that assist farmers in analysing their soil fertility management strategies and in planning, experimenting and adapting ways to improve the use of scarce local resources. Resource flows and farm nutrient balance studies were carried out in eastern Uganda to ascertain the movement of organic resources and nutrients in and out of the farm system during a participatory learning and action research (PLAR) process. The resource flows were transformed into nutrient flows and partial nutrient balances were calculated using the Resource Kit computer package. Results of a farmers' soil fertility management classification at the start of the PLAR intervention in 1999 revealed that 3% of the farmers were good soil fertility managers (class I), 10% were average soil fertility managers (class II) and 87% were poor soil fertility managers (class III). The results indicate that the net farm nutrient balances in kg ha^{-1} per season for all the nutrients [nitrogen (N), phosphorus (P), and potassium (K)] were negative for both the good and the poor soil fertility managers. Class 1 farm balances irrespective of the season, were however more negative than those of class 3 farms. For the long rains seasons (LR 2000, 2001 and 2002), the average net farm nutrient balances for N, P, and K for class I farms were −5.0, −0.6 and −8.0 kg ha^{-1} $year^{-1}$, while for the short rains seasons (SR 2000 and 2001), the nutrient balances were −3.5, −0.5 and −6.0 kg ha^{-1} $year^{-1}$, respectively. For the class III farms, the average net farm nutrient balances for N, P, and K in the long rain seasons (LR 2000, 2001 and 2002) were −3.3, −0.3 and −4.0 kg ha^{-1} $year^{-1}$ while for the short rains seasons (SR 2000 and 2001), the nutrient balances were −3.5, 0.5 and −5.0 kg ha^{-1} $year^{-1}$, respectively. Soil management interventions for these small-scale farmers should aim at reversing nutrient depletion with a focus on profitable management of the crop production system, which is the major cause of nutrient depletion.

Keywords: Farm classification; Farming systems; Nutrient balances; Resource flows; Soil fertility; Eastern Uganda

* Corresponding author. Present address: KARI Headquarters, Kenya Agricultural Research Institute, P.O. Box 57811, City Square, 00200 Nairobi, Kenya. Tel.: +254 20 583301x20; fax: +254 20 583344.
E-mail addresses: aoesilaba@kari.org, aesilaba@yahoo.co.uk (A.O. Esilaba).

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1. Introduction

Soil nutrient balance studies in Africa show evidence of widespread nutrient mining leading to severe nutrient deficiencies across ecological zones. Soil nutrient stocks are not static entities and studies in different parts of Africa at different spatial scales show that nutrients are being depleted at alarming rates (Stoorvogel and Smaling, 1990; Van der Pol, 1992; Smaling et al., 1993, 1997; Smaling and Braun, 1996; Scoones, 2001). Nutrients are annually taken away in crops or lost in processes such as leaching and erosion which far exceed the nutrient inputs through fertilisers, deposition and biological fixation (Smaling and Braun, 1996). Nutrient mining has been estimated to average 660 kg of nitrogen (N), 75 kg of phosphorus (P) and 450 kg of potassium (K) per hectare per year during the last 30 years from about 200 million hectares of cultivated land in 37 countries in Africa (Stoorvogel and Smaling, 1990; Sanchez et al., 1997; Smaling et al., 1997). Losses of 130 kg N, 5 kg P and 25 kg K ha^{-1} per year have been reported in the East African highlands (Smaling et al., 1997). Wortmann and Kaizzi (1998) estimated nutrient balances for small-scale farming systems in eastern and central Uganda to be negative for all crops except for nitrogen (N) and phosphorus (P) in the banana-based land use type (LUT).

The concern for soil nutrient depletion and low soil fertility has led to the development of several integrated soil fertility management technologies that offer potential for improving soil fertility management in Africa (Scoones and Toulmin, 1999). These include improved soil erosion control using living barriers or micro-catchments, inoculation of grain legumes for improved N-fixation, efficient use of manure and other locally available organic materials, use of green manure and cover crops (Delve and Jama, in press) and use of low levels of N and P fertilisers on maize (*Zea mays*) and beans (*Phaseolus vulgaris*) (Wortmann et al., 1998; Wortmann and Kaizzi, 1998) in eastern Uganda. However, there has been limited uptake of these "improved" INM practices.

There are a limited number of long-term studies monitoring the nutrient status of soils, nutrient balances, and crop productivity in Uganda (Bekunda et al., 1997; Swift et al., 1994). It is important to calculate and monitor nutrient flows to quantify the impact of integrated nutrient management (INM) systems on soil fertility and sustainable agricultural productivity (Smaling and Braun, 1996; Defoer et al., 2000). Monitoring of nutrient stocks and flows is a tool for assessing the degree of nutrient mining in an agro-ecosystem. When applied to systems where INM practices are being introduced, nutrient monitoring can be used to assess the effects of INM strategies on soil nutrient stocks and flows (Van den Bosch et al., 1998).

Improved soil nutrient management is important for maintaining and improving soil productivity in Uganda and strategies are required that more closely address farmer requirements and priorities (Deugd et al., 1998). In this study resource/nutrient flows were used to work with farmers to better understand their current practice, their constraints and their opportunities for reversing nutrient depletion. Therefore, the objectives of this study were to determine resource flows and estimate nutrient balances in three different farm typologies and to investigate if improved soil fertility management impact on sustaining agricultural productivity on the smallholder farms in eastern Uganda.

2. Materials and methods

2.1. Characteristics of the farming system

A study was carried out in three villages of Magada, Mayuge and Buyemba in Imanyiro sub-county of Mayuge District in eastern Uganda. This area is located at $0^{\circ}\ 35^{1}$N, $32^{\circ}29^{1}$ E and lies at an altitude of 1070–1161 m.a.s.l (meters above sea level) covering an area of about 11,113 km^2. The area has a bimodal rainfall pattern varying from 1250 to 2200 mm (average 1345 mm for 22 years) per annum. The first rains (long rain (LR) season) occur between March and June and the second rains (short rain (SR) season) between August and December. The soils are reddish brown sandy loams and sandy clay loams (Harrop, 1970) and classified as Orthic Ferralsols (FAO, 1977). Most soils in the area have an average organic matter content of 11.0–31.0 g kg^{-1} but are deficient in N and P (Fischler, 1997; Wortmann and Kaizzi, 1998).

The farming systems show a high degree of biological and agronomic diversity and complexity.

Average farm size is 1.8–2.0 ha and 90% of the farmers are the sole owners of the land. The main crops grown in the area are bananas (*Musa spp.*), maize, cassava (*Manihot esculenta*), beans, coffee (*Coffea canephora*), fruits, vegetables and sweet potato (*Ipomea batatas*) (Esilaba et al., 2001b; Woelcke and Berger, 2002). The majority of the farms have few or no livestock and the mean numbers are 1.5 local cows, 0.2 improved cows, 1.7 goats or sheep, 0.9 pigs and 12.0 chickens per farm (Wortmann et al., 1998; Wortmann and Kaizzi, 1998).

2.2. The PLAR process

A Participatory Learning and Action Research (PLAR) process (Defoer et al., 2000) was initiated in September 1999 in Imanyiro sub-county, Mayuge District. The PLAR process comprises four phases: diagnosis and analysis, planning, implementation and evaluation. During the diagnostic phase of the PLAR process, farmers analysed soil fertility management diversity and resource endowment of farms in Buyemba, Mayuge and Magada villages (Esilaba et al., 2001b). The soil fertility management diversity classification were standardised into three categories (good, average, and poor managers) using the farmers' criteria and were attributed to: (1) use of fertilisers (both organic and inorganic), (2) use of soil erosion control measures, such as vetiver grass strips, terracing and mulching, (3) use of green manure, such as mucuna, canavalia, crotalaria and lablab, (4) leaving land to fallow and (5) use of agroforestry technologies. Farms/households using four or more of these measures were considered "good" (class I). Farms using one to three measures were considered "average" (class II), while those farms not using any of these measures were considered "poor" (class III).

Twenty farmers representing the three soil fertility management classes in the three villages were selected as test farmers for intensive monitoring, on-farm experimentation and resource flow mapping. Soil samples (topsoils at 0–20 cm depth) were collected from the proposed on farm experimental sites on 28 farmers' plots for laboratory analysis according to methods by Foster (1971) and Okalebo et al., (1993) for available Bray-P. Organic matter was determined using an oxidation procedure derived from the Walkley and Black method as described by Jackson (1958). Total nitrogen (N) was determined by the standard Kjeldahl procedure. The extracting solution used for calcium (Ca), Magnesium (Mg), sodium (Na) and potassium (K) was hydrolyzed lactic acid in ammonia solution based on Egner's extracting solution (Foster, 1971). Data on soil properties for farms in the three soil management classes are presented in Table 1. Data analysis for analysis of variance (ANOVA) on soil properties was conducted using SAS (SAS, 1990) and SPSS (SPSS, 2002) for cross tabulation of soil fertility management classes with resource endowment parameters that included wealth ranking (Esilaba et al., 2001a,b).

Table 1
Soil chemical and physical properties (top soils 0–20 cm depth) of typical farms in the three soil fertility management classes[a]

Parameter	Class I ($n = 9$)	Class II ($n = 5$)	Class III ($n = 14$)
pH (water)	5.5	5.2	5.0
Organic matter (g kg^{-1})	28.4	29.4	21.6
N (g kg^{-1})	1.0	1.0	1.0
P (Bray P-2, mg kg^{-1})	4.6	3.3	1.9
K (cmol kg^{-1})	24.6	22.6	15.1
Na (cmol kg^{-1})	6.2	5.7	3.9
Ca (cmol kg^{-1})	53.6	51.6	35.2
Mg (cmol kg^{-1})	29.7	27.6	19.2
Sand (g kg^{-1})	619	642	711
Clay (g kg^{-1})	272	266	201
Silt (g kg^{-1})	109	92	81

[a] Class I = good soil fertility managers; class II = average soil fertility managers; class III = poor soil fertility managers.

2.3. Resource flow-mapping

Resource flow maps were used to visualise the farmers' soil fertility management situation of the farm during of the PLAR process. The selected farmers drew resource flow maps (RFMs) to visualise, plan and analyse their current, planned and implemented soil fertility management practices and to identify possible improvements at the beginning and end of each season. Test farmers from the three soil fertility management diversity classes drew resource maps indicating the different elements of their farms, including fields, food stores, livestock shelters and compost pits (Budelman and Defoer, 2000a,b). The current and preceding crops were noted for each field and farmers drew arrows to show the flows of resources entering and leaving the farm as well as

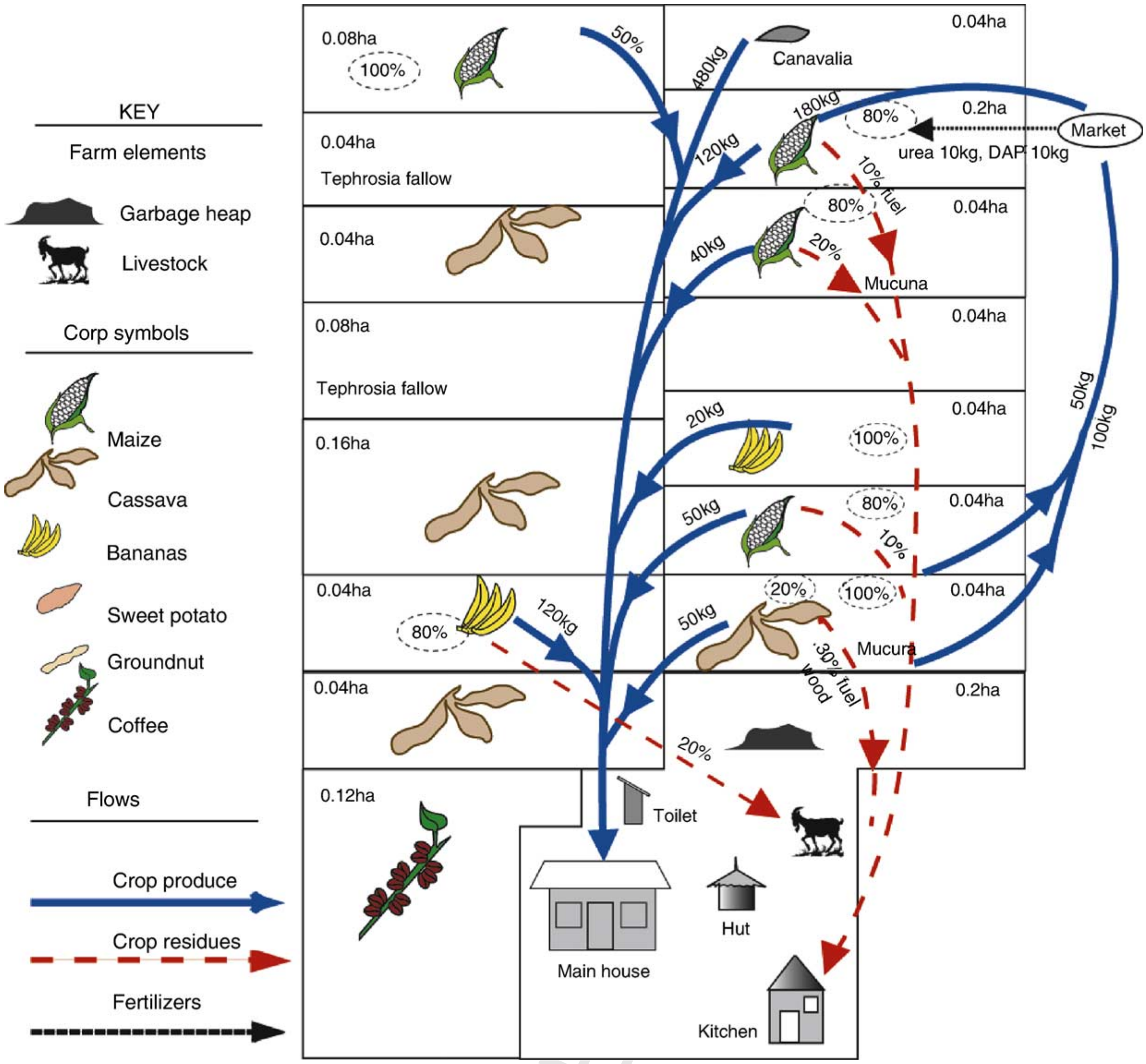

Fig. 1. Typical resource flow map.

flows between fields and other farm components (Fig. 1).

Farmers estimated the quantity of resources using simple local units of measurement [such as tins (1–10 kg containers), debes (20 kg containers) etc.] and labelled the direction of flow of the resources accordingly using appropriate arrows and symbols. Similar information was recorded on several recording forms relating to (1) farm level data, (2) field level data and to various flows, (3) resources leaving the fields (produce and crop residues); (4) resources entering the fields (fertilisers); (5) resources leaving the household and animal production system; (6) resources entering the household and animal production system and fed into a computer using the Resource Kit software for analysis (Defoer et al., 2000; Defoer and Budelman, 2000).

Nutrient flow analysis was used in evaluating land use, the relative intensity of cropping, the ratios between inputs and outputs and comparing systems

Table 2
Soil fertility management classification (diversity) continuum over three years[a]

Village	Number of farmers							
	Class I		Class II		Class III		Total	
	1999	2002	1999	2002	1999	2002	1999	2002
Buyemba	7	10	19	35	165	153	191	198[b]
Mayuge	8	10	28	18	94	104	131	132
Magada	4	4	8	51	235	192	247	247
Total	20	24	55	104	494	449	569	577

[a] Class I = good soil fertility managers; class II = average soil fertility managers; class III = poor soil fertility managers.
[b] Other new farmers had joined the village hence the increase in the number.

along these lines (Budelman and Defoer, 2000a). The unit of analysis was the farm system, which is part of the village land use system (consisting of several farms and communally used resources). There are three sub-systems within the farm: the crop production system (CPS), the animal production system (APS), and the household system (HHS). For each of the sub-systems, links with the elements outside the farm system are presented as flows entering (i.e. IN) the farm from outside, and as flows leaving (i.e. OUT) the farm. Links between the sub-systems (i.e. INT) of the farm are identified and refer to internal flows (Defoer et al., 1998; Defoer and Budelman, 2000). After five seasons of experimentation and resource flow mapping, farmers evaluated themselves to establish a continuum as to whether they had moved from one soil fertility management class to another or remained in the same class and establish factors that led to these scenarios (Table 2).

3. Results and discussion

3.1. Soil fertility management diversity classification

The results indicate that out of a total of 569 households only 20 (3.5%) were in class I, 55 (10%) in class II and the majority (494 or 87%) were in class III (Table 2). Therefore, most farmers were not carrying out any improved soil fertility management practices, despite the previous National Agricultural Research Organisation (NARO), Uganda and the International Centre for Tropical Agriculture (CIAT) work in this area (Fischler, 1997; Wortmann et al., 1998; Wortmann and Kaizzi, 1998). When key informants from the farmer groups were asked to reclassify the farmers after two years they indicated that 10% of the farmers from the 1999 class III classification had moved to class I and II. Some farmers in class I had to be relegated to class II and III (Table 2). The PLAR process had more impact on farmers in the newest research village (Magada).

Wealth rankings (Grandin, 1988) obtained during the diagnostic phase of the PLAR process (Esilaba et al., 2001b) were compared with data from the soil fertility management diversity classification for the same households in the three villages. The wealth ranks were standardised into four categories (wealthy, average, poor and very poor) for correlation with soil fertility management classes using SPSS (Table 3). The majority of the respondents (74%) were in soil fertility class III while class II and I each had 13%, respectively. There were trends indicating a relationship between wealth ranks and soil fertility management classes. Seventy five percent (75%) of the farmers in soil fertility management class 1 were wealthy, another 25% average, and none were poor or very poor. For class 2 farms, 67% of the farmers were average, 33% were very poor and none was wealthy or poor. In class 3, 7% of the farm households were wealthy, 23% average, 31% were poor and 39% were very poor.

No significant differences ($P < 0.05$) were observed in the soil chemical and physical properties among the three soil fertility management classes despite farmers' assessment (Table 1). The soil pH was generally

Table 3
Relationship between soil fertility management classification and wealth ranking[a]

Soil fertility management			Wealth rank[c]			
Class[b]	Number of farmers		Number of farmers (%)			
	1999	2002	Wealthy	Average	Poor	Very poor
Class I	20 (3)	24 (4)	75	25	0	0
Class II	55 (10)	104 (18)	0	67	0	33
Class III	494 (87)	449 (78)	7	23	31	39

[a] Values in parentheses are the percentage of farmers.
[b] Class I = good soil fertility managers; class II = average soil fertility managers; class III = poor soil fertility managers.
[c] Wealth ranks classified according to the farmers criteria into four classes (wealthy, average, poor and very poor).

favourable except on farms in class III, which had a low average pH. Total (Kjeldahl) N, soil organic matter (SOM), available P are inadequate while exchangeable K is relatively adequate (Foster, 1971, 1973; Landon, 1984). Critical values for soil pH, organic matter, total N and K in Uganda are 5.2, 30.0 g kg^{-1}, 1.8 g kg^{-1}, 5 mg kg^{-1} and 13.3 cmol kg^{-1}, respectively (Foster, 1971). The soil textural class at all sites was dominantly loam.

3.2. Resource flow mapping and resource flows

The resource flow mapping exercise was used as a learning tool for the researchers, extension staff and farmers to visualise the farm system and its subsystems, the flow of resources within the farm systems and outside the farm system. The complexity of the flows within and outside the farm system was evident from the exercise. The farmers together with the extension staff were able to examine the quantities and direction of the flows of the main agricultural resources and possible options to minimise losses and concentrate resources in key areas. The results show that farmers using different soil fertility management measures varied also in terms of resource endowment, for example, farm size, land tenure, livestock ownership, off-farm employment and farm structures. The average class I total farm size was considerably larger (3.3 ha) than class III (1.4 ha) with the implication that class I farmers can therefore leave more land under fallow (0.7 ha) than class 3 farmers (0.2 ha) to restore soil fertility. Most of the maps were characterised by one field but with many plots (1–20) and of different sizes (Fig. 1). The plot sizes ranged from 0.125 to 2 ha. Farmers in this area divide their land into many plots because of the need to distribute the risk of crop failure by growing a variety of crops. The fields/plots were divided, according to the crop growing or intended to be grown for that particular season.

For all the farm classes, most of the resources within the farm system came from crop fields (crop production system) into the household system (CPS-HHS) as food, and out of the farm system (OUTcps) as sale of surplus food (Figs. 2–4). On the other hand, very limited resources were returned to the farm and to the crop production system (INcps). There were no seasonal differences in the direction of flow of the resources but there was for the quantities of resource flows.

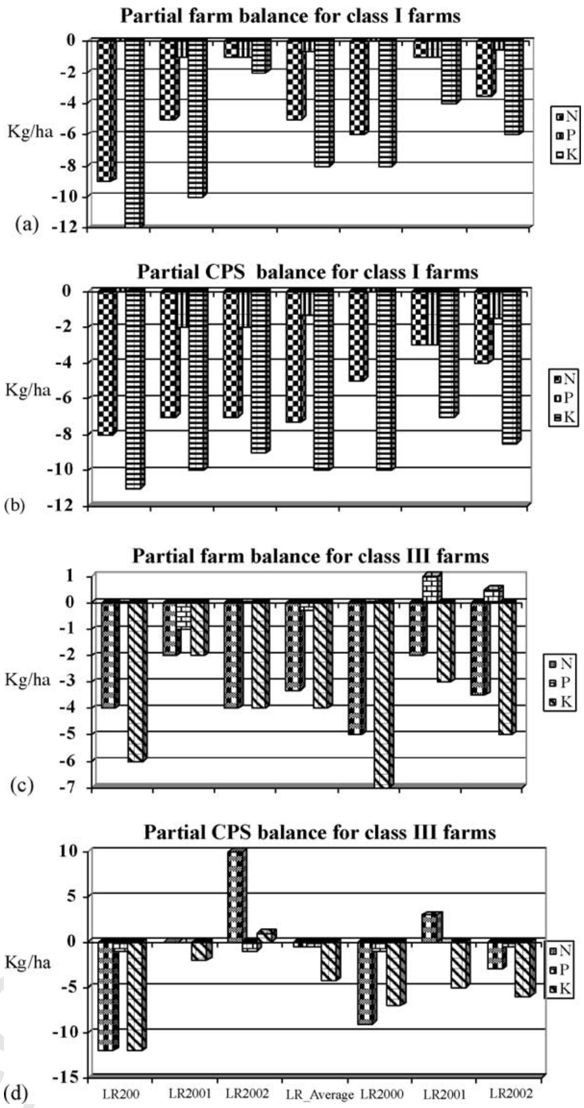

Fig. 2. Net partial farm balances and partial crop production system (CPS) balances for class I (2000–2002) and III (2000–2002) farms. Net partial farm balances = INcps + INaps + INhhs − OUTcps − OUTaps − OUThhs;Partial crop production system (CPS) balances = INcps + INTaps − cps + INThhs − cps − OUTcps − INTcps − aps − INTcps − hhs; where IN = input flow; OUT = output flow; INT = internal flow; aps = animal production system; cps = crop production system; hhs = household system; LR = long rains; SR = short rains.

Food crops are either consumed immediately when they come from the field or are temporarily stored for food or sale to the market. However, these are subsistence farmers and therefore most of the produce

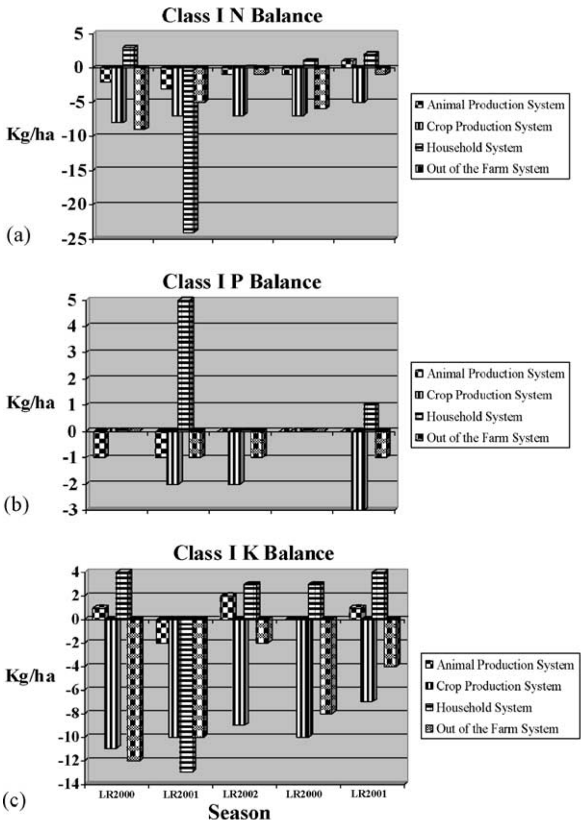

Fig. 3. Average N, P and K balances per hectare per season for all locations of typical class I farms for the crop production system (CPS), animal production system (APS), household system (HHS) and out of the farm system (OFS) over five seasons in the 2000, 2001 and 2002 long rains (LR) and 2000 and 2001 short rains (SR).

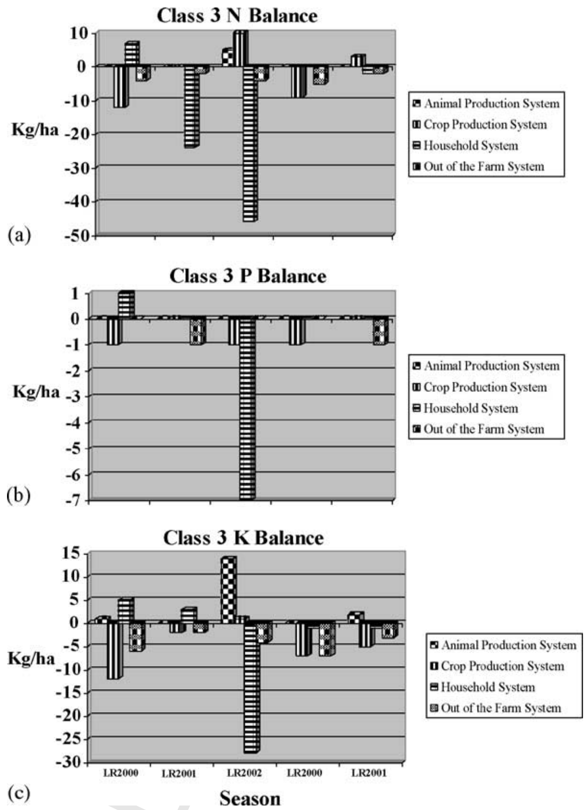

Fig. 4. Average N, P and K balances per hectare per season for all locations of typical class III for the crop production system (CPS), animal production system (APS), household system (HHS) and out of the farm system (OFS) over five seasons in the 2000, 2001 and 2002 long rains (LR) and 2000 and 2001 short rains (SR).

(80%) is consumed on the farm, with the exception of coffee. Intercropping is practised to reduce on labour demands, maximise land use and reduce risk due to drought. Apart from land allocation for crops, there is no significant difference in the crops cultivated, crop pattern (sole versus intercropping), yields, crop residue management and general crop husbandry between the two farm classes, despite farmers in class I being known to be 'good' soil managers. There are also no major differences in yield, crop types and size of land allocation between the long rains and short rain seasons. Nutrients are exported from the farms mainly through coffee, food crops and crop residues (banana) fed to livestock and also used as compost. There was very little evidence of fertilizer use on the farms apart from previous on-farm testing by research and development organisations. Soil fertility is maintained mainly through natural fallows, improved fallows and leguminous cover crops such as *Mucuna, Canavalia* and *Tephrosia* (Wortmann et al., 1998; Wortmann and Kaizzi, 1998).

3.3. Nutrient flows and balances

Nutrient flow analysis (NFA) was used to compare situations and outcomes in relative terms (Budelman and Defoer, 2000a,b). Nutrient balances of the three production subsystems (crop, animal and household production systems) and out of the farm system for N, P and K are presented in Figs. 3 and 4. For the crop production system, N, P and K balances were negative in all the five seasons for both class I and III. The nutrient balances for the LR seasons are about twice as much as for the SR seasons. In the LR more crops are cultivated and therefore there are more harvests. Thus, in the LR season, farmers have more surplus of produce for sale and therefore, export more nutrients out of the farm. The animal production system had zero or positive nutrient balance in both LR and SR seasons for both farm classes. The household system had positive N balance but with either zero or negative P and K balances for both classes in all the five seasons. This further emphasises the point that nutrient stocks of individual plots within farms and village territories can differ considerably due to management. Thus plots around the homestead, which receive substantial amounts of nutrients from animal manure and household waste, maintain a relatively high level of productivity (Smaling and Braun, 1996; Hilhorst et al., 2000). However, the farm system had net negative balance for all nutrients in all the seasons and for all the farm classes. The average N, P and K balances due to crop removal from the partial crop production system for class I and III farmers in the LR and SR seasons were -7.3 kg N ha^{-1}, -1.3 kg P ha^{-1}, -10.0 kg K ha^{-1} and -4.0 kg N ha^{-1}, -1.5 kg P ha^{-1}, -8.5 kg K ha^{-1} and -0.6 kg N ha^{-1}, -0.6 kg P ha^{-1}, -4.3 kg K ha^{-1} and -3.0 kg N ha^{-1}, -0.5 kg P ha^{-1}, -6.0 kg K ha^{-1}, respectively (Fig. 2a–d). The balance was negative due to crop removal of maize, beans sweet potatoes, cassava, and bananas. Nitrogen, P and K balances for the animal production system were marginal or zero as no nutrient entered or left the system. The household system had positive N, P and K balance because of the food crops that entered the system from the crop production system. Looking at the whole farm system, the export of nutrients from the farm as sales was greater than the imports. The average farm-level nutrient exports for class I and III farmers were more in the LR season than in the SR season (Fig. 2a–d). Of all the nutrients, substantial amounts of K were exported through banana fruit and residues', thus making the K balances more negative. Potassium export through banana either consumed or sold also poses a problem as much of it remains in the bodies of the farm inhabitants, while the rest is excreted but not returned to the fields.

The limited nutrients that enter the farm system are mainly added to the crop production system, with lower amounts entering into the household system as food or animal feed. Despite these additions, significant losses occur from the CPS. The crop production system, which is the major source of the nutrients leaving the farm, has the highest risk for soil nutrient depletion. Woelcke and Berger (2002) conducted bio-economic modelling studies in the area using different scenarios and they also found similar nutrient balances. For example, the N balances varied from -28 kg N ha^{-1} (subsistence farm households) to -77 kg N ha^{-1} (commercial farm households) in the case of the baseline scenario under current land management and socio-economic conditions (Woelcke and Berger, 2002). The commercial households had higher yields and therefore higher amounts of nutrients were exported in the harvested produce. The results of the NFA suggest that there is need for a more targeted approach to soil fertility interventions that differentiate between farm components and socio-economic conditions (Elias et al., 1998).

Though farmers classified themselves into three soil fertility management classes of good, average and poor soil fertility managers, however, soil chemical and physical properties revealed no significant fertility differences. Furthermore, the nutrient flows and balances also revealed that there is no significant difference in nutrient management for the three soil fertility classifications. It is instead observed that class 1 farmers', despite being good managers, lose/export more nutrients from the farm than class 3 farmers. The soil chemical analysis and the nutrient balance studies results do not reflect the farmers' soil fertility assessment and therefore require further analysis. However, De Jager et al. (1998) followed a budget approach in linking household objectives and wealth to nutrient management and mining and found a strong correlation between market orientation of farm households and the nutrient balance. Thus inspite of higher input use in market oriented farms, outputs were so high that the balance was more negative than in subsistence farming.

4. Conclusions

Resource flows and nutrient balances from this study show that soil nutrient depletion is a major problem in the study area. Nutrient mining is more intense in the crop production system of the smallholder farmers in eastern Uganda. Harvesting of crops for food and the surplus for sale are the most important sources of nutrient mining in the crop production system. Therefore attempts to correct the imbalance need to address these and other socio-economic factors. Given the high costs of fertilisers, intensifying use of legume cover crops as intercrops or improved fallows and strategic management of crop residues such as through home gardens are some of the options for minimising nutrient depletion.

The PLAR process enabled farmers to diagnose, plan, implement and evaluate their own activities for soil fertility improvement on their farms. The resource flow mapping exercise was an important tool in guiding farmers in selecting technologies and solutions according to the available farm resources as well as stimulating them to take action. This study also demonstrated that the maps drawn by the farmers were a source of information in determining resource flows and calculating nutrient balances that were used as indicators for improvements in soil fertility management.

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