Managing nutrient stocks and movement in smallholder gardens in Bena, Papua New Guinea

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ABSTRACT

In most intensive agricultural systems, the amount of nutrients leaving the soil in harvested crops exceeds the nutrient input to the system. The aims of this study were to identify and quantify the movement of nutrients into and out of food gardens in the Papua New Guinea highlands and interpret the net effects of these nutrient movements on soil fertility. Crops were sampled at maturity, separated into various parts, dried and ground and analysed for macronutrients and micronutrients. Soil samples (0 - 10 cm and 10 - 50 cm) were analysed for total C and N, Colwell P, and silver thiourea exchangeable K, Ca and Mg concentrations and cation exchange capacity, pH (water and calcium chloride) and electrical conductivity. The two main nutrient fluxes were the output in harvested crop and input in inorganic fertilizers. The amounts of N and K exported in harvested crops exceeded the amounts imported in inorganic fertilizers, resulting in a negative balance of those nutrients. A substantial portion of exported nutrients are in 'wastes (i.e. plant parts harvested and removed from the garden plot but not consumed). Crop harvesting and preparation produces residues or wastes that might be better managed to retain nutrients in the gardens. Some farmers do not apply the waste back to their gardens because they believe it makes their gardens look untidy, while others do not apply it as the waste provides a breeding ground for pests and diseases. However, the value of the nutrients in the waste should be considered for future soil fertility management.

KEYWORDS: **crop harvest, nutrient balance, coffee pulp, waste management, soil fertility**

INTRODUCTION

Developing countries like Papua New Guinea (PNG) maintain low input agricultural systems where the use of commercial fertilizers is minimal. In such agricultural systems, the crops depend almost entirely on the soil nutrient reserve for their growth. As a consequence, the soil nutrient reserve declines, resulting in lower crop yields over time. This declining soil fertility may be attributed to several processes, including natural processes like soil erosion and leaching, and anthropogenic processes like crop harvesting and crop residue removal. These processes are also influenced by environmental factors (e.g. climate) and socioeconomic factors (e.g. access to markets). This paper concentrates on some of the management processes that affect the soil fertility, like crop harvesting and organic matter movement. Substantial amounts of nutrients are removed from the soil when crops are harvested but considerable amounts of plant residues or wastes are also generated in food production systems. These residues contain nutrients in various forms more or less readily available that can be appropriately used to benefit the farming system. Farming systems and farming practices alter nutrient fluxes in time and space, so identifying the nutrient pathways is critical for the maintenance of soil fertility.

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MATERIALS AND METHODS

Study area

The study was conducted in Bena, situated at about 1700-1900 m.a.s.l and 6° 4' S 145° 27' E in Eastern Highlands Province, PNG. The average rainfall is 1800-2800 mm per annum. The wet season is between December and early April followed by a dry season from late April/May to November. The study area was selected due to its access to service centres and markets and its active participation with the CIC.

Selection of farms

To capture the nutrient dynamics in a smallholder farming system, six farmer households were selected, using the database from the Australian Centre for International Agricultural Research (ACIAR) coffee project ASEM/2008/036: 'Improving livelihoods of smallholder families through increased coffee-based farming systems'. Two criteria were used to select the farmer households:

1. Farmers who did and farmers who did not apply inorganic fertilizer in their food gardens
2. Farmers who grew crops specifically for market.

For the first criterion, most farmers do not use inorganic fertilizers in their food gardens, except those who grow vegetables for market that have a high demand for nutrients, such as cabbage, broccoli and bulb onion. Two of the six farmers did not grow high nutrient demand crops and hence, they did not use inorganic fertilizers anywhere on their farms. These farmers were selected for the purpose of comparison of soil nutrient concentration.

The second criterion was selected for the purpose of determining the amount of nutrients exported out of the farming system to markets, as this was identified as one of the main pathways of nutrient export from the farming system. Moreover, the process of harvesting and preparing crops for sale involves losses of nutrients and if the pathway of this loss can be identified, it can be mitigated.

Soil sampling

Soil samples were collected from food gardens from all six farmers, at 0-10 cm (topsoil) and 10-50 cm (subsoil) depths. In a garden, there were several plots on which different crops were grown. If the farmer grew the same crop in several plots within a garden, then one or two soil samples were taken in each plot and combined to obtain one composite sample for that crop. For example, if the farmer had three plots of sweet potato in a garden, two soil cores per plot were taken (2 soil cores x 3 plots) and the six soil cores were combined for each depth to obtain one composite soil sample for sweet potato in that garden. If the farmer grew a crop that occupied a large area (e.g., pineapple) then soil sampling was done along a transect through the area and the samples were combined to obtain a composite sample for that crop.

Food crop sampling

Crop yield was estimated from planting density and samples collected during the field trips. To assess the nutrient concentration of the plant parts that could potentially be left in the garden and the parts (usually edible or marketable parts) that were transported out of the plot, crops that were ready for harvest were sampled and the plants were separated into their main parts depending on the crop (e.g. leaves, stems, seeds, pods, tubers). The fresh weights of each part were measured separately. The number of crops sampled depended on the availability of the crop during sampling and, hence, the number harvested varied amongst farmers.

The term "harvested crop" is defined, per plant, as the part of the plant, irrespective of subsequent processing, that is removed from the plot. For example, with peanuts, the whole plant (leaves + stems, shell and seed) is removed from the plot; with cassava, only the tubers are removed and "crop harvest" refers to the 6-7 tubers harvested per plant (even if only one tuber was sampled and analysed); with broccoli, the leaves, stem and flower are removed; with orange, all the oranges on a single tree are removed, even if only a few oranges were sampled and analysed. Thus, harvested crop means the entire product removed from a plot per plant.

Soil analysis

Total C and N contents were determined by Dumas combustion analysis, undertaken on an elemental analyser (Costech 4010; Costech Analytical Technologies, CA, USA. Rayment and Lyons 2011, Method 6B3).

Electrical conductivity (EC) and pH were determined using a 1:5 soil: water extract. Air dried soil (6 g) was shaken with 30 mL water for one hour and left to settle for 20 minutes. The pHw and EC were then determined using calibrated meters. The soil was then resuspended and 1.5 ml of 0.21 m $CaCl^2$ was added to obtain a 0.01 m $CaCl^2$ solution. The suspension was shaken again for 15 minutes and allowed to settle for 20 minutes and $pHCaCl^2$ was measured (Rayment and Lyons 2011; method 3A1, 4A1 and 4B2).

Extractable P was determined colorimetrically on centrifuged and filtered extracts following Colwell extraction using 0.5 m $NaHCO^3$ at pH 8.5 (Rayment and Lyons 2011; method 9B1).

Exchangeable cations and cation exchange capacity (CEC) were determined using a 1:50 0.01 m AgTU+ extract. Exchangeable cations Ca, Mg, Na and K were determined on centrifuged and filtered extracts. Cation exchange capacity was determined by measuring the amount of silver ions exchanged (Rayment and Lyons 2011; method 15F1 and 15J1).

Plant analysis

Total C and N contents were determined as for soils (see above). Finely ground dried plant material was digested in nitric acid and hydrogen peroxide and analysed for P, K, Ca, Mg, Fe, B, Zn, Mn and Cu concentrations using ICPMS Method-1D2HeA (Wheal et al. 2011; method 3(12)). Ti concentration was also measured as an indicator of soil contamination of samples. No samples were deemed to be contaminated with soil.

Statistical analysis

The paired control and treatment soil data were analysed using paired t-test in Microsoft Excel and the rest of the analysis was done using ANOVA tests within the S-Plus software.

Nutrient pathways

Several inputs (mineral fertilisers, organic manure, atmospheric deposition, biological N fixation, sedimentation) and outputs (harvested products, residue removal, leaching, gaseous losses, water erosion) of plant nutrients are conceptualised (Figure 1) but not all could be measured. Observations were confined to nutrient flows that are managed directly by the farmer (mineral and organic fertilisers and harvested crops leaving the farm). Plot-specific input data from individual farmers were collected through interviews and outputs were estimated from the crop harvest of each garden.

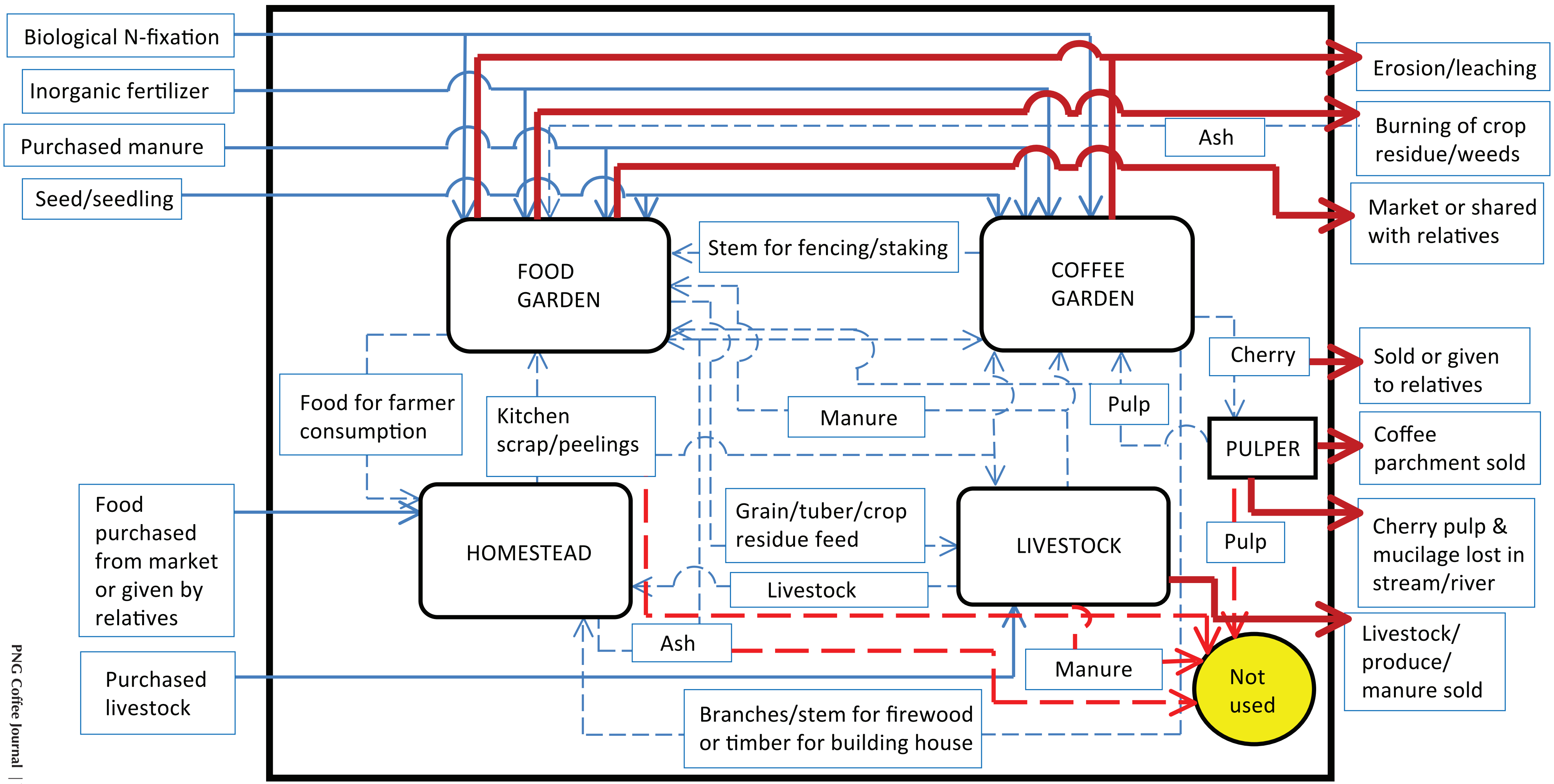

Figure 1: Nutrient inflows and outflows of a farm. Solid lines are 'farm gate' flows (thin lines, inflows; thick lines, outflows) and broken lines are internal flows in farm. Thick broken lines are materials which are not utilized further in the farm (e.g. pulp is left at pulping station and ash/kitchen scrap/peelings thrown in a pit).

RESULTS

Soil fertility status

Mean values of the chemical properties of topsoil in unfertilized plots were generally in the range considered optimum (Table 1). However, because of the wide variation in values, there will be many plots considered infertile. Although the mean concentration of N in the topsoil of unfertilized plots was in the optimum range, seven plots had an N concentration below the optimum range. In addition, even though the mean concentration of extractable P and exchangeable K in the topsoil of plots was slightly below the optimum range, more than half of the plots had the P and K concentrations that were below the optimum range (Table 1).

Nutrient export

The amount of nutrients exported in crops depended on the biomass of each plant, planting density and nutrient concentration. Crops such as cauliflower, cassava, peanut and bulb onion exported large amounts of N, i.e. 20.7, 13.6, 11.7 and 11.4 g/m^2, respectively (Table 2). However, cassava, cauliflower and bulb onion exported more K than N, i.e. 27.0, 26.9 and 16.3 g/m^2, respectively. Cabbage and orange exported the lowest amount of nutrients because of the low planting density. In addition, cauliflower exported more Ca and Fe than the other crops.

Effect of fertilizer on soil fertility status

The fertilized plots had significantly higher C, N (1.5-2x higher) and exchangeable K (3-4x higher)

Table 1: Mean nutrient status of unfertilized and fertilized garden soils at 0-10 cm (topsoil) and 10-50 cm (subsoil).

	Total (%)		**Extractable (mg/kg)**	**Exchangeable (cmol+/kg)**				**ECa (dS/m)**	**pHa (water)**	**pHa (CaCl2)**
	C	**N**	**P**	**K**	**Ca**	**Mg**	**CEC**			
Practice										
Unfertilized garden plots (topsoil n=22)	4.78 (3)	0.35 (7)	55.4 (17)	0.40 (16)	12.2 (0)	3.82 (0))	18.6 (0)	0.11 (1)	6.11 (0)	5.37 (0)
Fertilized garden plots (topsoil n=17)	6.69 (0)	0.58 (0)	68.1 (5)	1.28 (3)	13.3 (0)	3.58 (0)	18.3 (0)	0.16 (2)	6.17 (0)	5.49 (0)
Unfertilized garden plots (subsoil n=22)	3.15 (18)	0.25 (17)	31.4 (21)	0.15 (20)	7.83 (3)	2.63 (0)	13.6 (0)	0.11 (2)	6.02 (0)	5.37 (1)
Fertilized garden plots (subsoil n=17)	4.84 (7)	0.48 (3)	47.6 (13)	0.63 (8)	9.54 (2)	2.60 (1)	13.9 (0)	0.09 (0)	6.07 (0)	5.42 (0)
Optimum range[b]	4.9-9.9	0.3-0.6	60-80	0.5-0.8	5.0-9.9	1.0-2.9	5.0-20	<0.2	5.3-6.5	4.8-6.0
p-value (topsoil)	<0.01	<0.01	0.10	<0.01	0.25	0.42	0.80	0.12	0.53	0.15
p-value (subsoil)	<0.01	<0.001	<0.01	<0.001	0.10	0.93	0.83	0.62	0.55	0.57

All values are expressed on an oven-dried basis except for EC and pH

[a] 1:5 soil:water (air-dried)

[b] For coffee, from Winston et al. (2005 for extractable P and EC and Harding (1984) for all other values

Cation exchange capacity (CEC), Electrical conductivity (EC)

Values in parentheses represent the number of gardens with values lower than the optimum range; except for EC where it is the number of gardens with values greater than the optimum range

Table 2: Mean quantity of nutrients exported in harvested crops.

	C	N	P	K	Ca	Mg	Fe	B	Zn	Mn	Cu
Crops	g/m²						mg/m²				
Broccoli (n=5)	125	8.70	1.11	11.23	3.91	0.70	103	4.69	13.10	12.22	1.56
Bulb onion (n=5)	193	11.47	1.95	16.27	4.92	1.52	138	5.92	18.21	38.72	6.31
Cabbage (n=1)	30	1.38	0.25	2.16	0.42	0.15	23	0.55	1.78	2.31	0.51
Cassava (n=7)	1264	13.60	3.32	26.96	4.00	3.63	225	13.27	65.09	33.39	7.94
Cauliflower (n=2)	354	20.71	1.72	26.91	10.04	1.86	338	8.61	23.46	46.52	3.10
Orange (n=1)	108	2.41	0.38	2.43	0.90	0.22	6	3.33	1.52	1.01	0.55
Peanut (n=1)	206	11.67	1.14	3.63	2.20	2.63	88	6.37	13.13	12.51	5.68
Pineapple (n=7)	136	1.85	0.24	4.26	0.77	0.57	62	1.10	4.49	19.34	2.57
Spring onion (n=1)	59	3.06	0.41	1.62	1.84	0.62	36	1.45	7.41	3.61	1.34
Sugarcane (n=3)	303	2.19	0.26	2.48	0.29	0.36	23	2.21	20.50	13.43	4.19
Sweet potato (n=23)	249	3.18	0.73	8.04	0.82	0.45	92	2.58	6.27	9.20	3.17

concentrations than the unfertilized plots, in both the topsoil and subsoil (Table 1). In addition, the subsoil of fertilized plots had a significantly higher extractable P concentration than the unfertilized plots. In spite of this, the extractable P in topsoil of unfertilized plots and subsoil of fertilized and unfertilized plots was below the optimum range.

Nutrient budget of fertilized crops

Farmers applied inorganic fertilizers to a few crops that have a high nutrient requirement. To obtain a partial nutrient balance for these plots, the nutrients added in inorganic fertilizers were compared to the amounts exported in the harvested crop.

Overall, the N and K input from inorganic fertilizer was less than the amount exported in broccoli, cauliflower and bulb onion, resulting in a negative nutrient balance of N and K (Table 3). The P input from inorganic fertilizer exceeded the amount that was exported from these crops, resulting in a positive balance, so P is probably accumulating in the soil. However, the soils in the highlands of PNG are known to have a high P sorption capacity so much of the P in the soil may not be readily available for plant uptake. The negative balance of cauliflower (for N and K) was much greater than that in the other crops as it had a much greater export in the harvested crop (Table 3). However, this makes no allowance for the fertilizer efficiencies for N, P and K, so the negative balances are likely to be even worse.

Table 3: Mean nutrient budget (g/m²/yr) of broccoli, cauliflower and bulb onion crops.

	Broccoli	**Cauli-flower**	**Bulb onion**
Soil nutrient stock in 0 - 10 cm			
Total N	761	785	279
Extractable P	4.7	5.6	10.2
Exchangeable K	16.5	32.5	11.5
Nutrient export			
N	8.7	20.7	11.5
P	1.1	1.7	2.0
K	11.2	26.9	16.3
NPK fertilizer input			
N	4.4	5.5	6.8
P	4.8	6.1	2.8
K	4.4	5.5	7.9
Nutrient balance			
N	-4.3	-15.2	-4.7
P	3.7	4.3	0.9
K	-6.8	-21.4	-8.4

Harvested product management

In broccoli, the highest proportion of the P was located in the flower, and the highest proportion of N and K was in the leaves (Table 4). In cauliflower most of the N, P and K was in the leaves. For cassava and sweet potato, most of the nutrients were in the flesh, even though the skin had a higher nutrient concentration. Similarly, for pineapple, a high proportion of the N and K was in the flesh, but most of the P was in the skin and crown. In sugarcane, the skin contained a slightly higher proportion of N, P and K than the flesh. In peanut, most of the N and P and much of the K were in the seed but the leaves and stem also had a substantial proportion of these nutrients, especially K (Table 4).

Table 4: Proportion of nutrient content in plant parts.

Crops	N	P	K
Broccoli flower	0.43	0.46	0.30
Broccoli leaves	0.44	0.38	0.46
Broccoli stem	0.12	0.16	0.23
Bulb onion flesh	0.74	0.82	0.54
Bulb onion leaves	0.21	0.12	0.40
Bulb onion skin	0.06	0.06	0.06
Cassava flesh	0.73	0.87	0.85
Cassava skin	0.27	0.13	0.15
Cauliflower flower	0.17	0.19	0.20
Cauliflower leaves	0.73	0.68	0.64
Cauliflower stem	0.09	0.13	0.16
Peanut leaves and stem	0.36	0.24	0.42
Peanut seed	0.59	0.74	0.45
Peanut shell	0.05	0.02	0.13
Pineapple crown	0.25	0.30	0.14
Pineapple flesh	0.42	0.31	0.44
Pineapple skin	0.33	0.39	0.42
Sugarcane flesh	0.45	0.44	0.46
Sugarcane skin	0.55	0.56	0.54
Sweet potato flesh	0.84	0.83	0.79
Sweet potato skin	0.16	0.17	0.21

DISCUSSION

Nutrient content and export of harvested crops

Most of the crops in this study exported more nutrients per square metre than reported in other studies, especially K and N. This may be due to higher soil fertility or greater yields in the current study. Cauliflower, cassava, peanut and bulb onion exported large amounts of N per square metre and all the crops had a higher export of K than N, except peanut and spring onion. According to Anstett (1961, cited in Wichmann 1992: 278), cauliflower exports 19.8 g N/m^2, 2.9 g P/m^2 and 24.5 g K/m^2 which is a lower export of N and K but a higher P export than in this study. Amarasiri (1975, cited in Wichmann 1992: 144) and Howeler (1985, cited in Wichmann 1992: 144) indicated an export of 6.2-6.7 g N/m^2, 1.0-1.7 g P/m^2 and 10.1-16.4 g K/m^2 export in cassava, which is a lower export of N, P and K than in this study. Bradburg (1990, cited in Wichmann 1992: 139) reported an export of 2.3 g N/m^2, 0.51 g P/m^2 and 2.5 g K/m^2 in sweet potato, which is also a lower export of N, P and K than in this study. O'Sullivan, Asher, and Blamey (1997) reported N, P and K exports that were within the range found in this study.

Nutrient budget of fertilized crops

Data from the farms that used inorganic fertilizers revealed that the amount of N and K input from inorganic fertilizer was much lower than the amount exported in the fertilized crops (Table 4). However, the fertilizer efficiency of crops is not 100% so the negative balances may be greater. Broccoli, cauliflower and bulb onion exported more N and K than input from inorganic fertilizer, thus resulting in a negative nutrient balance of N and K. This was because the fertilizer application rate was not sufficient to replace the amount of N and K taken up by crops during growth and development. The negative N and K balance was similar to other studies (Bekunda and Manzi, 2003: 187-195; Goenster, Wiehle, Gebauer, Ali and Buerkert, 2014: 35-51; Haileslassie, Priess and Lesschen, 2006: 135-146).

The N export in crops was very small compared to the amount of total N in the soil but the amount of K exported was a substantial proportion of the exchangeable K in the soil (Kiup, 2017: 47). Although the proportion of soil N exported was small compared to the total N, the total N in the soil does not represent the readily available N that can be taken up by plants as most of it is in the form of organic matter and requires mineralisation to be made available. Hence, the negative balance may result in a temporary deficiency of available N in the soil. However, with K, the negative balance was large compared to the exchangeable K stock, but it is probably small compared to the reserve K. Exchangeable K will be replenished from the reserve K pool, but if the process is slower than K removal, K deficiency will result.

Crop harvest management

There is a direct loss of nutrients from the garden when root crops are harvested for marketing. However, if it is consumed in the house, the peelings can be utilized as an organic source of nutrient for the gardens. The farmer has the option to either uproot the whole plant (including stem and leaves) and take it home for processing, or to process in the garden. This choice is influenced by the distance of the gardens from the house. For example, with peanut, if the garden is near to the house, the farmer prefers to uproot the whole plant and process it at home, which is more comfortable and convenient. This practice results in a loss of nutrients from the garden. If the gardens are further away, the farmer might decide to process the peanut in the garden before taking it home as it would lessen the load to carry. Even so, the farmer would preferably process the peanut at the side of the garden, usually under a tree, away from the heat of the sun. In this case, it is still a removal of nutrients from the plot. However, in this case, it would be an easy option for the farmer to disperse the waste leaves and stems back to the plot. Therefore, these 'convenience' factors determine whether nutrients are retained or lost from the garden.

Peanut had the highest export of N and P per square metre when harvested compared to other crops, and most of these nutrients are located in the seeds. The proportion of nutrients in the seed was higher in our study than previously reported work. Longanathan and Krishnamoorthy (1977, cited in Wichmann 1992: 202) reported that, of the nutrients in peanut plants, 40% of the N, 42% of the P and 17% of the K was in the kernel. Loss of nutrients from the system in the seeds cannot be avoided, but the stem, leaves and shell also export substantial amounts of nutrients from the garden if the whole plant is removed.

Effect of residue management on soil fertility

The main nutrient input in the food gardens is from crop residues, but there are other nutrient sources within the farming system that can be utilized as a source of nutrients for the gardens. Coffee pulp, kitchen peelings and crop residues are sources of nutrients within the farming system that can be used as an organic amendment for food gardens.

Coffee pulp contains 0.38, 0.04 and 0.80 N, P and K kg/bag of parchment (typically 60 kg) respectively, and can be beneficial as an organic amendment (Webb et al., 2013: 9-14). However, a recent survey of coffee farmers in Bena showed that only a few farmers apply coffee pulp to their food or coffee gardens; most farmers leave the coffee pulp at the pulping site to decay (Curry, Webb, Koczberski, Pakatul, Inu, Kiup, Hamago, Aroga, Kenny, Kukhang, Tilden and Ryan, 2017). The few farmers who use coffee pulp effectively apply it to only one point or section in the coffee or food garden. Although this is a good practice, continual addition at the same point or section would lead to a build-up of nutrients to levels exceeding plant demand. Therefore, it would be better to vary the location of where pulp is placed from year to year. Similar to coffee pulp, the kitchen peelings and crop residues were usually applied to certain points or locations in gardens; therefore, this practice might also be improved by varying application points or locations. On the other hand, some farmers do not apply the food peelings or crop residues back to their gardens as it makes their gardens look untidy while others do not apply it as the waste provides a breeding ground for pests and diseases. However, the value of the nutrients in the waste should be considered for future soil fertility management.

CONCLUSION

This study showed that with current practices, the soils in Bena are likely to become deficient in N, P and K. The increase in commercial food production to supply urban markets has led to increased export of nutrients from gardens in crops. Better use of nutrient sources such as coffee pulp, kitchen peelings and crop residues could help to meet crop needs for N and K, as an application of those materials to soil will likely increase soil N and K concentrations. This will require education about the value of nutrients in waste products versus the value of convenience.

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