Maximizing Nutrient Utilisation and Soil Fertility in Smallholder Coffee and Food Garden Systems in Papua New Guinea by Managing Nutrient Stocks and Movement

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Copyright Declaration

Statement on Sources

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

Abstract

Smallholder farming systems in Papua New Guinea (PNG) are intensifying and becoming increasingly reliant on cash cropping. In the Highlands of PNG, coffee is the main cash crop and sweet potato the predominant subsistence crop. Due to the seasonality of coffee and low prices, farmers are increasingly growing vegetables and fruits for sale. This diversification in the cropping system has implications for nutrient dynamics and soil fertility. The aim of this study was to identify and quantify the movement of nutrient in food garden systems and interpret the effects of these nutrient movements on soil fertility. The study was conducted on six farms in Bena in the Eastern Highlands of PNG. At each farm, soil samples were collected from three food gardens. The aim of the soil sampling was to collect samples from areas with and without application of coffee pulp, fire ash, mulch or fertilizer. Harvested crop samples were also collected, washed and separated into consumable and non-consumable parts (e.g. skin), weighed, oven dried, ground and analysed for nutrient content. The two main pathways of nutrient flow quantified in this study were the output in harvested crop and input in inorganic fertilizers.

Soil fertility was generally adequate, except for extractable P and exchangeable K. Many individual gardens also had low soil N concentrations. The application of nutrient sources such as coffee pulp, kitchen peelings and ash was limited, but the areas that had physical evidence of such applications generally had higher soil K concentrations. Crops grown for market had the highest nutrient concentrations because of the addition of fertilizers. Crops like broccoli and sweet potato had high nutrient concentrations but the amount exported per square meter was lower than cauliflower and cassava due to lower planting density and plant biomass. Market demand also affects the net export of nutrients, as greater market demand for certain vegetables like broccoli and sweet potato will result in greater nutrient export. 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. The P balance was positive, which may result in its accumulation. However, the extractable P concentration in soil was low so the accumulated P may still not be fully available to crops.

The low input farming system currently practiced by smallholder farmers will continue to deplete the soil nutrients and the soil may become deficient in N, P and K. The process of crop harvesting and preparation results in the production of residues or wastes that might be better managed to retain nutrients. However, this option may be perceived as inconvenient and not practiced because the value of the nutrients in the waste is not appreciated. Therefore, adoption of these nutrient retention methods will require education about the value of nutrients in waste products versus the value of convenience.

Table of Contents

List of Tables

List of Figures

Chapter 1: Background

1.1 Introduction and Objectives

Agriculture is an important sector in Papua New Guinea (PNG) as most of the food consumed in PNG is produced locally. However, increased population, climate change and low crop productivity are factors affecting the countryôs agricultural systems. Since 2000, PNGôs population has been growing at a rate of 3.1% per year (PNG Census, 2011). The majority of this population (88%) reside in rural areas where subsistence farming forms the basis of their livelihoods. As a response to population pressure and land scarcity, agricultural production has intensified to maintain the food supply (Bourke, 2001; Gray, 2005). The intensification techniques practised by smallholder farmers are mostly facilitated by adoption of new food crops and more productive cultivars (Bourke, 2001). However, agricultural intensification may put the land resource under pressure leading to a decline in crop yield if the farming practices employed are unsustainable (Mtambanengwe & Mapfumo, 2005). Moreover, changes in climate such as increased temperature and less regular rainfall patterns have also contributed to a decline in productivity and instability of agricultural systems (Singh, 2012).

Traditional subsistence farming is solely for household consumption and surplus is either used as animal feed or for customary practices. However, agricultural practices have changed with the economic and social changes (Allen et al., 1995). Farmers are now farming not only to feed themselves but to improve their standard of living. Agricultural systems are now more economically driven than in the past. Furthermore, with the introduction of commercial tree crops like coffee, cocoa and oil palm into PNG, an integrated smallholder farming system has emerged where commercial crops are cultivated together with subsistence gardens.

Arabica coffee (*Coffea arabica* L.) has been widely adopted and cultivated since introduction in the 1930ôs into the Central Highlands of PNG by Lutheran Missionaries (Bourke, 1986) and it is currently the second largest agriculture export earning product in PNG. However, PNG contributes only 1% to world coffee production, partially due to the low input and low output system of production. Coffee is the main source of income for the vast majority of the people living in the rural areas of the Highlands. However, coffee is a seasonal crop so during the coffee off-peak season the farmers attain an income primarily through farming vegetables and fruits that are sold in the local or urban markets. Therefore, while the coffee and food garden systems complement each other, they require considerable labour, time and resources to manage.

Developing countries like PNG maintain low input agricultural systems where the use of commercial fertilizers is minimal. In such agricultural systems, the crops depend 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 thesis will concentrate on some of the anthropogenic processes that affect the soil fertility, like crop harvesting and organic matter movement.

Several studies have indicated that in smallholder farming systems there is spatial and temporal variability in soil fertility across and within different farm types (Diarisso et al., 2015; Mtambanengwe & Mapfumo, 2005; Nezomba et al., 2015). This variability was mainly associated with resource management strategies. Farms that were closer to the homestead were advantaged in comparison to farms that were located further away in terms of organic fertilizer application, giving rise to a soil fertility gradient. Moreover farms that were commercially oriented were also managed differently, for example, commercial fertilizers were applied to broccoli gardens but not to sweet potato gardens. These aspects will also be considered in this thesis.

The type of farming system and farming practices alter nutrient fluxes in time and space, so identifying these nutrient pathways is critical for the maintenance of soil fertility. Substantial amounts of nutrients are removed from the soil when crops are harvested but considerable amounts of plant residues are also generated in tree and 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. The nutrient concentration of the coffee cherry and the amount being exported out of the coffee system in PNG has been quantified by Webb et al. (2013). However, the nutrient concentrations of the food crops (both edible and non-edible parts) have not been sampled in a comparable manner. As such it is not possible to fully quantify the amount of nutrients being exported from the food gardens by these parts. This project will address this aspect of the food garden farming systems by:

1. Identifying and quantifying the movement of nutrients in harvested food crops from food gardens and the fate of those nutrient stocks.

2. Interpreting these nutrient movements in terms of the effect on soil fertility in food gardens.

This thesis will examine current agricultural practices of smallholder farmers and measure some of the fluxes in the system. Understanding how farmers manage their farms will help explain the factors that regulate the soil nutrient fertility.

1.2 Papua New Guinea Smallholder Coffee Farming System

1.2.1 Cultivation and Management of Coffee

Bourke (1986) gives a detailed review of the first introduction of coffee into the Highlands of PNG and states that village coffee was first introduced into the Central Highlands of PNG by Lutheran missionaries in the 1930ǿs. The coffee was planted mostly in plantations until 1944 when smallholder farmers begin cultivating it in the Eastern Highlands Province (EHP) of PNG. Currently, PNG produces both Arabica and Robusta coffee but 95% of the production comes from the Arabica coffee, which is grown mainly in the Highlands (Imbun, 2014).

Coffee in PNG is grown by three major sectors, smallholders, block-holders and plantations. Eighty five percent of the coffee is produced by the smallholder sector, 6% from the block-holder sector and 9% from the plantations sector (Giovannucci & Hunt, 2009). The three sectors are differentiated mainly by the size of their land holdings. The smallholder sector is comprised mainly of village farmers with less than 5 ha of coffee with a low-input, low-output system. Blocks are comprised of 5-29 ha and plantations are more than 30 ha. Block-holders and plantations use high-input, high-output systems.

Smallholder coffee farmers grow their coffee in several (2-4) small gardens of less than 1-2 ha each. The land selected for coffee planting is based on the availability of land; low fertility land may be chosen, resulting in coffee performing poorly. During the first 1-2 years of a coffee garden, annual food crops are intercropped with the coffee plants. Crops like banana, taro, sweet potato, corn, bean etc. are grown in the spaces between the coffee plants (Figure 1). These crops provide shade for the young coffee tree, minimize weeds, produce mulch and provide food for the farmerǿs household, additional to that provided from the main food gardens. Sometimes, animals like, pigs, goats and chickens are allowed to forage within mature coffee gardens and their faeces are an additional source of nutrient in the system.

Figure 1: Young coffee trees intercropped with taro

Most smallholder coffee is grown under shade trees. *Casuarina oligodon* is the tree species that is commonly planted within the coffee gardens of smallholders but other shade trees like, *Albizzia stipulate*, *Leucaena leucocephala* and fruit trees (e.g. banana and pandanus) are often planted together with *Casuarina oligodon* in the coffee gardens (Figure 2). The shade trees reduce the amount of light reaching the coffee trees resulting in low photosynthetic rates and consequently lower coffee yields. Due to the lower yields there is less demand for plant nutrients than in non-shaded systems.

The shade trees provide not only shade for the coffee trees but also a source of firewood for cooking and timber for building fences or houses. Additionally, the litter from the shade trees contributes to organic matter and nutrient recycling within the system. Moreover, the deep root systems of shade trees access nutrients from the lower part of the soil and make it available to the coffee through its litter or prunings.

Figure 2: Smallholder shaded coffee garden

In shade grown coffee systems, pruning of the shade and coffee trees is an important management practice. Shade trees should be pruned as required as too much shade may encourage disease and pest infestation of the coffee trees (Coffee Research Institute, 1998). Pruning of the coffee trees allows the removal of old or multiple coffee stems so that new stems can grow and give better yields. Also shade grown coffee trees tend to grow tall and bushy making it difficult to harvest so pruning makes harvesting easier. The recommended pruning time for coffee is between September and December after the peak harvest period (Coffee Research Institute, 1998). But smallholder farmers generally do not practise an organised pruning system. From observations, few farmers are willing to prune their coffee as they perceive pruning coffee trees results in a decline in the amount of coffee harvested the following year which they cannot afford. The few who prune their coffee, use the stems for firewood, to build or repair fences, or just leave them to decompose in the coffee garden.

The weeds are manually removed using hands and spade in young coffee gardens and slashed in mature coffee gardens whenever required, especially towards the coffee peak season to enable easy access to coffee trees for harvesting. The use of weedicides is minimal and they are only used whenever a farmer can afford to purchase them. The same applies to the use of inorganic fertilizers. The high cost of fertilizer makes it unaffordable for most smallholder farmers. Hence, most smallholder coffee farmers in PNG practice óorganicô based farming by default.

1.2.2 Coffee Harvesting and Processing

Coffee fruits take 7-9 months to fully mature after flowering. As the fruit ripens, the colour of the fruit changes from a dark green to a medium red colour. The peak coffee harvesting season is usually between April and August in PNG. The ripe coffee fruit is hand- picked and mostly processed to parchment coffee, but some is sold directly as cherry (unprocessed coffee fruit) especially when farmers urgently require cash .

The coffee cherry has three major sections that are separated during coffee processing. The first section is the exocarp (skin) and mesocarp which are collectively known as the coffee pulp. The second section is the mucilage layer under the mesocarp that covers the coffee bean, and the third section is the parchment coffee that contains the green bean (Figure 3).

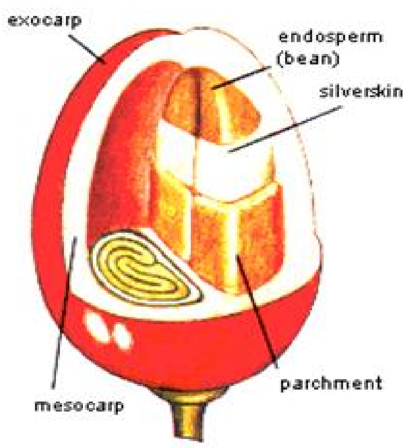

Figure 3: Cross section of a coffee (www.mercicoffee.com on 05/05/14).

Smallholder farmers in PNG process the harvested coffee cherry using the ówet methodô. In the wet method, cherry is squeezed with water in a manually powered pulping machine that removes the outer fleshy material (pulp) and leaves the bean that is covered in a mucilaginous layer. The mucilaginous beans are fermented in plastic buckets or bags for 34-36 hours. The mucilage is broken down by natural enzymes until it can be washed away; the purpose of this is to remove the mucilage layer that can, if not removed, taint the flavour of the coffee. The coffee is then thoroughly washed with clean water. The moisture content of the wet parchment coffee at this stage is approximately 57%. To reduce the moisture to an optimum 12.5% the parchment coffee is dried in the sun for up to 10 days.

The processing of coffee produces residues that have substantial nutrient value. All the sections of the coffee fruit (except the parchment coffee, which is sold) contain nutrients that can be recycled for soil nutrient management (Figure 4). However, the pulp (mesocarp and exocarp) in most cases is left in a heap at the pulping site to degrade without further utilization. From observation, one of the reasons that farmers do not use the pulp is due to the distance of the pulping site from the coffee garden, or they are too busy with harvesting. Most farmers tend to pulp their coffee near the house for ease of washing (closer to water source) and drying and security (to avoid coffee theft). Since wet pulp is heavy, it is quite laborious to carry the pulp back to the coffee gardens further away from the house, so farmers are reluctant to transport pulp to those coffee gardens. Sometimes the pulp is applied to the coffee and food gardens next to the house. The farmerôs time and family labour is divided between the coffee and food garden activities so time and labour allocated to coffee farming is limited. Ultimately, the use of coffee residues as a source of fertilizer depends on the farmerôs decision.

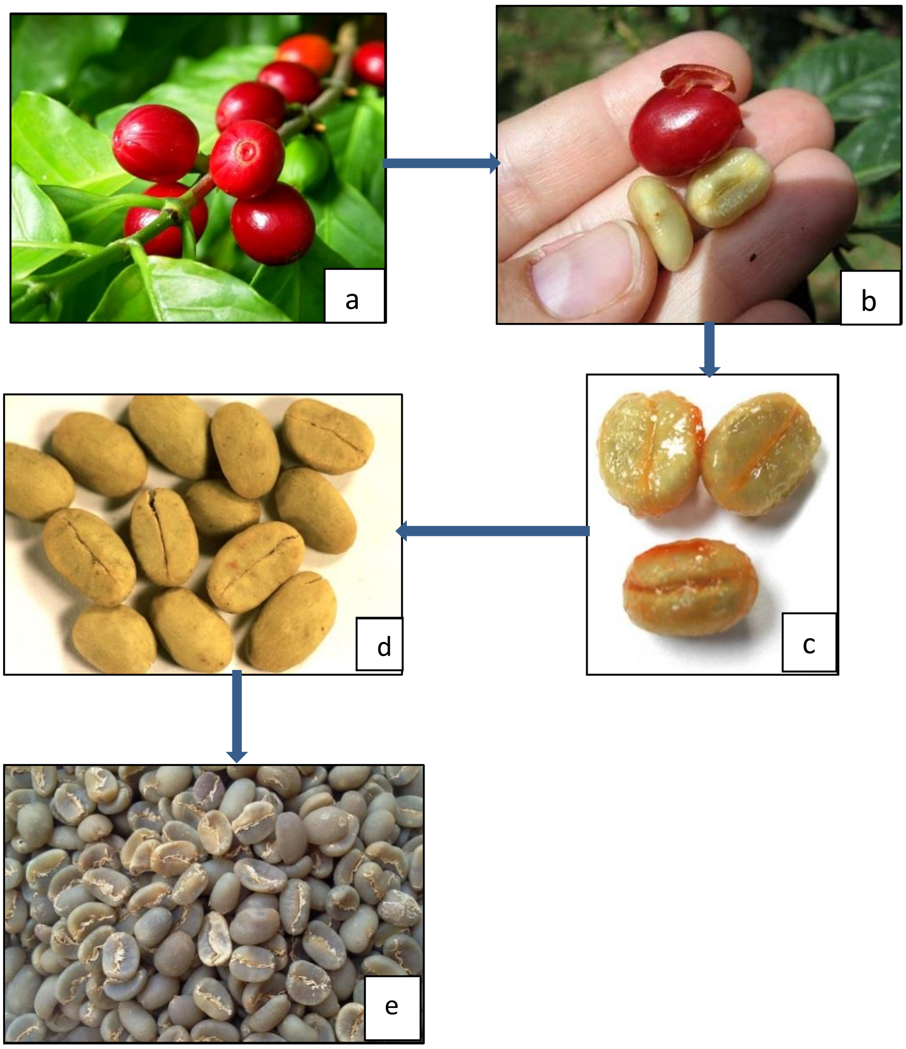

Figure 4: The stages in processing coffee cherry to coffee green bean: a. coffee cherry b. coffee pulp c. mucilage bean d. parchment coffee e. green bean

1.3 Papua New Guinea Food Farming Systems

Agriculture has been practiced in PNG for more than 10,000 years and continues to be an important sector of the country (Bourke & Harwood, 2009). The agricultural system has evolved over the years due to a variety of factors, with population growth being the most prominent of all. Initially, agricultural production was aimed at establishing a constant source of food supply for the household. However, economic and social changes brought about the need to establish an improved standard of living.

Subsistence farming is characterised by the cultivation of crops on small plots with low or non-use of external inputs (e.g. commercial fertilizer). In PNG, the subsistence gardens are usually less than one hectare and are cultivated with a mixture of crops or a single crop. Normally, a farmer would have several gardens, each garden cultivated for different purposes. For example, a sweet potato garden may be specifically cultivated for feeding pigs as pigs are commonly reared for meat and customary exchanges (e.g. marriage ceremonies).

When preparing new gardens, farmers usually use a shifting cultivation technique, which starts with cutting and burning of the fallow vegetation. This practise enables the release of nutrients in the natural cover, reduce soil acidity and minimize weed and pest infestation. Shifting cultivation systems are favoured because labour requirements are fairly low. The ploughing of the soil and planting is done by women while the men dig drains and build fences around the gardens that are prone to be disturbed by pigs.

The planting material or seeds for the new gardens are normally taken from old food gardens or provided by relatives whereas some are transplanted from a nursery. The garden fences are built using timber from forest trees or sometimes large branches from the pruned coffee trees or shade trees.

After planting, the food gardens are maintained mostly by weeding, staking of crops and maintenance of fences. Similar to the coffee system, the food garden system has minimum inputs and relies on the soil nutrient reserve and internal nutrient cycling of the system to maintain productivity. The weeds, crop litter and crop residues are the main nutrient sources that are recycled in the food garden system. Some farmers use external organic inputs in their food gardens like animal manure or coffee pulp. From observation, the farmers who use inorganic fertilizers are usually those who grow vegetables that have a high demand for nutrients (e.g. cabbage, broccoli and cauliflower) and are produced for sale.

Generally, when food crops are harvested, the parts that are edible or marketable are the only parts that are transported out of the food garden whilst the crop residues (stubble, stalk and leaves) are left on the garden or piled on the side of the garden. Sometimes some of the non-edible parts (e.g. carrot leaves, pineapple crowns, sugarcane sheaths, etc.) are removed from the garden and prepared at the farmerĝs house and these parts are then sometimes discarded in the gardens near to the house.

Overall, apart from land, one of the most important resources in a smallholder agricultural system is human labour, as it is an essential input in a non-mechanical production system. The availability of labour in a farmerĝs household may affect the management practices, such as frequency of weeding and application of external organic nutrient inputs. In a survey in Mozambique, farmers identified weeding as the most labour demanding activity (Leonardo et al., 2015). Since weeds were removed by hand-hoeing, the delay in weeding due to limited labour resulted in lower crop yields. Also, crops have different growth cycles so farmers have to consider the seasonality labour demand of crops when deciding which crop to cultivate and the cropping sequence to avoid labour shortage problems.

Figure 5: Intercropping of pineapple and peanut

Summary

Traditional agriculture is associated with subsistence farming, however, this system is now changing as farmers are venturing into a diversified farming system where they not only farm to feed themselves but to improve their livelihoods. Introduction of new crops, improved cultivars and cash crops has resulted in changes in the farming system. The introduction of cash crops has exposed farmers to the fact that food crops can be commercialized.

In a diversified farming system, all the different plots complement each other and require an allocation of resources for their productivity. In smallholder farming systems, the most import resource is human labour. Hence, the farmer has to make necessary decisions on what type of crops to cultivate and the cropping sequence so that the seasonality of labour demand for each crop does not create problems for the farmer. In the Highlands of PNG, farmers tend to conduct their food gardening activities during the coffee off-peak season. Within that period, new gardens are cultivated, crops are planted, gardens and fences are maintained or harvesting and marketing is done. All of the activities from cultivating, planting, maintaining, harvesting and marketing are associated with nutrient fluxes in the system which may affect soil fertility.

Most smallholder farmers maintain a low input system in both the coffee and food gardens so the use of external inputs (commercial fertilizers or insecticides) is very minimal or not at all. Such a system enables continuous loss of nutrients if no other nutrient inputs are utilized to replace the amount of nutrients that are removed naturally or by humans. Most farmers are probably unaware of the detrimental effects of their agricultural practices on soil nutrients; hence this study will enable the farmers to understand the consequences of the type of agricultural practices they employ in their coffee and food garden system so that they can decide whether to adopt better and more sustainable practices in relation to nutrient re-use.

Chapter 2: Literature Review

2.1 Nutrient Stocks and Fluxes in the Coffee System

Most of the smallholder farmers in PNG cultivate shade-grown coffee. Shade-grown coffee requires less nutrient input than unshaded coffee because of the moderate to low coffee yields. A study by Hombunaka and Harding (1994) revealed that traditionally managed, heavily shaded smallholder coffee gardens did not respond to inorganic fertilizer applications. The nutritional requirements of shade-grown coffee trees are met by nutrients recycled within the system and the nutrients provided by the soil and shade trees. Nevertheless, even under shaded conditions, coffee is a perennial crop so nutrients from the coffee system are continuously removed through the harvested coffee cherry and leaching of nutrients below the rooting zone or immobilized in stems and branches. A study conducted in Kenya by Cannell and Kimeu (1971) on the uptake and distribution of major nutrients in a conventionally managed coffee system showed that 100 g nitrogen (N), 6 g phosphorus (P), 100 g potassium (K), 35 g calcium (Ca) and 10 g magnesium (Mg) was utilized by a coffee tree in a year. From this amount, about 8-9% is exported from the coffee system in the harvested coffee cherry and 50-81% is returned to the soil in prunings and leaf litter (Cannell & Kimeu, 1971).

2.1.1 Coffee Cherry

The coffee cherry is rich in nutrients, particularly K (Braham & Bressani, 1979), which are exported out of the coffee system when the coffee cherry is harvested for processing. From the cherry that goes out of the coffee garden, 55% of the dry weight is in the coffee bean while 29% is in the coffee pulp and the other 16% is in the mucilage and coffee hulls (Braham & Bressani, 1979). Almost half of the K in the cherry is in the coffee pulp (Valkila, 2009; Webb et al., 2013). Several studies show that when coffee cherry is exported out of the coffee system (without returning skin, pulp or parchment to the field), 31-34 kg N, 2.18-2.49 kg P and 39.3-53.5 kg K per 1000 kg green bean is removed (Wichmann, 1992, pg. 502). Webb et al. (2013) found that from 300 kg of coffee cherry (required to produce a 60 kg bag of parchment coffee), 1.4 kg N, 0.1 kg P and 1.6 kg of K is lost from a smallholder coffee garden in PNG. These losses reflect the high K content of the coffee cherry.

In a fertilized shaded coffee garden in India, the nutrient content of coffee pulp (dry weight) was found to be 2.4% N, 0.5% P and 4.2% K (Korikanthimath & Hosmani, 1998). In PNG, Kiup (2014) reported that the average nutrient concentration of coffee pulp (dry weight) ranged from 1.4-1.6% N, 0.12-0.16% P and 2.9-3.9% K. The lower nutrient values in PNG may be due to the low nutrient input management system of smallholder shaded coffee.

Coffee pulp requires proper composting before it can be applied safely to the soil under coffee trees because fresh coffee pulp emits heat and gas when it ferments and can be harmful to plants (Korikanthimath & Hosmani, 1998). However, Naidu (2000, cited in Van der Vossen, 2005) reported that composted pulp contained 2% N, 0.2% P and 2.5% K. This is somewhat lower than uncomposted pulp and thus indicates that substantial amounts of nutrients in the pulp are lost during composting, especially K. The lower K content of composted pulp may be attributed to leaching because of its exposure to rainfall. However the N and P contents are higher than the uncomposted pulp as it is retained by the decomposing organism while carbon is respired away as carbon dioxide resulting in reduced biomass of pulp.

In PNG, the value of K may be lower than the original pulp due to greater leaching because of high rainfall. In most cases, when coffee farmers process the coffee cherry, the coffee pulp is left in a heap at the pulping site to rot without utilizing it further. The few who do use coffee pulp as an organic fertilizer usually do not apply it directly to food or coffee gardens after processing hence the decayed pulp that is applied is of lower nutrient value than original pulp.

Suárez de Castro (1960) compared the chemical composition of coffee pulp with various organic fertilizers (e.g. manure and compost) and coffee pulp had higher N and K content. He also reported that the chemical composition of 45 kg dried coffee pulp was equivalent to 4.5 kg of inorganic fertilizer 14:3:37($N:P_2O_5:K_2O$) or to 9 kg of 7:1.5:18.5($N:P_2O_5:K_2O$). Due to the difficulty in transporting coffee pulp, it would be more convenient to use inorganic fertilizers as they are nutrient dense and easier to transport than dried coffee pulp.

2.1.2 Coffee leaf, branch and stem

Coffee trees grown under shade grow taller and have larger and fewer leaves, branches and flowers than unshaded coffee trees (Campanha et al., 2004). The vegetative parts of the coffee tree take up more N than the coffee fruit as it is needed for its growth (Van Der Vossen, 2005). Subsequently, the amount taken up depends on the fertility of the soil. A study in PNG found that the N, P and K concentration in shaded coffee leaves ranged between 2.0-3.0% DM, 0.14-0.17% DM and 1.7-2.2% DM respectively (Kiup, 2014). Willson (1985) reported that a coffee stem contained 0.6% N, 0.05% P and 0.4% K in dry matter. This would imply that most of the nutrients that are taken up by the vegetative parts of the coffee tree are stored in the leaves (Mangal, 2006).

The smaller branches and leaves of the coffee trees are usually recycled within the coffee system from natural fall and contribute to the organic matter of the soil. However, in PNG some of the pruned coffee stems and large branches are taken out of the coffee system and used as stakes for crops in food gardens, for firewood, for pig fences or coffee/food garden fences. Moreover, in some villages the coffee leaves are swept and piled at the side of the coffee garden and burnt. Removal of the coffee stem/branches and leaves can cause substantial loss of nutrients from the coffee system, particularly N. On the other hand, some smallholder farmers do not prune their coffee trees. Since, the vegetative parts take up nutrients for its growth; the nutrients stored in these parts may be permanently sequestered in the system if the coffee tree is not pruned.

2.1.3 Coffee shade trees

The shade tree plays a vital role in the coffee system. Beer (1987) and Alemu (2015) have described the characteristics of shade trees in the coffee system. Apart from its main role as a shade provider, shade trees also help in maintaining nutrients in the coffee system.

Aranguren et al. (1982) stated that the amount of nitrogen and other nutrients exported by the harvest from shade-grown coffee is small compared to amounts removed by high-yielding unshaded coffee. Moreover, the nutrients lost by soil erosion and leaching in shaded coffee is lower than unshaded coffee systems. De Castro and Rodriguez (1955, cited in Willson, 1985) demonstrated that loss of nutrients through erosion exceeded the amount removed by the coffee crop harvest in unshaded coffee systems.

Some shade trees can fix nitrogen that is an added nutrient source in the shaded coffee system. *Casuarina* species, a common shade tree in coffee gardens, can fix about 60 kg N/ha/yr (Dommergues, 1987). A study conducted on the fixation rate of *Casuarina equisetifolia* showed that 40-60 kg N was fixed per hectare per year (Gauthier et al., 1985). Bino and Kanua (1996) estimated that 39 kg N, 3 kg P and 10 kg K were returned to the soil from 3 year old *Casuarina* leaf litter. Parfitt (1976) found that soil under *Casuarina oligodon* shade trees can accumulate N at a rate of 0.015-0.018% per year.

Nitrogen fixed by the shade trees and added to the soil in the shade tree litter fall could replace the amount exported from the coffee system (Aranguren et al., 1982). However, the shade tree roots can compete with the coffee for soil nutrients if it has a shallow rooting system (Beer, 1987). On the other hand, nutrients absorbed by the deep rooted shade trees may be made available to the coffee crop through its leaf litter or when the shade tree is pruned.

In PNG, smallholder coffee gardens are usually intercropped with fruit trees like banana during the initial establishment of the coffee garden. These fruit trees provide shade and mulch for the coffee trees. However, the fruit trees also take up nutrients for their growth and fruit development. Moreover, the harvesting of fruits for household consumption presents another pathway of nutrient loss from the coffee system.

2.2 Nutrient Stocks and Fluxes in Food Garden Systems

Crop production systems in most developing countries rely on the natural fertility of the soil, as the use of inorganic fertilizers is minimal. In the past, the soil fertility of the gardens was sustained by the shifting and fallow cultivation practice. However, with increasing population pressure, land use has intensified; the cropping period is extended and fallow period is reduced. With reduced fallow periods, the soil does not have enough time to replenish the amount of nutrients removed from the farming system. In addition, the fallow vegetation or crop residues are usually burnt during land preparation: this practice results in substantial losses of C, N and S in the form of gases but some nutrients such as K, Ca and Mg are present in the ash left after burning. Holscher et al. (1996) estimated a loss of 73% N and 71% S from burning. However the amount of nutrients lost as gas also depends on the fire temperature and plant species. Different plant species have different nutrient concentrations and flammability so different amounts of nutrients may be lost when burnt. Moreover, when crop residues are burnt it leaves the soil exposed hence it is prone to soil erosion and leaching which are pathways for nutrient loss. Therefore, continuous mining of the soil nutrient reserve for crop production will inevitably lead to a decline in productivity. Several studies (Haileslassie et al., 2005; Kamau, 2015; Richard, 2014; Tiwari et al., 2010) have indicated the main pathways of nutrient input and output in the food farming system. The inputs were mainly through retention of crop residues, application of animal manure, nitrogen fixation by legumes plants and atmospheric deposition, whilst the main nutrient losses were via harvested food crops, soil erosion and leaching.

2.2.1 Shifting cultivation and fallowing to maintain soil fertility

Traditionally, smallholder farmers restore soil fertility through the shifting and fallowing practice of farming. After 1-4 years of cultivation the land is abandoned to fallow for 5-15 years while farmers move to another area to do gardening. This fallow period allows the soil to accumulate nutrients for the next cropping period. The type of fallow vegetation and length of fallow period has a substantial influence on the content of nutrients accumulated in the soil. Longer fallow periods allow woody secondary vegetation to establish, which results in high rate of biomass accumulation. In shorter fallow periods weeds are more dominant thus producing lower biomass accumulation. However, a study in West Africa showed that longer fallow periods did not significantly improve soil fertility and shorter fallow periods (1 year) were sufficient to replenish soil fertility (Tian et al., 2005). This study recommended cover cropping and alley cropping rather than natural fallow.

Another study was conducted in PNG on the nutrient restoring capacity of two common fallow species; *Piper aduncum* (woody) and *Imperata cylindrica* (non-woody) and an improved fallow species *Gliricidia sepium* (woody legume) (Hartemink, 2004). The study revealed that the *Gliricidia sepium* accumulated the largest amount of all major nutrients except K, which was highest under *Piper aduncum* fallow. *Imperata cylindrica* had the lowest nutrient concentration in its biomass. It was recommended that shorter fallow periods should consist of leguminous species.

2.2.2 Organic Amendment

With reduced fallow periods, some farmers are now employing other means to improve soil fertility, mainly through the use of organic amendments. External organic amendments like animal manure, organic residues, compost and kitchen litter are sometimes applied to food gardens. Also, the natural nutrient recycling in the cropping system from the crop litter, weed litter and crop residues also help to retain soil fertility if it is not removed.

In integrated farming systems where livestock are reared together with food production, the two systems complement each other in terms of nutrient re-use. The manure from the livestock is used as an organic fertilizer in food gardens and the crop residues are used as animal fodder for the livestock. On the other hand, this system also presents an avenue for nutrient loss. In semi-humid regions where such integrated farming systems are practiced, the crop residues are removed for fodder and fuel and animal manure is used for household energy, resulting in nutrient losses in this system. Moreover, in most cases the amount of organic amendment used in a smallholder agriculture system is usually below the optimal amount of nutrient that is required to replenish the amount that leaves the system. Materechera (2010) reported that low quality fodder, improper management and application methods of manure are some of the reasons behind the suboptimal manure levels in cropping systems.

2.2.3 Legume Crop Rotation

Crop rotation with leguminous crops is another strategy for soil fertility management. The use of legume crops as a fallow crop or break crop allows the subsequent crops to benefit from the nitrogen fixed by the legume crop. Several studies have demonstrated an increase in yield of subsequent crops following a legume rotation (Adjei-Nsiah et al., 2007; Rahman et al., 2014; Scalise et al., 2015; Shah et al., 2003). Apart from yield increase, legume rotation also improves soil chemical properties and controls weeds and pests (Tarfa et al., 2006) . However, the choice of legume crop for rotation may depend on access to resources and the needs of a farmer (Adjei-Nsiah et al., 2007). Although some legumes give higher yields than others; the farmers may not cultivate them if they do not provide food or have any market value. Moreover, some legumes require additional inputs and labour when incorporating into the soil or harvesting/removal for subsequent crop.

2.3 Nutrient Losses from Food Garden Systems

The nutrient losses from food production system are influenced by environmental factors, management practices/farmers decisions and socio-economic factors. The amount of nutrients removed from a food system also depends on the farm size and crop density. More nutrients are removed from a larger and denser crop production system. Therefore, in developed countries, substantial amounts of inorganic fertilizers are used to meet the high nutrient demands of the intensive cropping system. On the other hand, in developing countries, farmers are also intensifying crop production, but with limited use of inorganic fertilizers, resulting in nutrient mining. When the natural ecosystem is manipulated for agricultural production, the normal nutrient cycle is disrupted and may result in nutrient imbalance.

The major pathways of nutrient losses in food production systems are through crop harvesting, residue removal, soil erosion, leaching of nutrients and burning (Smaling et al., 1993). Some studies have identified crop harvesting as the major pathway of nutrient loss in food farming systems (Goenster et al., 2014; Smaling et al., 1993; Tiwari et al., 2010). Other studies reported that soil erosion and burning were the main nutrient loss pathway in the farming system (Kanmegne et al., 2007; Richard, 2014). This indicates that variability in farming practices within or among cropping systems should be taken into account when assessing the nutrient fluxes of a farming system in order to gain insight into the main nutrient losses and gains of the farming system.

2.3.1 Crops and Nutrient Loss

Different crops have different nutrient requirements for their growth and productivity so the amount of nutrients removed from the soil by a crop varies. De Jager et al. (1998) found that the nutrients removed by cash crops were lower than that of major food crops (maize and maize-beans) but the results were not significant. In PNG, nutrient export from coffee gardens has been quantified but information on nutrient export in food crops is limited and ambiguous.

Farmers with access to markets are increasingly commercializing their agricultural systems (Thompson, 1986). In the highlands of PNG, farmers are growing vegetables and fruits at a larger scale to sell as a source of income, apart from the main coffee crop income. Generally, farmers have different resource management strategies within their farms that result in a spatial fertility gradient. For example, in subsistence gardens external inputs and maintenance are very low compared to commercial vegetable gardens (e.g. cabbage and broccoli). This indicates that the market orientation of farms has an effect on farming practices. De Jager et al. (1998)

reported that farms that were highly market oriented had greater amounts of nutrients removed despite the smaller cultivation area because of intensive cropping activities.

In a low input smallholder farming system, the farmerӧs choice of crops for cultivation is very important as it subsequently affects the soil fertility. With the introduction of new crops and improved cultivars, farmers have the benefit of selecting from a range of crops to grow. But this decision is also affected by the fertility of the soil, the climate and social and economic factors.

The estimated percentage of food crop production in PNG in 2000 was; 64% sweet potatoes, 10% banana, 10% taro, 6% cassava and 6% yam (Bourke & Harwood, 2009). These crops are usually grown in mixed systems. Farmers also forage for some food from the forest, exchange food crops with relatives or contribute food crops to cultural/traditional ceremonies. Hence, food farming is not solely for human consumption but for social purposes as well (Bourke & Harwood, 2009). The nutrient concentrations and amount of nutrients removed in common food crops grown in the highlands of PNG are discussed below.

2.3.2 Sweet potato

Sweet potato (*Ipomoea batatas)* is grown in both the highlands and lowlands but it is the staple food for the people in the highlands of PNG (Thompson, 1986). Sweet potato sustains 2.5 million people in the highlands of PNG (Bailey et al., 2009). However, there has been a decline in the sweet potato yield over recent decades. Several studies (Allen et al., 1995; Bourke, 2005; Sem, 1996) have attributed this decline to decreasing soil fertility because of the shorter fallow periods. In fertile soils, continuous cultivation resulted in a decline in tuber yield but not vine yield; but in low fertility soils, both tuber yield and vine yield were low with continuous cultivation (Hartemink et al., 2000). According to Hartemink et al. (2000) ӧcontinuous cultivation reduces tuber yields and then reduces vine productionӧ. Enyi (1977) reported that the decline in sweet potato yield was not due to fewer numbers of tubers per plant but a decrease in the size of individual tubers. Hence, there was a competition for nutrients between the tubers and the vines of the sweet potato.

In many areas in PNG, sweet potato does not require a high input of N. Hartemink et al. (2000) reported that when N fertilizers were applied to sweet potato there was no positive response in the yield. However, a study by Sillitoe (1996) in East New Britain showed that sweet potato yields increased with an increase in N input. Sweet potato can grow in soils low in P levels because of its association with vesicular arbuscular mycorrhizae, which enables it to acquire P from soils (Floyd et al., 1988). Sweet potato has a high requirement for K (Bourke, 2005). The study by Bailey et al. (2009) identified an overall deficiency in K and P in volcanic soils and an S deficiency in non-volcanic soils, which affected the sweet potato production. They concluded that the removal of vines from the cultivation area, shorter fallow periods and burning of weed and crop residues were the factors leading to the decline in K and S.

Sweet potato has a high requirement for K so a significant amount of K is removed from the soil when sweet potato is cultivated (Bourke, 2005). Ishida et al (2000) found that two different sweet potato varieties grown under the same conditions had different nutrient concentrations in the vegetative parts and tuber. The Kognesengan variety had higher K concentrations than the Beniazuma variety and most of it was concentrated in the leaf and stem (Table 1).

Therefore, the K that is removed by sweet potato tubers may be replaced by retaining the leaves and stems of sweet potato as mulch.

Table 1 Mineral concentration of each part of two kinds of sweet potato in Japan

Variety	**Parts**	**Concentration (mg/kg)**							
		Ca	P	Fe	Na	K	Mg	Zn	Cu
Kognesengan	Leaf	1870	680	543	38	6390	790	9	4
	Stalk	1930	147	12	18	4670	410	5	2
	Stem	1790	217	24	52	5740	300	7	3
	Tuber	737	400	16	223	5020	270	4	3
Beniazuma	Leaf	1740	367	55	21	3570	1070	6	6
	Stalk	1620	83	28	14	1880	620	2	2
	Stem	1550	187	39	24	2470	353	3	4
	Tuber	680	427	23	266	2350	267	2	2

Source: Ishida et al. (2000)[1]

2.3.3 Taro

Taro (*Colocasia sp.*) is the second-most consumed crop in PNG (Singh et al., 2006). It has several varieties that are grown mainly in the lowlands. Taro is usually grown as a sole crop or intercropped with sweet potato or sometimes in between cash crops like coffee and oil palm. However, there has been a gradual decline in its production mainly due to the taro leaf blight disease (Nath et al., 2013). A study done by Villanueva et al. (1983) on the performance of taro under different fertilizer treatments, population density and different production systems showed that an increase in N fertilizer rate resulted in taller plants and larger leaf area while the corm yield was variable but an application of 30 kg N/ha was sufficient to obtain an optimum yield. They also found that taro cultivated by either mono-cropping, rotation cropping with corn or intercropping with mung bean all had a similar production. De la Pena and Plucknett (1972) found that an increase in the rate of N fertilizer application increased the N concentration in the taro but resulted in a decrease of P, K and Ca. They concluded that N fertilizer should be

[1] I have assumed that the values in Table 1 are on a dry weight basis but the methodology is not clear. It is not stated clearly in the original article.

applied in the earlier stages of the taro growth (3-6 months) because the crop requires most of its N during the early stages of growth.

The other taro species now commonly grown in both the lowlands and highlands are the *Xanthosoma* sp., commonly known as ótaro kongkongô in PNG. This species is less prone to taro leaf blight (Bradbury et al., 1988). However, there is limited data on the nutrient composition of *Xanthosoma* species. Bradbury and Holloway (1988) suggest that the nutrient composition of *Xanthosoma* sp. is similar to that of *Colocasia* sp.

Similar to sweet potato, taro has a high concentration of K in the corm, which would suggest a depletion of soil K if large amounts are continuously exported (Table 2).

Table 2 Mineral composition of taro corms and nutrient removal by 8t/ha and 65t/ha yield

	Concentration (dry matter)	**Nutrient removal (kg/ha) with corm yield of:**	
Nutrient		**8 t/ha**	**65 t/ha**
N (%)	0.60-1.43	14-34	117-280
P (%)	0.17-0.47	4.0-11.2	39-91
K (%)	1.08-1.77	25-42	210-345
Ca (%)	0.04-0.13	1.0-3.0	8.5-24.7
Mg (%)	0.07-0.38	1.6-9.2	13-75
S (%)	0.03	0.68	5.5
Fe (mg/kg)	16-57	0.038-0.14	0.31-1.11
Mn (mg/kg)	11-16	0.027-0.038	0.22-0.31
Cu (mg/kg)	7-9	0.016-0.019	0.13-0.16
Zn (mg/kg)	40-120	0.10-0.29	0.78-2.34
B (mg/kg)	3.0	0.007	0.06

Source: Blamey (1995)

2.3.4 Cassava

Cassava (*Manihot esculenta*), known as ‗tapioka' in PNG, has recently gained importance in the PNG farming system and accounts for 6% of the total staple food production in PNG (Bourke & Harwood, 2009). Cassava is usually planted after sweet potato and taro due to its ability to grow well in low fertility soils (Denoon et al., 1981). When compared with other crops, cassava is higher yielding but removal of N is lower and K is higher per unit area (Table 3).

The cassava tubers removed less N and P than other crops with a yield of 11 t/ha (Putthacharoen et al., 1998). Lebot (2008) concluded that cassava absorbs nutrients depending on the yield of the plant. Therefore, higher yields of cassava imply a fertile soil.

Table 3 Average nutrient removal from cassava compared to other crops

Crop/plant part	**Yield**	**N**	**P**	**K**	**N**	**P**	**K**
	(t/ha)		**(kg/ha)**			**DM (kg/t)**	
Cassava/fresh root	13	55	13.2	112	4.5	0.83	6.6
Sweet potato/fresh root	5.1	61	13.3	97	12	2.63	19
Maize/dry grain	5.6	96	17.4	26	17	3.13	4.7
Rice/dry grain	4.0	60	7.5	13	17.1	2.4	4.1

Source: Howeler (2002)

2.3.5 Yam

Yam is mostly grown in the lowlands of PNG, but the highland farmers are now planting white yam (*Dioscorea rotundata*) also known as óAfrican yamö, which was introduced by PNG National Agricultural Research Institute (PNGNARI) during a drought in the highlands. The African yam is now widely grown in the Eastern Highlands of PNG because of its high yield compared to other yam species. Compared to other yam species, *D. rotundata* has lower moisture content and a higher starch and energy content (Bradbury & Holloway, 1988). Obigbesan and Agboola (1978) found that *D. rotundata* removed 11.5-12.8 kg N and 12.7-14.5 kg K per tonne dry matter in the harvested tuber (Table 4). Therefore, if the tubers are consumed by the farm household, returning peelings to the garden would slightly reduce nutrient losses.

Table 4 Average nutrient concentration in yam tubers in 1974 and 1975

Species	**Type of tubers analysed**	**N**	**P**	**K**	**Ca**	**Mg**
		(g/kg tuber dry weight)				
D. alata	Unpeeled	14.2	1.9	17.9	0.3	0.1
	Peeled	13.2	1.3	15.5	0.2	
D. rotundata, cv Efuru	Unpeeled	12.8	1.5	14.5	0.3	0.1
	Pealed	12.2	1.2	13.3	0.2	
D. rotundata, cv Aro	Unpeeled	11.5	1.5	12.7	0.3	0.1
	Peeled	11.2	1.3	11.7	0.2	
D. cayenensis	Unpeeled	9.1	1.3	11.9	0.3	0.1
	Peeled	8.3	1.0	9.3	0.2	

Source: Obigbesan and Agboola (1978)

2.3.6 Banana

Banana is another staple crop grown in PNG. It is usually grown as single stands within or at the boundary of food gardens. Also, it is commonly grown in coffee gardens as shade and food source. The harvested banana is mostly used for household consumption but some selected cultivars are sold at the market for income. Occasionally, the banana leaves and pseudostem are used as materials for preparing traditional feast (ómumuõ). Since banana is mostly intercropped in food gardens or in between cash crops, it is difficult to quantify the amount of nutrients removed in the harvested banana on a ópper land areaô basis (Kambuou, 2004). Banana has high K and Mg concentration (Table 5).

Table 5 Mineral concentration in diverse banana varieties (mg/100g)

	Sweet Banana[1]		Plantain[1]		Cavendish (AAA)[2]	Plantain (AAB)[2]
	Ripe	Unripe	Ripe	Unripe		
K	385	-	500	-	319	342
P	22	-	30	35	22	26
Ca	8.0	8.0	3.0	7.0	4.9	7.2
Mg	30	-	35	33	31	39
Na	1.0	-	4.0	-	17.4	16.0
Fe	0.4	0.9	0.6	0.5	0.8	0.8
Mn	0.2	-	-	15	0.2	0.7
Zn	0.2	-	-	0.1	0.2	0.4
Cu	0.1	-	-	0.2	0.3	0.3

Source: [1]Aurore et al. (2009); [2]Mohapatra et al. (2010)

2.3.7 Maize

Maize iscommonly grown together with the main staple crops in PNG. In smallholder gardens, maize is usually planted in a mixed cropping system with the staple food crops for household consumption. During harvesting, farmers usually harvest the corn ear and the stalk and leaves are left in the garden or piled at the side of the garden. The corn ear is made up of the husk, cob and grain. The husk is removed when prepared for household consumption and disposed-of as mulch at nearby gardens or thrown in a rubbish dump. The cob is also discarded after the grain has been consumed. Sometimes the cob is fed to goats or pigs.

Maize has a high concentration of N in the grain whilst the stover, which includes the stalk, leaves and husk, has a high concentration of K (Table 6). Therefore, there is an implication of a loss of N when the maize grains are harvested. The stover, when left in the garden, can return substantial amounts of K to the soil.

Table 6 Nutrient concentration (dry weight basis) in maize grain and stover (stalk and leaves)

	(g/kg)		
Parameter	**N**	**P**	**K**
Grain	13.30	2.63	3.63
Stover	8.11	0.52	21.82

Source: Setiyono et al. (2010)

2.3.8 Pineapple

Pineapple (*Ananas comosus*) is grown and consumed in both the highlands and lowlands of PNG. It is usually consumed locally and not processed further for export. The drought tolerant feature of pineapple enables it to thrive in areas too dry for other crops. The part that is harvested is usually the fruit with the crown. The crown is removed and thrown away with the pineapple skin or it is sometimes taken to other gardens for planting. Also, the pineapple sucker is often removed from the parent pineapple to be planted in other gardens.

The pineapple fruit has a high concentration of N, P and K compared to the vegetative parts; hence, there is a high export of these nutrients when the fruit is harvested (Table 7 & 8).

Table 7 Nutrient content in raw pineapple

Nutrient	**mg/fruit**
P	8
K	109
Ca	13
Mg	12
Fe	0.29
Mn	0.93
Cu	0.11
Zn	0.12
Na	1

Source: Paull and Lobo (2012)

Table 8 Nutrient removed by pineapple crowns, fruit and suckers

Organ	Fresh mass (g)	(kg/ha) N	P	K	Ca	Mg
Crown	205	19	5.0	49.0	6.1	6.3
Crown	295	28	6.7	73.9	8.2	7.8
Crown	390	36	8.8	92.1	20.9	9.9
Fruit		43	7.2	108.7	12.1	6.0
Sucker		25	3.5	35.7	7.1	3.7

Source: Malézieux and Bartholomew (2002)

Summary

The smallholder coffee and food farming systems rely largely on the natural fertility of the soil for production. However, nutrients are continuously removed from the farming systems through human and natural processes like crop harvesting, residue removal, leaching and soil erosion.

In a smallholder coffee system, nutrients are lost mainly though the harvesting of coffee cherries and removal of coffee/shade tree prunings; in contrast the main nutrient source is from the natural litter fall in the system. The literature show that the coffee cherry has a high content of K so there is a substantial export of K from the coffee system when coffee cherries are harvested for processing. However, most of the K is found in the pulp of the coffee cherry, which is a by-product of coffee processing, and could be re-used in the coffee and food garden system as an organic amendment. However, recycling of pulp is not a common practice since; it is generally left at the pulping station

Crop harvesting has been identified as the main pathway of nutrient loss in food garden systems. However, soil erosion and burning have also been reported as the main nutrient losses in other farming systems. This indicates that the variability of farming practices has an effect on the nutrient removal in an agricultural system.

In traditional cropping systems, soil fertility was maintained through fallow and shifting cultivation. However, with increasing population pressure, fallow periods have been reduced and production has intensified. Some farmers are now employing practices like leguminous crop rotation and use of organic amendments to retain soil fertility. Studies show an increase in yield of crops when they follow leguminous crops, as the crop benefits from the fixed N and residues of the legume crop. However, the choice of legume crop to use in rotation depends on the farmerõs needs and availability of resources. As a consequence, high N fixing legumes are usually not used in crop rotations. Moreover, in most cases the use of organic amendments for soil fertility maintenance is usually below the amount required to replace that removed.

Nutrient fluxes in a farming system are determined by the famerõs management practices/decisions coupled with the environmental and socioeconomic factors. Hence, a better understanding of a farmerõs practices in both systems is necessary to determine an effective management practice to conserve and sustain soil fertility that is applicable to the farm.

Therefore the study aims to quantify some of the nutrient fluxes in the farming systems and interpret the effect of these movements on soil fertility.

Chapter 3: Methodology

3.1 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 (Figure 6). 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 soil types of Bena include Dystrandept, Humitropepts, Plinthaqualfs, Palehumults, Tropothents and the parent material is mainly alluvial fan deposits, lake deposits and minor recrystallized limestone (Bryan & Shearman, 2008). The study area was selected due to its access to service centers and markets and its active participation with the PNG Coffee Industry Corporation.

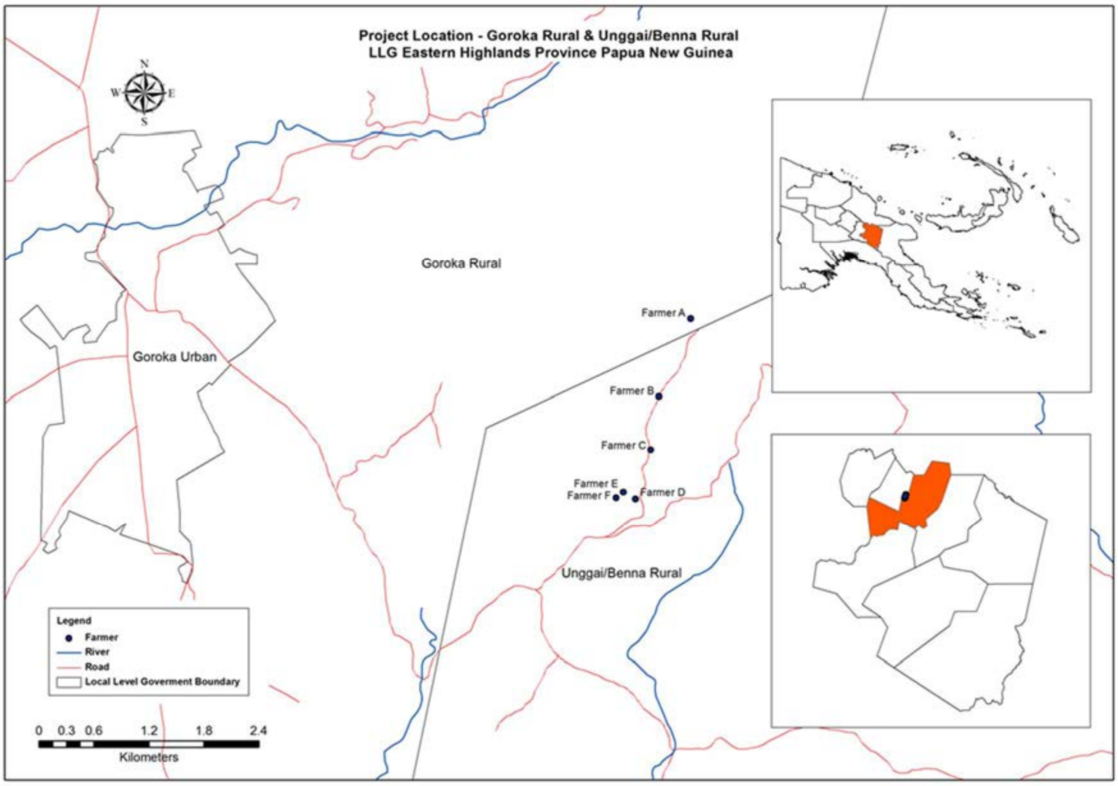

Figure 6: Location of study site and sample farms in Bena, Eastern Highlands Province.

3.2 Selection of farms

In order to capture the nutrient dynamics in a smallholder farming system, six farmer households were selected, using the database from the ACIAR coffee project ASEM/2008/036: ‘*Improving livelihoods of smallholder families through increased of coffee-based farming systems’*. Three criteria were used to select the farmer households:

1. Farmers that had a garden near the house and applied organic material to this garden (kitchen waste, coffee pulp, manure, weeds, ash)

2. Some farmers who did and some farmers who did not apply inorganic fertilizer in their food gardens

3. Farmers that grew crops specifically for market.

The first criterion was selected to identify if there is a management effect on nutrients in gardens depending on how organic wastes are used. Because most farmers tend to add kitchen waste to gardens close to the house but not the main food gardens (which can be a considerable distance away from the household), soil under kitchen peelings was analysed. Similarly, coffee pulp is sometimes used on food crops, so soil under coffee pulp was also analysed. Thirdly, often household and food wastes are burned. So again soil under ash was analysed for soil chemical characteristics.

For the second criterion, most farmers do not use inorganic fertilizers in their food gardens, except the ones who grow vegetables for market that have a high demand for nutrients for their development, such as cabbage, broccoli and bulb onion. Two of the six farmers did not grow high nutrient demanding 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 third criterion was selected for the purpose of determining the amount of nutrients exported out of the farming system to the 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 which can be identified and better utilized.

Upon arrival in the village, I had a meeting with a village leader and explained the purpose of the study and discussed the criteria used in selecting the six farmers. In consultation with the village leader, two of the originally selected farmers were replaced with two others who met the same criteria and who were also in the database. The final six farmers were then visited on the first day of the field work to explain the purpose of the study and obtain their prior and informed consent for participation in the study before commencing (JCU Ethics Approval H6223).

3.3 Description of the selected farms

All the farms selected had at least one subsistence garden and one market-oriented garden except farmer F. All farmers cultivated sweet potato, mostly for consumption, and most grew pineapple, mostly for sale (Table 9). One farmer grew broccoli and cauliflower for sale, but not pineapple. Four of the six grew bulb onion. The sixth farmer had only one food garden but actively produced commercial bulb onion and oranges. He also reared pigs and goats for sale. Three gardens per farmer (except farmer F) were initially selected for sampling, one near the house (kitchen garden, for subsistence) and the other two being the main gardens, further away. Of the main gardens, garden plots that were fertilized with inorganic fertilizers, which were generally bulb onion, broccoli and cauliflower, were compared to garden plots that were not.

Table 9 Crops grown and animals reared by the six farmer households

Farmer	Crop cultivated for sale/household consumption	Animal reared for meat	Use of inorganic fertilizers
A	Sweet potato, broccoli, cauliflower, bulb onion, sugarcane	Pig	Yes
B	Sweet potato, pineapple, bulb onion, spring onion, peanut, sugarcane	Pig	Yes
C	Sweet potato, pineapple	Pig	No
D	Sweet potato, pineapple, cassava, sugarcane	Pig	No
E	Sweet potato, pineapple, bulb onion, sugarcane	Pig	Yes
F	Sweet potato, pineapple, bulb onion, cassava, spring onion, orange	Pig, goat	Yes

3.4 Data collection

The collection of data involved two field trips to Bena. The first field work occurred from 18th of August to 25th of September, 2015. During that period, Bena was experiencing, the lowest six-month period of rainfall on record, more severe than the 1997 drought. Most farmers did not work in their food gardens as the soil was too hard and dry to do gardening. The second field work occurred from the 29th of May to 9th June 2016, when the weather was close to the long-term average for that time of year.

3.5 Farmer interviews

Each farmer was interviewed using a questionnaire (Appendix 1). The interviews enabled collection of information that was not always possible to collect from observation or sampling; such as the type of crops planted on each garden/plot in the past, and what sort of organic or inorganic materials were applied to the gardens.

3.6 Garden measurement

Gardens and plots were identified and delineated during the first field trip (Figure 7). A garden refers to a fixed area, usually less than a hectare, which farmers cultivated and grew crops either for household consumption or for market. Within the gardens, crops are cultivated on plots, which are raised beds that are usually rectangular in shape except for pineapple and orange, which are planted on level ground.

The garden boundary was delineated with a GPS. For plots within the gardens, the length and width of smaller plots (<3m) were measured using a tape measure, and a GPS was used to delineate the boundary of larger plots (>3m). The GPS coordinates were imported into MapInfo software and polygons were created for each garden and plot and the area of the polygons were obtained.

3.7 Soil sampling

3.7.1 Food gardens

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. All three gardens were sampled in farms A, B and C. In farms D and E, two gardens were sampled and farm F had only one garden.

3.7.2 Management and sampling of crop/food wastes

In farms A, B and C, kitchen peelings were spread over areas of the house garden (garden one) and soils under these peelings were sampled in the same way as above. The soil samples were taken several months after application of peelings. In farms D and E, the house garden had kitchen peeling applied to bases of certain crops within the garden whereas farmer Fôs garden, only the orange plot had kitchen peelings applied, to the base of orange trees. To address this situation, a different sampling approach was taken. In garden one of farms D and E, two trees/crops that had kitchen peelings applied to their base were selected and the kitchen peeling boundary was delineated visually. Then two soil cores were taken inside and halfway between the stem base and the kitchen peeling boundary of both trees/crops (Figure 8). The soil cores were kept separate as replicates of soil ñunder kitchen peelingsò. Two soil cores were taken 2m from the outside of the kitchen peeling application area, in line with the samples taken within the kitchen peeling area (Figure 8). These soil samples were also kept separate as replicates of soil designated as ñno kitchen peelingò.

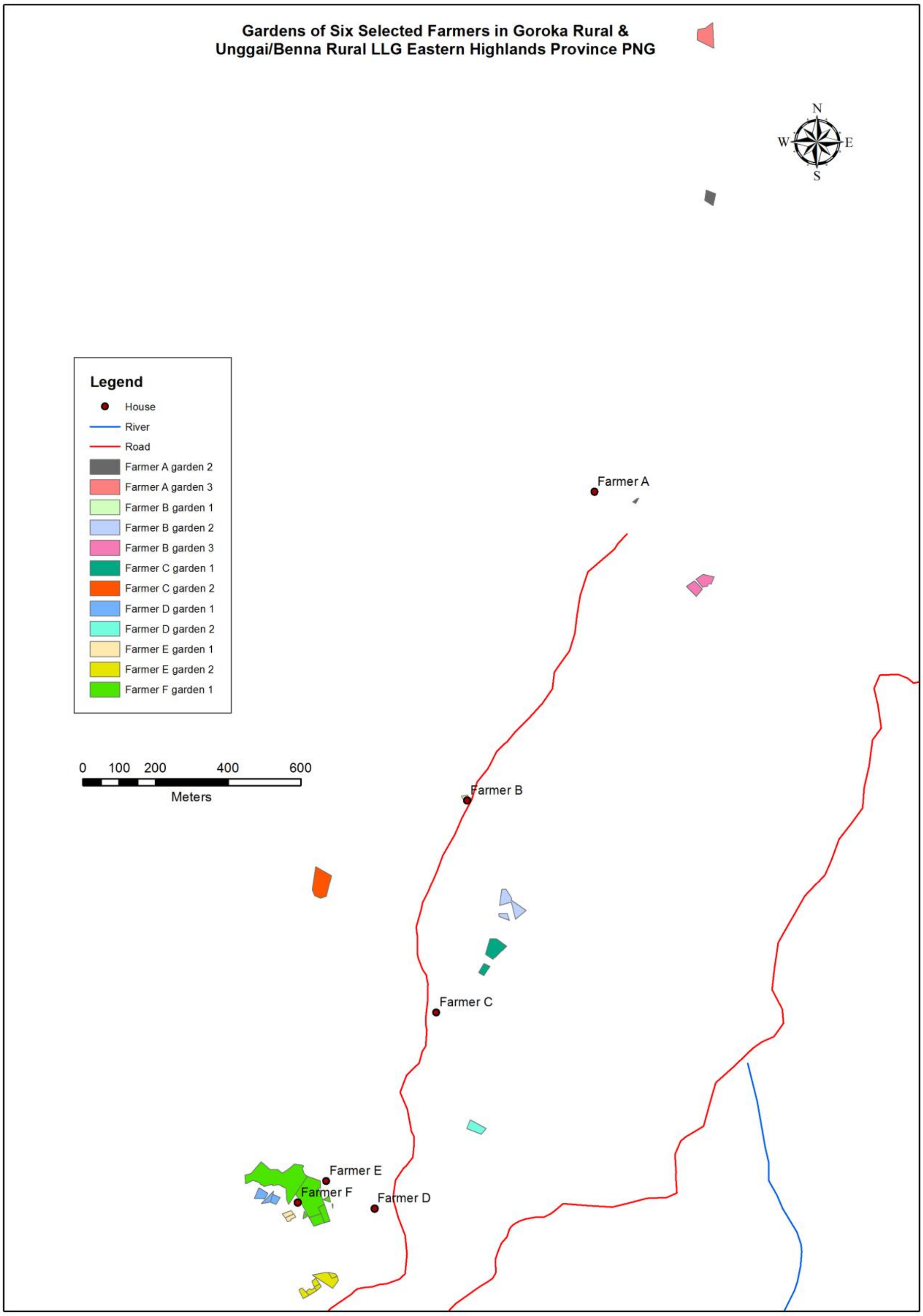

Figure 7: Location of farmer's homestead and gardens

In farmer Fôs garden, the orange plot was sampled differently because the farmer applied kitchen peelings to the base of orange trees in a sequence; first to the first row, next time to the second row and so forth. To address this situation, a transect was laid out through the whole orange plot and four soil cores were taken along the transect and near to the base of the orange trees. These four soil cores were kept separate as replicates of soil ñwith kitchen peeling ñ. Another set of four soil cores was taken in areas in between the orange trees, with no visible evidence of kitchen peeling application, but in line with the ñwith kitchen peelingò samples. These four soil cores were also kept separate as replicates of soil ñno kitchen peelingsò.

In addition to the soil sampling in food gardens and areas with/without kitchen peeling application, soil samples were taken from areas with or without coffee pulp and wood ash application. The way coffee pulp and wood ash are used varies within and between farms. In most cases, farmers leave the coffee pulp at the pulping station after pulping coffee cherries (Figure 9). Therefore, to sample the soil, the coffee pulp on the surface of the soil at the pulping station was cleared and two soil samples (one on either side of the pulper, but under the main bulk of pulp) were taken and combined to obtain a composite sample for ñsoil under pulpò. A composite pair (ñno pulpò) was taken a meter away from the pulp boundary (visibly delineated). Soil ñunder pulpò and ñno pulpò samples were taken from five farms, as farmer E did not own a pulping machine and pulped his coffee at farmer Fôs pulping station. On the other hand, farmer A had two pulping stations so sampling was done at both pulping stations. Therefore, there were a total of six samples for soil ñunder pulpò and ñno pulpò.

For areas ñunder ashò and ñno ashò, areas that had visible evidence of ash remaining either on a plot (Figure 9) or an area outside the garden where burning was usually done were selected and sampled in a similar way to soil ñunder pulpò and ñno pulpò. Soil samples were obtained from two farms only; two sets of samples were taken from farm E and one set was taken from farm F.

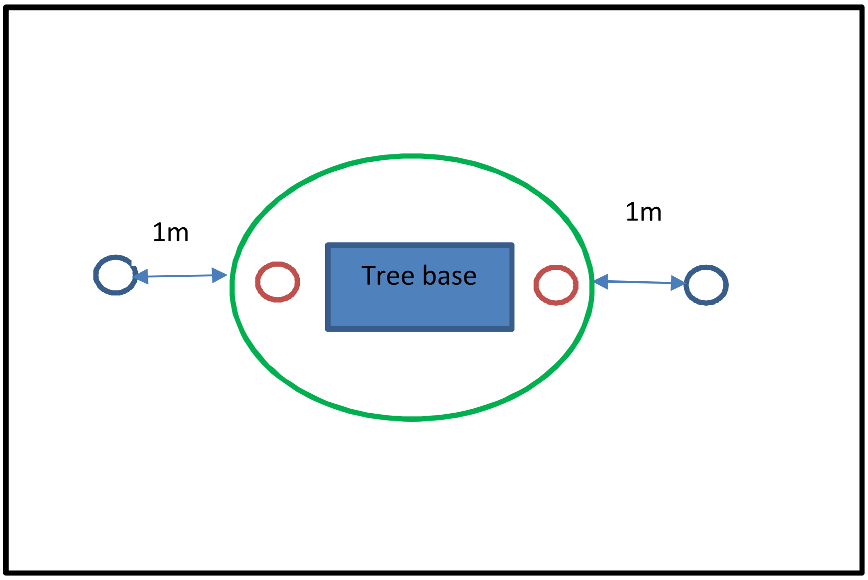

Figure 8: Soil sampling of kitchen peelings around banana or other tree. Red circles are the kitchen peelings soil cores, blue circles are the no kitchen peelings soil cores and green circle is the kitchen peelings boundary.

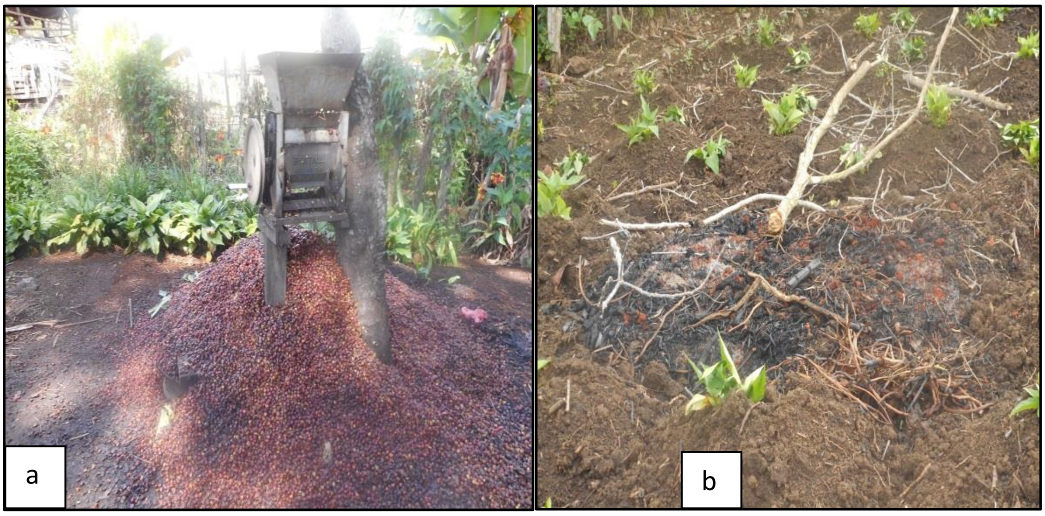

Figure 9: (a) Pulping station with pulp around base and (b) ash area from burning residues

3.8 Calculation of Soil Nutrient Stocks

Soil nutrient stocks (0-10cm depth) were calculated by multiplying soil nutrient contents by soil bulk density. The soil bulk density data was taken from the ACIAR coffee project ASEM/2008/036: ó*Improving livelihoods of smallholder families through increased of coffee-based farming systems'*. The bulk density measurements were not from the six farms but were within the study region. The bulk density ranged between 0.88 and 1.21, which was not a large variation so an average of bulk density measurements taken in that project was used.

3.9 Food Crop Sampling

During the first field work in August 2015, Bena was experiencing a drought. The drought affected the food sampling because only a few gardens had crops growing as the soil was too dry and hard to do any gardening. The crop that was available for harvest was pineapple, as they were in season. A few other crops were also sampled, where present. The second field trip was in May 2016; when the weather was close to long-term average for that time of year so there were more crops in the gardens for sampling.

To assess the quantity of food harvested during the study period, the farmers were asked to keep records. An exercise book was left with each of the six households and a literate family member was asked to keep a record of the weight (using 10 kg scale provided) of the harvested produce from each food gardens from October 2015 to May 2016. However, most of the farmers were not able to keep good records so it was difficult to calculate the crop yield using this data. Therefore, crop yield was estimated from 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 plant was separated into its main parts depending on the crop (e.g. leaves, stems, seeds, pods, tuber) and fresh weights of each part was measured separately. The number of crops sampled depended on the availability of the crop during sampling and, hence, the number harvested varied amongst farmers (Table 10).

In this thesis, the term ñharvested cropò is defined, per plant, as the part of the plant, irrespective of subsequent processing, which is removed from the plot. For example: with peanuts, the whole plant (leaves + stems, shell and seed) is removed from the plot; with cassava, it is only the tuber that is removed, but on a single-plant basis, there are 6-7 tubers removed per plant, so ñcrop harvestò represents those 6-7 tubers (even if only one tuber was sampled and analysed); with broccoli, leaves, stem and flower are removed; with orange, it refers to all of the oranges on a single tree again even if only a few oranges were sampled and analysed. Thus harvested crop means the entire product removed from a plot per plant.

Table 10 Type and number of crops sampled

Crop	Number of samples in first field trip	Number of samples in second field trip
Sweet potato	8 (4)	15 (5)
Pineapple	7 (4)	-
Cassava	-	6 (2)
Broccoli	2 (1)	3 (1)
Bulb onion	-	5 (2)
Sugarcane	-	3 (3)
Cauliflower	2 (1)	-
Cabbage	1 (1)	-
Orange	1 (1)	-
Peanut	-	1 (1)
Spring onion	1 (1)	-

* The number of farmers from which the samples were collected is indicated in the brackets
* - no samples collected

Crops that were ready for harvest were sampled using the following protocols.

<u>Tuber crops:</u>

After counting the number mounds/plants in a plot, one plant was selected randomly from each plot, and one tuber was selected for weighing and analysis. The sampled tubers were washed, towel-dried and peeled. The tuber flesh and skin were weighed separately for fresh weights. Harvested crop refers to all the tubers on one plant (usually 6-7).

<u>Sugarcane:</u>

The number of stems in the clump of sugarcane was counted and two stems were randomly collected. The outer leaves covering the sugarcane stem were removed and left in garden. The sugarcane skin was then separated from the flesh and weighed separately to obtain fresh weights. Harvested crop refers to all the stems in a clump of sugarcane (usually 10).

<u>Pineapple:</u>

One pineapple was selected randomly from each plot. The pineapple was separated into three parts, skin, flesh and crown and weighed separately for fresh weights. Harvested crop refers to the pineapple fruit including crown (leaves).

Broccoli and Cauliflower:

One plant was selected randomly per plot and separated into leaves, stem and flower and weighed separately for fresh weights. Harvested crop refers to the above ground portion, thus includes leaves, stem and flower.

Bulb onion:

One plant was sampled per plot and separated into skin, flesh and leaves and weighed separately for fresh weights. Harvested crop refers to the whole plant. This includes the onion flesh, its skin and leaves.

Spring onion:

Six plants were sampled per plot and weighed for fresh weights. Harvested crop refers to just the above-ground part of the plant.

Cabbage:

Three plants were sampled per plot and weighed for fresh weights. Harvested crop refers to the just the above-ground part of the plant.

Peanut:

Six plants were sampled and separated into leaves+stem, shell and seed and weighed separately to obtain fresh weights. Harvested crop refers to the whole plant.

Orange:

One tree was selected at random, and three oranges were selected at random and weighed for fresh weights. Harvested crop refers to all the oranges on one tree.

After fresh weights had been recorded, the food samples were cut into smaller pieces, sun dried for 1-2 days and packed in paper bags that were then sent for oven-drying at Aiyura Research Station. The oven-dried samples were weighed, ground and packed and sent for nutrient analysis.

3.10 Sampling and recording of coffee garden harvest, litterfall and prunings

Sampling and recording of coffee cherry harvest, litterfall from shade and coffee trees and coffee prunnings was arranged. However, none of the results are presented in this thesis because some of the records (collected by farmers) proved to be unreliable. The sampling and recording is described here simply as a complete record of the work done for the thesis.

On each farm, litter nets were set up in the coffee garden nearest to the house. In each coffee garden, four 1 m (length) x 1 m (width) x 50 cm (depth) nylon litter traps of 1 mm mesh size were suspended 1 m above the ground. Depending on the arrangement of the coffee trees and shade trees, the four litter nets were placed at four locations along transect of the garden to obtain a representative sample of litter fall for the garden. The litter from these traps was collected at the end of every month from December 2015 to April 2016. One of the literate farmers in the study was asked to collect and record the litter data. Litter from the four traps in each coffee garden were separated into shade and coffee and then combined to obtain one composite sample for each plant type and weighed for fresh weights. The total litter (coffee & shade) weights, total trap area ($4m^2$) and total days of collection (181) were used to calculate the estimated nutrient input per garden (kg/ha/year). The litter sample was oven-dried, ground and 5 g subsamples were sent for nutrient analysis.

In August 2015, coffee stem samples were collected from coffee gardens of farmers who pruned their trees. From a tree, a single stem was sampled and cut into smaller sizes to obtain subsamples that were then weighed and sent for oven-drying. The coffee stem samples were dried until they reached constant weight, then ground and sent for nutrient analysis.

Farmers were asked to keep a record of the amount of cherry harvested from all their coffee gardens during the study period. An exercise book was left with each of the farmers to record weights of harvested coffee cherry (using a 10 kg scale provided).

3.11 Chemical Analysis

3.11.1 Soil Analysis

Soil samples were analysed for total C and N at the Advanced Analytical Centre, James Cook University (Cairns). I analysed the samples for electrical conductivity (EC), pH_w and pH_{cacl2} at James Cook University (Townsville). Analyses of exchangeable cations and extractable P were done at the University of Queensland.

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

Electrical conductivity (EC) and pH were determined using a 1:5 soil: water extract. Air dried soil (6g) was shaken with 30 mL water for one hour and left to settle for 20 minutes. The pH_w and EC were then determined using calibrated meters. The soil was then resuspended and 1.5 mL of 0.21M $CaCl_2$ was added to obtain a 0.01M $CaCl_2$ solution. The suspension was shaken again for 15 minutes and allowed to settle for 20 minutes and pH_{cacl2} was measured (Rayment & Lyons, 2011; method 3A1, 4A1 and 4B2).

Extractable P was determined colorimetrically on centrifuged and filtered extracts following Colwell extraction using 0.5M $NaHCO_3$ at pH 8.5 (Rayment & Lyons, 2011; method 9B1).

Exchangeable cations and cation exchange capacity (CEC) were determined using a 1:50 0.01M $AgTU^+$ 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 & Lyons, 2011; method 15F1 and 15J1).

3.11.2 Plant analysis

Plant samples were analysed for total C, ^{13}C, N and ^{15}N at the Advanced Analytical Centre, James Cook University (Cairns) and for all other elements at Flinders University. Only total C and N data are presented, not ^{13}C or ^{15}N.

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 Fe, Mn, B, Cu, Mo, Co, Ni, Zn, Ca, Mg, Na, K, P, Al, Ti, Cr, Cd, Pb, As, and Se contents using ICPMS Method-1D2HeA (Wheal et al., 2011; method 3(12)).

3.12 Statistical Analysis

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

3.13 Nutrient inflows and outflows

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 were conceptualised (Figure 10) 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 per garden by individual farmers.

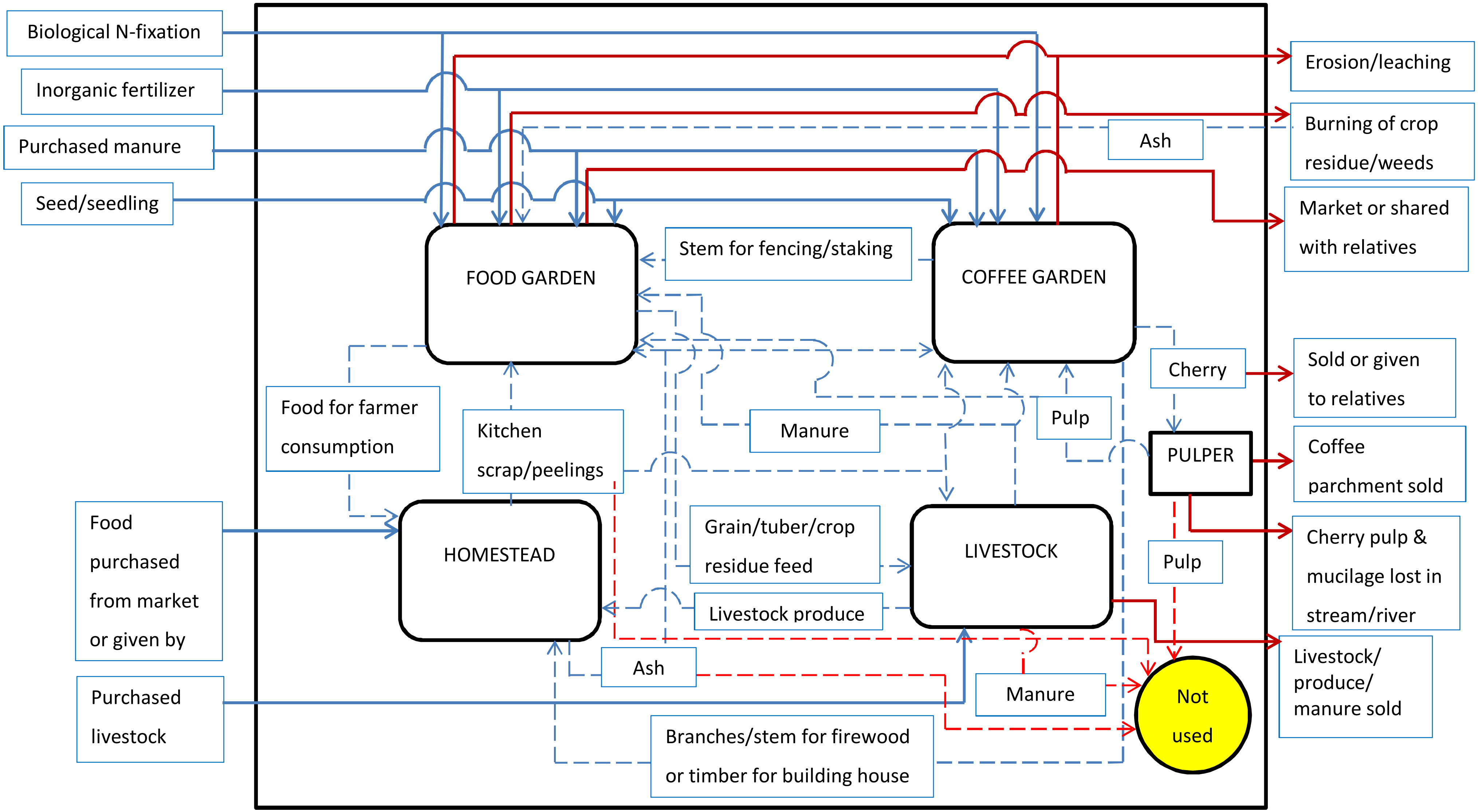

Figure 10: Nutrient inflows and outflows of a farm. Solid lines are farm gate flows and broken lines are internal flows in farm. Red broken lines are materials which are not utilized further in the farm (e.g. pulp is left at pulping station & ash/kitchen scrap/peelings thrown in a pit.

Chapter 4: Results

4.1 Nutrient status of Bena food gardens

The mean values of the chemical properties of topsoil in unfertilized plots were generally in the range considered optimum (Table 11). However, because of the wide variation in values, there will be many plots considered infertile. The total C and N and exchangeable Ca and Mg and CEC concentrations in the topsoil (0-10cm) of unfertilized plots were in or above the optimum range but extractable P and exchangeable K were not. Although the mean concentration of N in the topsoil of unfertilized plots was in the optimum range, seven plots had a 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 was below the optimum range. Concentrations of all elements in the subsoil (10-50cm) of unfertilized plots were below the optimum range, except Ca and Mg. Generally, the soil EC and pH was also in the optimum range (Table 11).

Most of the smallholder food gardens are cultivated with mixed cropping having a variety of crops grown in small plots within each garden. Nutrient concentrations differed substantially between crops but most crops had high concentrations of K; mostly higher than N (Table 12). Overall, broccoli, cauliflower, peanut (N only) and bulb onion had the highest N and K concentrations. In addition, cauliflower had the highest Fe concentration and broccoli had the highest B concentrations amongst the other crops. Peanut and orange had the highest C concentrations. Of the two root crops, sweet potato had a higher concentration of all nutrients than cassava, except for Mg and Zn. Overall, sugarcane had the lowest concentration of all macronutrients, except C (Table 12).

Table 11 Mean nutrient status of unfertilized garden soils at 0-10cm (topsoil) and 10-50cm (subsoil)

	Total (%)		Extractable (mg/kg)	Exchangeable ($cmol^+/kg$)				EC[a] (dS/m)	pH[a] (water)	pH[a] ($CaCl_2$)
	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)
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)
Range (topsoil)	3.58-7.33	0.25-0.60	21.0-106	0.16-1.21	7.72-16.5	1.89-5.05	12.2-25.6	0.06-0.65	5.5-6.5	4.8-5.7
Range (subsoil)	1.86-5.17	0.14-0.43	12.4-75.7	0.04-0.69	2.71-15.0	0.99-4.69	6.93-22.4	0.05-0.77	5.3-6.4	4.6-5.8
Optimum range[b]	4.0-9.9	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

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 12 Mean nutrient concentration of harvested crops

	C	N	P	K	Ca	Mg	Fe	B	Zn	Mn	Cu
Crops	% DM						mg/kg DM				
Broccoli (n=5)	35.4	2.78	0.39	3.83	1.30	0.22	273	16.9	38.3	36.5	4.8
Bulb onion (n=5)	36.3	2.20	0.37	3.19	0.95	0.30	251	11.3	35.5	78.1	12.5
Cabbage (n=1)	37.4	1.72	0.31	2.70	0.52	0.19	290	6.9	22.2	28.9	6.4
Cassava (n=7)	36.0	0.39	0.09	0.81	0.12	0.10	68	3.9	18.9	10.0	2.3
Cauliflower (n=2)	38.7	2.47	0.21	3.11	1.17	0.23	380	10.6	29.0	51.2	3.7
Orange (n=1)	41.0	0.91	0.14	0.92	0.34	0.08	23	12.6	5.8	3.8	2.1
Peanut (n=1)	44.9	2.55	0.25	0.79	0.48	0.57	191	13.9	28.6	27.3	12.4
Pineapple (n=7)	38.4	0.51	0.07	1.16	0.23	0.17	158	3.1	12.5	52.7	7.1
Spring onion (n=1)	37.4	1.94	0.26	1.02	1.16	0.39	230	9.1	46.8	22.8	8.5
Sugarcane (n=3)	38.4	0.28	0.03	0.37	0.03	0.04	30	2.8	26.8	17.4	5.1
Sweet potato (n=23)	36.9	0.50	0.11	1.19	0.13	0.07	134	4.0	9.1	13.4	4.9

-Broccoli, bulb onion, cauliflower and spring onion is the whole crop excluding roots;
-Cassava and sweet potato is just the tuber/root;
-Orange is a single fruit; peanut is the whole plant (leaves+stem+roots+nuts); pineapple is the fruit+crown; sugarcane is the stem

4.2 Nutrient stocks

In order to determine the amount of nutrients in the soil relative to the nutrient needs of the crops, the soil nutrient stock and crop nutrient content were assessed.

The soil nutrient stock varied greatly between plots in the same garden (Table 13).The nutrient stock in the topsoil (0-10cm) of the six farms were expressed as nutrient/m^2 in order to calculate the nutrient budgets.

Overall, farmer Aʼs gardens one and two had the highest C and N stock in the soil. The high C and N stock may be because the garden was initially cleared of secondary vegetation when established (Appendix 2). The soil with the highest K stock was also in farmer Aʼs garden but in the broccoli plot of garden three which also had high P, Ca and Mg. However, the lowest Ca, and Mg stocks were in the cauliflower plot of garden three in farmer Aʼs garden.

In farmer Bʼs gardens, the highest C, N and P stock in the soil were in garden three; the highest K stock was in garden one, which had the lowest Ca and Mg stock (Table 13). In farmer Cʼs gardens, garden three had the highest C, N, P and K stock in the pineapple plot but the lowest C, N, K, Ca and Mg stock was also in the same garden, in the sweet potato plot. This may be because the sweet potato was continuously cropped for some time whilst the pineapple crop just came out of fallow (Appendix 2).

Farmer D had the highest C, P, Ca and Mg nutrient stock in the sweet potato plot of garden one, but this plot also had the lowest N and, K nutrient stock (Table 13). The cassava plot in garden one had the lowest C stock, but it had the highest N and, K stock. Farmer Dôs garden two had the lowest P, Ca and Mg nutrient stock.

In farmer Eôs gardens the soil nutrient stock was higher in garden one than in garden two. Finally, farmer F had the highest C and N soil stock under the spring onion plot, but the bulb onion plot had the highest P, K and Mg soil stock (Table 13). The lowest C, N and K soil stock was in the pineapple plot.

The crops grown by farmers have different demands for nutrients during their growth and development so there were substantial differences in the nutrient contents of crops (Table 14). In harvested crop, orange and cassava generally had the largest quantities of both the macro and micro elements compared to other crops. Although sweet potato had a higher nutrient concentration than cassava, two times more N, P and K were found in cassava because of the greater biomass. Similarly, cauliflower had greater amounts of nutrients than broccoli even though broccoli had a higher nutrient concentration. Of all crops, spring onion, bulb onion and peanut had the least amount of all nutrients (Table 14).

Table 13 Nutrient stock in the topsoil (0-10cm) of plots under various crops of the six farms

			Total (g/m^2)		Extractable (g/m^2)	Exchangeable (g/m^2)		
Farmer	Garden	Plot	C	N	P	K	Ca	Mg
A	1	Bulb onion	11131	840	4.69	12.3	129	31.3
	2	Broccoli	8352	761	4.68	16.5	172	21.4
		Cauliflower	8540	785	5.58	32.5	167	28.2
		Sweet potato	8462	790	3.24	17.8	177	22.1
	3	Broccoli	5723	548	10.7	104	303	43.6
		Cauliflower	1908	183	3.56	34.6	101	14.5
		Sweet potato	5819	559	7.31	67.3	268	37.4
B	1	Bulb onion	4500	290	3.94	31.8	192	38.7
	2	Pineapple	5119	323	3.74	5.89	244	52.1
	3	Pineapple	5794	428	5.43	11.1	244	44.7
		Sweet potato	6152	443	5.39	17.7	209	38.9
C	1	Cabbage	4736	327	1.96	12.2	286	41.9
	2	Sweet potato	4470	336	2.13	12.8	311	50.5
	3	Pineapple	7072	581	2.60	14.1	223	32.0
		Sweet potato	3826	290	2.03	7.06	172	21.9
D	1	Sweet potato	4545	352	5.53	30.4	288	49.9
		Cassava	4005	424	5.37	45.0	247	45.5
	2	Pineapple	4471	403	3.59	35.3	196	36.1
E	1	Bulb onion	4922	322	6.47	36.5	258	57.0
		Sweet potato	5141	397	6.38	56.9	265	56.9
	2	Pineapple	3857	270	4.72	7.35	168	36.6
		Sweet potato	3950	294	4.86	9.43	165	37.3
F	1	Bulb onion	3767	279	10.2	11.5	307	63.0
		Cassava	4385	255	10.1	8.52	293	54.9
		Pineapple	3394	238	8.29	7.60	312	56.9
		Spring onion	4590	282	7.58	10.0	302	57.8
		Sweet potato	4104	266	9.03	10.6	254	54.1

Table 14 Mean nutrient content of harvested crops per plant

	C	N	P	K	Ca	Mg	Fe	B	Zn	Mn	Cu
Crop	(g)						(mg)				
Broccoli (n=5)	27	1.85	0.23	2.38	0.84	0.15	22.4	0.99	2.76	2.64	0.33
Bulb onion (n=5)	6	0.34	0.06	0.49	0.15	0.05	4.1	0.18	0.55	1.16	0.19
Cabbage (n=1)	30	1.38	0.25	2.16	0.42	0.15	23.2	0.55	1.78	2.31	0.51
Cassava (n=7)	749	7.92	1.90	17.38	2.69	2.16	153.2	8.23	38.32	22.10	4.83
Cauliflower (n=2)	71	4.14	0.34	5.38	2.01	0.37	67.5	1.72	4.69	9.30	0.62
Orange (n=1)	1622	36.12	5.70	36.43	13.46	3.25	91.4	49.95	22.86	15.22	8.21
Peanut (n=1)	8	0.47	0.05	0.15	0.09	0.11	3.5	0.25	0.53	0.50	0.23
Pineapple (n=7)	56	0.75	0.10	1.73	0.32	0.23	24.8	0.45	1.81	7.88	1.04
Spring onion (n=1)	1	0.06	0.01	0.03	0.04	0.01	0.7	0.03	0.15	0.07	0.03
Sugarcane (n=3)	303	2.19	0.26	2.48	0.29	0.36	22.5	2.21	20.50	13.43	4.19
Sweet potato (n=23)	266	3.40	0.81	8.69	0.88	0.49	99.4	2.76	6.86	9.89	3.44

4.3 Nutrient export

The amount of nutrients exported in crops depended on the biomass of each plant, planting density (Table 15), and nutrient concentration (Table **12**). Farmers E and F plant bulb onion using the same planting density(Table **15**), but the bulb onion plants in farm F had greater biomass than those in farm E. Similarly, broccoli and cauliflower had the same planting density, but cauliflower plants had a greater biomass. Furthermore, farmer F planted cassava at a higher density than farmer D, but farmer Fôs cassava plants had lower biomass than farmer Dôs (Table 15). On the contrary, farm B had the highest pineapple planting density and also the highest pineapple biomass. In addition, farm B had the highest sweet potato planting density, but farm D had the highest sweet potato biomass (Table 15).

Crops such as cauliflower, cassava, peanut and bulb onion exported large amounts of N at 20.7, 13.6, 11.7 and 11.4 g/m^2, respectively (Table 16). However, cassava, cauliflower and bulb onion exported more K than N at 27.0, 26.9 and 16.3 g/m^2, respectively.

Examining farms individually, overall, the highest amount of N export from harvested crops was from farms E and F; whereas the highest P and K export was from farm F and D, respectively (Table 17). Export of N, P and K in bulb onion was greater in farm F than in farm E. Farm F also had the highest export of N, P and K in cassava out of the two farms sampled. The pineapple in farm D exported the highest N and K compared to pineapples in the other farms. Farmer Bôs sugarcane exported more N than farmer A and Dôs sugarcane but farmer Dôs sugarcane exported more P and K than sugarcane in the other farms. Moreover, the sweet potato in farmer Côs garden exported the most N and P whereas the highest K export was from farm D (Table 17).

Table 15 Mean plant density and fresh weight of harvested crop on each farm.

Farm	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
Crop	plants/m^2						Fresh weight (kg/plant)						kg/m^2					
Broccoli	4.80						0.50						2.40					
Bulb onion					33.30	33.30					0.17	0.29					5.66	9.66
Cabbage			1.00						0.59						0.59			
Cassava				0.85		4.00				6.51		3.01				5.53		12.04
Cauliflower	5.00						1.42						7.10					
Orange						0.07						17.06						1.19
Peanut		25.00						0.07						1.75				
Pineapple		2.78	2.37	2.56		1.56		1.36	0.76	1.35		0.64		3.78	1.80	3.46		1.00
Spring onion						50.00						0.02						1.00
Sugarcane	1.00	1.00		1.00			2.59	6.55		3.93			2.59	6.55		3.93		
Sweet potato	0.95	1.08	0.95	0.95	0.87	0.67	2.73	2.28	3.79	4.01	1.39	1.58	2.59	2.46	3.60	3.81	1.21	1.06

Empty cells -crops not grown by farmer or not ready for harvest during sampling period

Table 16 Mean quantity of nutrients exported in harvested crops.

Crop	C	N	P	K	Ca	Mg	Fe	B	Zn	Mn	Cu
	g/m^2						mg/m^2				
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

Table 17 Crop macronutrient export (g/m^2) in each of the farms

	Farm A			Farm B			Farm C			Farm D			Farm E			Farm F		
Crop	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
Broccoli	8.70	1.11	11.23															
Bulb onion													10.36	1.72	15.48	15.91	2.85	19.44
Cabbage							1.38	0.25	2.16									
Cassava										8.54	2.01	20.10				20.40	5.06	36.10
Cauliflower	20.71	1.72	26.91															
Orange																2.41	0.38	2.43
Peanut				11.70	1.14	3.63												
Pineapple				2.60	0.42	4.94	1.36	0.16	2.72	2.81	0.29	7.63				0.69	0.18	1.51
Spring onion																3.06	0.41	1.62
Sugarcane	1.21	0.08	2.19	3.33	0.27	1.90				2.04	0.42	3.36						
Sweet potato	3.42	0.84	8.52	3.58	0.57	7.55	9.40	1.17	10.61	4.47	1.06	15.41	1.37	0.27	4.83	1.20	0.54	3.83

Empty cells -crops not grown by farmer or not ready for harvest during sampling period

4.4 Effect of fertilizer and waste management on soil fertility status

The use of inorganic fertilizer is very limited in smallholder farming systems, so the use of available nutrient sources within the farming system, like coffee pulp, kitchen waste and fire ash, is desirable. However, these materials are either under-utilized or not used at all. The location where these materials were discarded or left was identified and soil samples were taken and analysed to assess the nutrient concentration of the soil that was directly under these materials. Also, there were four farmers who used inorganic fertilizers in their gardens so soil samples were also taken from their gardens for nutrient analyses.

Nutrient contents of soil in fertilized plots were generally higher than soils in unfertilized plots (Table 18). The fertilized plots had significantly higher C, N (1.5-2x higher) and exchangeable K (3-4x higher) concentrations than the unfertilized plots, in both the topsoil and subsoil. 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. Although there was a substantially higher mean exchangeable Ca concentration in fertilized plots, the difference was not significant. On the other hand, the Mg concentration was slightly higher in the unfertilized plots than in the fertilized plots. There was also a slight increase in the soil pH of fertilized plots (Table 18).

Processing of coffee cherry results in generation of the by-product coffee pulp, which can be used as an organic fertilizer. However, farmers often leave the pulp at the pulping station to decompose without utilizing it. Therefore, the soil under pulp piles at the pulping station was analysed for its chemical composition. Topsoil and subsoil with pulp generally had higher nutrient concentrations than topsoil and subsoil without pulp (Table 19). However, the difference was significant only for exchangeable K concentration in the subsoil. Topsoil with pulp had a mean exchangeable K concentration 3.5 times higher than topsoil without pulp, but the difference was not significant because of the wide variability in the exchangeable K concentrations; exchangeable K concentrations ranged between 0.76 and 14.6 mg/kg. Overall, the pH of soils with pulp also increased but not significantly. The pulp at all of the farms were left exposed to rain for some months hence natural processes like leaching and denitrification may have resulted in nutrient losses in soil under pulp.

With or without pulp, the concentration of all elements in the topsoil was in the optimum range except for extractable P in topsoil without pulp (Table 19). However, the subsoil (with or without pulp) had concentrations of total C, N and extractable P below the optimum range.

Food peelings remaining after food preparation are either fed to pigs or goats, or applied to the gardens near the house, at the base of certain crops or trees. Overall, the nutrient concentrations of soil with kitchen peelings were higher than soil without kitchen peelings but the difference was significant only with exchangeable K in topsoil, extractable P in subsoil and CEC in both topsoil and subsoil (Table 20). The EC, pH_w and pH_{CaCl2} of topsoil and pH_{CaCl2} of subsoil were also significantly different; the higher pH is probably due to the addition of organic matter.

The mean concentrations of all nutrients in the topsoil with and without kitchen peelings were in the optimum range although 50% of garden plots had extractable P lower than the optimum (Table 20). On the other hand, total C and N and extractable P concentrations in the subsoil (with and without kitchen peelings) were below the optimum range.

Burning of plant residues is commonly practiced during land preparation or maintenance of food gardens by smallholder farmers. The pile of ash that remains after burning is often left as it is and not utilized. In the topsoil with ash, the mean total C, total N and exchangeable Ca and Mg concentrations were lower and the extractable P and exchangeable K concentrations were higher than in topsoil without ash but the differences were not significant (Table 21). Mean exchangeable K concentration was almost two times higher under ash piles. On the other hand, the subsoil with ash had nutrient concentrations higher than subsoil without ash, except for C, but the only significant difference was the exchangeable Ca concentration. The mean nutrient concentrations of the topsoil with and without ash were in the optimum range (Table 21). On the other hand, the subsoil with and without ash had mean total C, total N, extractable P and exchangeable K concentrations below the optimum range.

Table 18 Mean nutrient status of unfertilized and fertilized garden soils at 0-10cm (topsoil) and 10-50cm (subsoil)

	Total (%)		Extractable (mg/kg)	Exchangeable ($cmol^+/kg$)				EC[a] (dS/m)	pH[a] (water)	pH[a] ($CaCl_2$)
	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]	4.0-9.9	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 19 Mean nutrient status of soil with/without pulp at 0-10cm (topsoil) and 10-50cm (subsoil)

	Total (%)		Extractable (mg/kg)	Exchangeable ($cmol^+/kg$)				EC[a] (dS/m)	pH[a] (water)	pH[a] ($CaCl_2$)
	C	N	P	K	Ca	Mg	CEC			
Practice										
No pulp (topsoil n=6)	4.66 (1)	0.32 (1)	52.0 (3)	1.63 (0)	13.2 (0)	3.29 (0)	20.0 (0)	0.16 (0)	6.50 (0)	5.88 (0)
Under pulp (topsoil n=6)	5.41 (2)	0.39 (1)	62.8 (2)	5.72 (0)	12.0 (0)	3.50 (0)	20.6 (0)	0.34 (3)	7.15 (0)	6.27 (0)
No pulp (subsoil n=4)	2.26 (4)	0.17 (4)	24.5 (4)	0.92 (0)	6.06 (3)	2.01 (1)	12.8 (0)	0.09 (0)	6.18 (0)	5.65 (0)
Under pulp (subsoil n=4)	2.55 (3)	0.20 (3)	25.2 (4)	2.57 (0)	7.94 (0)	3.03 (0)	13.8 (0)	0.16 (0)	6.98 (0)	6.28 (0)
Optimum range[b]	4.0-9.9	0.3-0.6	60-80	0.5-0.8	5.0-9.9	1.0-2.9	0.5-20	<0.2	5.3-6.5	4.8-6.0
p-value (topsoil)	0.50	0.49	0.33	0.11	0.57	0.65	0.76	0.13	0.08	0.19
p-value (subsoil)	0.30	0.23	0.78	0.05	0.29	0.11	0.43	0.11	0.12	0.10

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 20 Nutrient status of soil with/without kitchen peelings at 0-10cm (topsoil) and 10-50cm (subsoil)

	Total (%)		Extractable (mg/kg)	Exchangeable ($cmol^+/kg$)				EC[a] (dS/m)	pH[a] (water)	pH[a] ($CaCl_2$)
	C	N	P	K	Ca	Mg	CEC			
Practice										
No kitchen peelings (topsoil n=26)	4.97 (6)	0.33 (7)	62.1 (12)	1.35 (3)	13.4 (0)	4.02 (0)	19.6 (0)	0.14 (2)	6.48 (0)	5.75 (0)
Under kitchen peelings (topsoil n=26)	5.46 (5)	0.35 (8)	67.1 (9)	2.64 (1)	14.2 (0)	4.23 (0)	21.8 (0)	0.18 (4)	6.74 (0)	5.99 (0)
No kitchen peelings (subsoil n=24)	3.00 (19)	0.24 (16)	29.5 (5)	0.79 (13)	7.79 (7)	2.86 (0)	13.3 (0)	0.10 (1)	6.20 (1)	5.55 (1)
Under kitchen peelings (subsoil n=24)	3.18 (16)	0.24 (18)	37.6 (24)	1.23 (5)	9.40 (5)	3.16 (0)	15.8 (0)	0.11 (0)	6.38 (0)	5.74 (0)
Optimum range[b]	4.0-9.9	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)	0.15	0.40	0.41	<0.001	0.33	0.43	0.02	<0.01	0.03	0.03
p-value (subsoil)	0.62	0.87	0.02	0.06	0.12	0.28	0.05	0.18	0.09	0.02

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 EC where it is the number of gardens with values greater than the optimum range

Table 21 Nutrient status of soil with/without ash at 0-10cm (topsoil) and 10-50cm (subsoil)

	Total (%)		Extractable (mg/kg)	Exchangeable ($cmol^+/kg$)				EC[a] (dS/m)	pH[a] (water)	pH[a] ($CaCl_2$)
	C	N	P	K	Ca	Mg	CEC			
Practice										
No ash (topsoil n=3)	4.96 (1)	0.38 (0)	78.9 (0)	1.09 (0)	13.8 (0)	4.55 (0)	21.3 (0)	0.17 (0)	6.57 (0)	5.90 (0)
Under ash (topsoil n=3)	4.50 (1)	0.35 (1)	80.4 (0)	1.99 (0)	12.4 (0)	4.16 (0)	21.2 (0)	0.26 (2)	7.00 (0)	6.17 (0)
No ash (subsoil n=2)	2.54 (2)	0.17 (2)	42.3 (2)	0.15 (2)	10.2 (0)	3.83 (0)	15.9 (0)	0.11 (0)	6.55 (0)	5.85 (0)
Under ash (subsoil n=2)	2.34 (2)	0.20 (2)	54.8 (1)	0.29 (2)	11.5 (0)	4.15 (0)	17.8 (0)	0.12 (0)	6.45 (0)	5.90 (0)
Optimum range[b]	4.0-9.9	0.3-0.6	60-80	0.5-0.8	5.0-9.9	1.0-2.9	0.5-20	<0.2	5.3-6.5	4.8-6.0
p-value (topsoil)	0.65	0.70	0.79	0.53	0.38	0.48	0.98	0.28	0.25	0.32
p-value (subsoil)	0.80	0.76	0.35	0.37	<0.01	0.21	0.07	0.94	0.50	0.50

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

4.5 Nutrient budget of fertilized crops

Farmers apply inorganic fertilizers to a few crops that have a high nutrient requirement. In order to obtain a 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 22). On the other hand, 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 N export in these crops was very small compared to the amount of total N in the soil. On the other hand, the amount of K exported was substantial in relation to the amount of exchangeable K in the soil. 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 22).

Table 22 Mean nutrient budget (g/m^2) of broccoli, cauliflower and bulb onion crops

	Broccoli	Cauliflower	Bulb onion
Soil nutrient stock in 0-10cm			
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

4.6 Harvested product management

Ultimately, the harvested crop is separated into parts for consumption and waste. For example, cassava will be peeled and, peanut will have the tops and shells removed before consumption. The ówasteô parts can be processed in various places: at the plot, near or in the house, at the market, or at the buyersô house. So the crops that were sampled were separated into leaves, stem, flesh etc. and analysed for their nutrient concentrations in order to calculate nutrient content of each part and thus its importance to the many different pathways that the nutrients from the harvested crop can take (Figure 10).

The nutrient concentration in the various parts differed markedly between crops. In broccoli, the flower had the highest N and P concentration, but the stem had the highest K concentration (Table 23). On the other hand, in cauliflower the leaves had the highest N concentration and the stem had the highest P and K concentration.

In bulb onion, the flesh had a highest N and P concentration but the leaves had the highest K concentration (Table 23). In cassava, sweet potato and sugarcane, the skin had a higher N, P and K concentration than the flesh. Furthermore, the pineapple crown had higher N and P concentration than the flesh and skin, but the relative concentrations of K differed between farms. The highest K concentrations were in the skin in farms B and C but in the crown in farms D and F. Finally, in peanut the seed had higher N, P and K concentration than the shell, leaves and stem (Table 23).

From a unit of crop that was harvested, the proportions of nutrients in different parts of the harvested material differ between crops (Table 24). In broccoli, the highest proportion of the N and P was located in the flower, and the highest proportion of K was in the leaves. On the other hand, in cauliflower most of the N, P and K were in the leaves. For the 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 24).

When farmers harvest crops they usually do not count the number of plants harvested; instead they harvest a bag or bilum full (about 5-10 kg). Therefore, the amount of nutrient removed in harvested crop was expressed as g/kg in order for farmers to understand how much nutrients are removed in a bag or bilum of the harvested crop. Overall, the peanut and broccoli export a large quantity of N and P when harvested (Table 25). Also broccoli exports the most K from the harvested crops. Sugarcane exports the least amount of nutrients from the harvested crop.

Harvested crops are processed either for household consumption or for marketing thus generate crop residue or waste that can be recycled in gardens. If consumed in the house, the skins (peelings) are sometimes applied to gardens near the house, fed to animals or just left outside the house. On the other hand, when farmers take crops to the market, they either process the crops in the gardens or at the house before taking them to the market; or they may do the processing in the market. The parts that were removed during processing, e.g. leaves, crown, are a recycled nutrient source for food gardens if processed there or are lost if processed and discarded in the market. Therefore, it is important to quantify the amount of nutrients contained in the various parts.

Although most of the N, P and K in peanut are located in the seed, the leaves, stem and shell together export a substantial amount of nutrients if the whole plant is uprooted and taken out of the garden (Table 25). If processed in the garden, the nutrients in the stem and leaves would be retained in the plots and added back to the soil. Such in-field processing is not possible for crops such as pineapple, cassava and sweet potato, but the skin and crown contain valuable nutrients that could be returned to the garden of the consumer..

Table 23 Mean concentration of nutrients (%DM) in plant parts by farm

Crop	N						P						K					
Farmer	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
Broccoli flower	3.99						0.58						3.80					
Broccoli leaves	2.22						0.27						3.33					
Broccoli stem	2.01						0.41						6.14					
Bulb onion flesh					2.79	2.12					0.51	0.42					2.88	2.30
Bulb onion leaves					1.66	1.52					0.16	0.14					5.00	3.00
Bulb onion skin					1.18	1.15					0.25	0.14					1.79	1.64
Cassava flesh				0.31		0.34				0.09		0.10				0.87		0.66
Cassava skin				0.83		0.95				0.08		0.13				1.19		0.92
Cauliflower flower	2.54						0.23						3.75					
Cauliflower leaves	2.56						0.20						2.79					
Cauliflower stem	1.96						0.25						4.25					
Peanut leaves & stem		2.15						0.14						0.77				
Peanut seed		3.54						0.43						0.84				
Peanut shell		0.81						0.04						0.72				
Pineapple crown		1.09	1.05	1.27		1.04		0.22	0.19	0.16		0.27		1.26	0.76	2.36		1.38
Pineapple flesh		0.40	0.48	0.35		0.29		0.04	0.04	0.03		0.06		0.76	0.88	1.19		0.73
Pineapple skin		0.52	0.52	0.57		0.36		0.10	0.07	0.08		0.11		1.35	1.42	1.63		1.11
Sugarcane flesh	0.27	0.20		0.18			0.02	0.02		0.04			0.49	0.12		0.31		
Sugarcane skin	0.31	0.38		0.43			0.03	0.03		0.09			0.57	0.21		0.67		
Sweet potato flesh	0.55	0.46	0.79	0.38	0.37	0.39	0.09	0.06	0.10	0.09	0.07	0.18	0.97	0.76	0.87	1.41	1.16	1.30
Sweet potato skin	0.73	0.50	0.97	0.55	0.46	0.59	0.12	0.09	0.19	0.16	0.10	0.26	1.78	1.46	1.95	2.60	2.65	1.76

Empty cells -crops not grown by farmer or not ready for harvest during sampling period

Table 24 Proportion of nutrient content in plant parts

Crop	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

Table 25 Mean export of nutrients in plant parts of harvest crop

	N	P	K
Plant part	g/kg FW harvested crop		
Broccoli flower	2.15	0.32	2.06
Broccoli leaves	1.93	0.23	2.93
Broccoli stem	0.47	0.08	1.22
Total	**4.56**	**0.63**	**6.21**
Bulb onion flesh	1.30	0.24	1.35
Bulb onion leaves	0.37	0.04	1.06
Bulb onion skin	0.10	0.02	0.15
Total	**1.78**	**0.30**	**2.56**
Cabbage	2.32	0.42	3.64
Cassava flesh	1.17	0.35	2.94
Cassava skin	0.43	0.05	0.51
Total	**1.60**	**0.40**	**3.45**
Cauliflower flower	0.54	0.05	0.77
Cauliflower leaves	2.19	0.17	2.44
Cauliflower stem	0.29	0.03	0.59
Total	**3.02**	**0.25**	**3.81**
Orange	2.12	0.33	2.14
Peanut leaves and stem	2.51	0.16	0.90
Peanut seed	4.13	0.50	0.98
Peanut shell	0.32	0.02	0.29
Total	**6.97**	**0.68**	**2.17**
Pineapple crown	0.18	0.03	0.24
Pineapple flesh	0.32	0.03	0.75
Pineapple skin	0.25	0.04	0.69
Total	**0.75**	**0.10**	**1.68**
Spring onion	2.99	0.40	1.58
Sugarcane flesh	0.22	0.03	0.31
Sugarcane skin	0.27	0.03	0.35
Total	**0.50**	**0.06**	**0.66**
Sweet potato flesh	1.34	0.30	3.00
Sweet potato skin	0.26	0.06	0.74
Total	**1.61**	**0.35**	**3.74**

Chapter 5: Discussion

5.1 Soil fertility and farming practices in Bena

Generally, the mean nutrient status of soils in Bena was in the optimum range as recommended for coffee soils in similar climatic conditions (Harding, 1984; Winston et al., 2005) except for extractable P and exchangeable K concentrations, which were slightly below the optimum range. Although S was not analysed in this study, Bailey et al. (2009) indicated S deficiency in non-volcanic soils hence it may be deficient in the soils of Bena as farmers practice slash and burn when fallow vegetation is cleared. The mean N concentration in the topsoil of unfertilized plots was in the optimum range but it was in the lower end of the optimum range. The pH and EC were within the optimum range. Hence, except for exchangeable K and extractable P, the mean soil values indicate a reasonably fertile soil for coffee specifically and more generally for agricultural production.

However, on an individual basis, many of the plots were below the optimum for total N, extractable P and exchangeable K, indicating low fertility in many individual plots. This may be because farmers continuously grow crops that have high N, P and K nutrient demand, leading to substantial export of N, P and K when these crops are harvested and the amount that has been exported is not being replaced.

One of the external nutrient inputs in the food gardens of smallholder farmers in Bena is the input of inorganic fertilizer (Figure 10). However, the use of inorganic fertilizers was limited to farmers who grew temperate vegetables like broccoli, cauliflower, cabbage and bulb onion; farmers who did not grow these crops did not use any inorganic fertilizers. A comparison of the nutrient status of the fertilized and unfertilized plots revealed that the fertilized plots had significantly higher N and exchangeable K concentration in the soil than the unfertilized plots. This was because the farmers used NPK fertilizers in their plots. Several studies (Agbede & Adekiya, 2012; Ayeni, 2008; Zahoor et al., 2016) have also shown an increase in soil nutrient concentration from the application of NPK fertilizers. The C concentration in the fertilized plots also increased significantly; this was assumed to be a result of greater crop and root residue inputs because of an increase in plant biomass from the use of inorganic fertilizers (Russell et al., 2009; Trost et al., 2014)

Farmer A, B, E and F applied inorganic fertilizers in some of their gardens whilst farmer C applied inorganic fertilizer to cabbages only which were intercropped with coffee and farmer D did not use any inorganic fertilizers in his garden (Appendix 2). All of the farmers did not have any fallow period because they did not have extra land to practice shifting cultivation hence they practiced rotational planting instead. Pineapple gardens were usually cropped for 5 years before being rotated with either sweet potato or cassava. Farmer A usually rotated cauliflower and broccoli with sweet potato while farmer B and F rotated the bulb onion with peanut and farmer E rotated the bulb onion with sweet potato.

5.2 Effect of waste 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 ash are sources of nutrients within the farming system that can be used as an organic amendment for food gardens (Figure 10). However, in most cases these nutrient sources are either under-utilized or not used at all.

Coffee cherry processing results in coffee pulp as a by-product. Pulp contains 0.38, 0.04 and 0.80 N, P and K kg/60 kg parchment respectively, and can be beneficial as an organic amendment (Webb et al., 2013) However, a recent survey of coffee farmers in Bena showed that only a few farmers use coffee pulp in their food or coffee gardens; most farmers leave the coffee pulp at the pulping site to decay (Curry et al., 2017). Chemical analysis of soil at the pulping site revealed that soil directly under pulp had greater nutrient concentrations than the soil without coffee pulp, especially K. However, the increase was not significant because of the wide variability of soil nutrient concentrations at pulping sites of the farms. The variability of concentrations was affected by farming practices. For example, the nutrient concentration of the soil with pulp at one of the farmerȏs pulping site was low compared to other farms because of the small amount of coffee cherry processed due to smaller coffee garden size. On the other hand, one of the few farmers who used pulp effectively as an organic amendment in gardens near the house had left little pulp at the pulping station. The few farmers who use coffee pulp effectively apply it to 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.

Crops that are harvested for household consumption usually generate food peelings or other residues containing nutrients that can be recycled. Farmers often apply the kitchen peelings back to food gardens near the house (kitchen gardens) or sometimes feed them to pigs or goats if they are reared. The chemical analysis of the soil with kitchen peelings showed an increase in soil nutrient concentrations compared to soil without kitchen peelings. The concentration of K increased significantly in the soils with kitchen peelings. The increase may have been from the addition of peelings that had a high K concentration. However, similar to coffee pulp, the kitchen peelings were usually applied to certain points or locations in gardens; therefore, this practice might also be improved by varying application points or locations.

Burning of crop residues is commonly practiced during land preparation or maintenance of food gardens by smallholder farmers. Fire acts as a rapid mineralizing agent and enables the release of nutrients into the soil but it also results in a loss of some nutrients into the atmosphere through volatilization (Theodore & Rundel, 1976; Woods et al., 1985). The soil with ash had lower concentrations of N and C compared to soil without ash. This may have been a result of a decline in soil organic matter from combustion and also the loss of C as carbon dioxide and N through volatilization (Woods et al., 1985). Holscher et al. (1996) estimated a loss of 96%, 47% and 48% N, P and K respectively, from burning. Burning is also done in certain locations and points therefore varying the locations where burning is done would be beneficial to the soil on a wider scale.

5.3 Plant and soil nutrient stock

The proportion of staple crops and vegetables/fruits cultivated by smallholders in Bena reflected the need to sustain a constant food supply for household consumption and also to supply the increasing market demand of vegetable crops and fruits in urban centres.

A large proportion of the production of staple crops like sweet potato, banana and cassava is consumed by the rural population of PNG compared to the urban population (Bourke et al., 2001). On the other hand, the demand for temperate vegetable crops is increasing as the middle class population in the urban centres of PNG is increasing (Birch et al., 2011). Therefore, farmers are increasing production to meet the market demands and this in turn puts pressure on the soil resource.

Crops differ in their demand for nutrients for growth and development and this difference is reflected in their nutrient concentrations. Although N is often considered to be the most important element for plant growth and development, all of the crops had higher concentrations of K than N, except for peanut and spring onion.

Broccoli, cauliflower and bulb onion generally had substantially higher concentrations of N and K than the other crops. Therefore these crops require greater amounts of N and K than other crops (Tiwari et al., 2010). Moreover, these crops were fertilized with NPK and thus had access to greater amounts of these nutrients. On the other hand, peanut was grown without any fertilizer input but it had the second highest N concentration of 2.55%. The high N concentration in peanut may be associated with its nitrogen fixing capacity. Of the two root crops, sweet potato had higher nutrient concentrations than cassava, except for Mg and Zn. Howeler (1985, cited in Hillocks et al., 2002, pg. 129) reported that unfertilized cassava tubers had concentrations of 0.42%, 0.10% and 0.71% N, P and K respectively, which is slightly higher than the cassava tuber concentrations in this study, except for K concentration, which was lower. Even so, this high concentration was still lower than the sweet potato concentration in this study. The concentration of P and K in sweet potato in this study was much higher than the P and K concentrations in sweet potato reported in other studies (Bradbury & Holloway, 1988; Ishida et al., 2000). Other studies of nutrient concentrations in tuber or root crops show that taro had concentrations of 0.16-1.43% N, 0.17-0.47% P and 1.08-1.77% K, whilst four different yam species had nutrient concentrations of 0.91-1.42% N, 0.13-0.19% P and 1.19-1.79% K (Blamey, 1995; Obigbesan & Agboola, 1978). These nutrient concentrations of taro and yam are much higher than the concentrations measured in cassava and sweet potato in this study, implying that greater yields of taro and yam would lower the soil nutrient stock more quickly because of the higher nutrient demands of these crops.

The soil nutrient stock also varied considerably, presumably at least partly due to the differing nutrient demands of crops, farming practices and garden history. Generally, the soils with the highest N and K stock were in plots to which NPK fertilizer had been applied. Substantial amounts of exchangeable K were also found in some sweet potato plots. Farmer A had 67.3g/m^2 of exchangeable K stock in the sweet potato plot in garden three. This may be due to several reasons; firstly, Farmer Aφs garden three was located near to the mountains where the soil is generally more fertile than the soil in the grassland area. Secondly, farmer A grew cauliflower and broccoli, which received NPK fertilizer, and then rotated other crops so the subsequent crops benefited from the fertilizer residues in the soil. . Similarly, Farmer E had high exchangeable K stock in the sweet potato plot in garden one. This garden was a new garden (2 years old) that had come out of a long bush fallow, so the soil fertility was higher.

5.4 Nutrient content and export of harvested crops

Overall, the export of nutrients was a function of nutrient concentration in the plants, biomass of the plants, and planting density. The nutrient content and nutrient export of the harvested crops differed between crops. Orange and cassava had the highest content of nutrients per plant because of the large biomass of the harvested crop per plant. While broccoli had higher N and K concentrations than cauliflower, the N and K content in cauliflower is twice as much as the content in broccoli because of the greater biomass of cauliflower even though both crops had the same planting density and fertilizer rate. Pascale et al. (2005) also reported that cauliflower had a higher biomass (2.9x more) than broccoli at the same planting density of 1.8 plants/m^2.

However, considering there is a higher demand for broccoli than cauliflower in the urban markets, the cropping rounds and plot size of broccoli exceeds that of cauliflower so the total amount of nutrients exported from broccoli might be greater than the amount exported from the cauliflower per year per farm. Similarly, sweet potato had a higher nutrient concentration than cassava but cassava exports more N, P and K per square meter because of greater biomass and planting density. Howeler (2002) reported that cassava exported slightly more K, about the same P but slightly less N than sweet potato. However, the reported export of nutrients for cassava by Howeler (2002) were about half of that (on average) reported in this study. This can be attributed to the much lower yields reported by Howeler (2002) than in this study. The higher yields in this study can be attributed to the high density of planting practiced by some farmers. Even though in this study cassava exported a greater amount of nutrients per square meter than sweet potato, similar to the case with broccoli and cauliflower, on a per year per farm basis, sweet potato would export more nutrients than cassava as it has a greater demand in the market place, and thus greater areas are planted to sweet potato.

Most of the crops in this study exported more nutrients, especially K and N, per square meter than reported in other studies. This may be due to higher soil fertility or greater yields. On the other hand, the number of samples collected was quite small; the average nutrient export might have been lower if more samples were collected. Cauliflower, cassava, peanut and bulb onion exported large amounts of N per square meter but all the crops had a higher export of K than N, except peanut and spring onion. According to Anstett (1961, cited in Wichmann, 1992, pg. 278)[2], 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, pg. 144) and Howeler (1985, cited in Wichmann, 1992, pg. 144) indicated an export of 6.2-6.7 N, 1.0-1.7 P and 10.1-16.4 K g/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, pg. 139) reported an export of 2.3 N, 0.51 P and 2.5 K g/m^2 in sweet potato which is also a lower export of N, P and K than in this study. On the other hand, O'Sullivan et al. (1997) reported N, P and K exports that were within the range found in this study.

The export of nutrients from individual farms varied because of different planting densities. For example, farm D and farm F both grew cassava but it was planted at a density of 0.85 $plants/m^2$ in farm D and 4 $plants/m^2$ in farm F. This yielded a higher cassava biomass per plant in farm D than in farm F. On the other hand, cassava in farm F exported more N, P and K in the cassava because of the higher density. But considering the area under cultivation, the total amount of nutrients exported from cassava in farm D would exceed farm F because of a larger cultivation area in farm D. Pineapple had the lowest export of nutrients compared to all the crops, partly due to the low planting density of 1 $plant/m^2$.

Peanut exported the highest N content per square meter of all crops, probably due to its high density planting and nitrogen fixing capacity. Several studies indicated an export of 6-27 N, 0.6-2.4 P and 3.4-13.7 K g/m^2 in peanut and the N, P and K export in this study falls within that range (Wichmann, 1992, pg. 203).

[2] The Wichmann (1992) publication often cites a source of information but without the reference to that information

5.5 Nutrient budget of fertilized crops

The different pathways of nutrient input and output from a smallholder farming system were conceptualized (Figure 10), but only two of the external nutrient pathways directly controlled by the famers were measured, nutrient input from inorganic fertilizers and nutrient export through crop harvest.

The use of inorganic fertilizers in smallholder farming system in Bena is very limited. The use of inorganic fertilizers was mostly limited to farmers who grew temperate vegetables such as, broccoli, cauliflower, cabbage and bulb onion. The staple crops like sweet potato and cassava were not fertilized probably because these crops have been cultivated for decades without the use of inorganic fertilizers and farmers do not perceive any need to apply inorganic fertilizers to these crops to maintain soil fertility. Moreover, the introduced temperate vegetables have a recommended fertilizer application rate provided by Papua New Guinea Fresh Produce Development Agency (PNGFPDA), but there is no recommended fertilizer application rate for other 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 22). 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 & Manzi, 2003; Goenster et a.l, 2014; Haileslassie et al., 2006) . The smallholder systems show similar trends where there is more export from crop harvesting than inputs from fertilizers.

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. Although the proportion of soil N exported was small, the total N in the soil does not represent the readily available N that can be taken up by plants; 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 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 would be replenished from the reserve K pool, but if the process is slower than K removal, K deficiency will result.

On the other hand, the fertilizer P budget is in surplus resulting in its accumulation in the soil, assuming other losses are minimal. The concentrations of extractable P in unfertilized plots were below the optimum range so this accumulation of P may be beneficial to other crops if the fertilized plots are rotated with other crops.The fertilizer application rates of broccoli, cauliflower and bulb onion are quite low resulting in a negative balance of N and K. For example, farmer A applies 0.044 kg of NPK (10:25:12) to four broccoli plants which are sold in the market for K1.50-2.00/plant. The cost of 0.044kg of NPK fertilizer is about K0.46. To replace the 8.7 N, 1.1P and 11.2 K/m^2 exported by broccoli, farmer A has to apply NPK (10:25:12) at a rate of 0.112g/m^2 , which would cost about K1.16. Hence the farmer would recoup the fertilizer cost (K1.16) from the K6.00 she receives from selling the four broccoli plants.

Therefore the farmer can either increase the current fertilizer application rate or employ practices that retain as much of the nutrients in the field as possible..

5.6 Crop harvest management

The problem is that the óvalueô of time is recognised and appreciated but the óvalueô of nutrients is not recognised or appreciated. That is, a farmerøs decision to process crops in certain locations due to óconvenienceô affects the fate of crop residues or waste.

In the low input system that is practised by farmers, the efficient use of available nutrient sources within the system is vital for maintaining productivity (see internal nutrient pathways; Figure 10). The main export from the gardens is through crop harvest, but a large amount of plant residue and plant ówasteô is generated from the harvesting and preparation of food crops, either for household consumption or for marketing. Plant residue refers to plant parts that remain in the garden after harvest, and plant waste refers to plant parts that are harvested but are left elsewhere after crop preparation, like the skin, shell, stalk and leaves. This study has shown that these ówasteô products are a nutrient source that should potentially be better utilized.

When crops are harvested, they are separated into parts for consumption; for example, the tuber crops are peeled or nuts are shelled. If sold in the market the whole product is taken to the market resulting in a direct loss of nutrients. Peanut had the highest export of N and P per square meter 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, pg. 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.

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. 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 óconvenienceô factors determine whether nutrients are retained or lost from the garden.

Broccoli was the crop in which the highest concentration of K is in the exported product. Most of the K is located in the leaves (Table 25). When broccoli is harvested, leaves that have been damaged by insects or disease are removed and fed to the pigs or applied to a garden near the house if prepared at home. However, if the crop is processed at the market, these leaves are dumped in the market rubbish area, which represents a loss of nutrients, especially K. On the other hand, the leaves are left on the crop to protect the broccoli heads during transport and to help prevent them from wilting before sale.

There is a direct loss of nutrient 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 skin of the sweet potato contains 16%, 17% and 21% of the N, P and K in the tubers, respectively, which is a considerable portion of nutrients in relation to the low ratio of skin to flesh biomass. Similarly, the cassava has most of the nutrient in the flesh but the skin also contains substantial amounts of nutrients that can add nutrients to the soil if returned to the garden.

Pineapple is another crop that could be better managed for retention of nutrients in the garden. The pineapple is usually taken to market with the crown attached. In the market, the pineapple is then prepared by trimming the sharp points of the crown before selling and the ó wasteô is then dumped in the market rubbish area. If this process was done in the garden, a substantial amount of nutrients would be retained (Table 24). However, again óconvenienceô determines the practices involved with the harvesting and processing of harvested crops and thus determines whether nutrients are retained or lost from the garden system. For example, it is óconvenientô to process crops in the market while waiting to sell the crop. The farmer will be at the market all day, so will utilise the waiting time to process the crop. It is an efficient use of time but not an efficient use of nutrients. Another example of óconvenienceô is that the crown makes a good ôhandleô for carrying pineapples.

Summary

Mean soil nutrient concentrations in smallholder food gardens in Bena were mostly in the optimum range except for extractable P and exchangeable K. However, many individual gardens had N concentrations below the optimum range, indicating low soil fertility. With the current low input farming system practiced by the smallholder farmers the soil nutrients will continue to deplete and the soil may become deficient in N, P and K. The application of nutrient sources such as coffee pulp, kitchen peelings and ash was limited, but the areas that had physical evidence of such applications generally had higher K concentrations. This implies that application of these nutrient sources is beneficial for maintaining crop productivity. The soil nutrient stock was also higher under soils that received a regular dose of N, P and K fertilizer but new gardens also had high soil nutrient stock.

The nutrient demands of crops grown by the farmers differed considerably. Crops grown for market, like broccoli, cauliflower and bulb onion had the highest nutrient concentrations. These vegetable crops were fertilized with N, P and K so they presumably had enhanced access to these nutrients.

The nutrient export in harvested crops also varied substantially. The amount of nutrients exported by crops is a function of the nutrient concentration, planting density and plant biomass. Therefore crops like broccoli and sweet potato had high nutrient concentrations but the amount exported per square meter was lower than cauliflower and cassava. However, market demand also affects the net export of nutrients in crops. For example, broccoli and sweet potato are more in demand in the market than cauliflower and cassava so the planting frequency and plot sizes are greater. Therefore, the total amount of nutrients exported in sweet potato and broccoli may exceed the amount exported in cassava and cauliflower.

The two main pathways of nutrient flow quantified in this study were the output in harvested crop and input in inorganic fertilizers. The amount of N and K exported in harvested crops exceeded the amount imported in inorganic fertilizers, resulting in a negative balance of those nutrients and this negative balance may be exacerbated by various loss processes such as leaching and run-off that were not quantified. The P balance was positive, which may result in its accumulation. However the extractable P concentration in soil was low so the accumulated P may still not be fully available to crops. Also, the available N was not analysed which would give a better indication of the N fertility. These nutrient balances were calculated for fertilized crops; with unfertilized crops, the negative balances is the entire amount exported in the harvested product.

Apart from the main inputs and outputs, the movement of nutrients within the farms could be better managed to retain and use nutrients. The process of crop harvesting and preparation results in the production of residues or wastes that might be better managed to retain some nutrients in the farming system. For example, instead of preparing crops at the house or market, the crops could be prepared in the garden to facilitate the application of the waste or residues back to the garden plots to retain some nutrients. However, this option may be perceived as inconvenient and not practiced because the value of the nutrients in the waste is not appreciated.

The negative N and K budgets imply that the current farming system is unsustainable even in fertilized crops and there is a need to improve or change the current practises to better maintain nutrients within the farming system.

5.7 Limitations and Future Research

This study had several limitations that could be addressed if future research is undertaken:

1. The 1m distance that was used in sampling soil that was not affected by coffee pulp, kitchen peelings and ash could be increased to 2-3 metres to ensure the differences are captured better.
2. Sulphur should also be analysed to confirm if it is deficient, as farmers in Bena practice slash and burn during garden establishment.
3. Samples of coffee pulp, kitchen peelings and ash should be collected and analysed to establish nutrient value during time of sampling
4. The time frame of sampling soil under coffee pulp, kitchen peelings and ash should also be considered when sampling as nutrients are lost by natural processes like leaching, denitrification, runoff etc. if these materials are left too long in an exposed area.
5. Available N should be analysed apart from Total N, to give a better N fertility status of soil.
6. The number of food crops sampled was quite low and may not give a good representation of nutrient concentration of crops hence samples should be increased to get a better representation of nutrients exported per farm.
7. Future research should consider other pathways of nutrient loss from farming system such as leaching, denitrification, runoff, etc. to get a better representation of total export of nutrient from farming system.

Chapter 6: Conclusions and Recommendations

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 production to supply food for the increasing population has led to increased export of nutrients from gardens in crops sent to market. This will put immense pressure on the soil resource to sustain production.

Better use of nutrient sources such as coffee pulp, kitchen peelings and ash could help to meet crop needs for N and K, as an application of those materials to soil increased soil N and K concentrations. Current inorganic fertilizer inputs are not replenishing the amount exported, resulting in a negative balance of N and K. The P balance is positive in fertilized crops but the amount available in the soil is below the published optimum so availability to plants may still be suboptimal. Given the net export of nutrients from gardens, especially the unfertilized ones, farmers should use other nutrient sources and make better use of waste products or increase fertilizer N and K rates to make up the deficit.

Nutrient availability and stocks in gardens, and hence sustainability of production, could be improved by changing practices to better conserve and use the nutrients within these systems. The process of harvesting and preparation of crops results in the production of crop residues or waste that could be applied back to the gardens to retain a portion of the nutrients that are currently being lost from the gardens. This will require education about the value of nutrients in waste products versus the value of convenience.

6.1 Recommendations

- The application of coffee pulp, kitchen peelings and ash to food gardens should be encouraged so these nutrient sources are exploited rather than wasted.
- The current fertilizer application rate is not sufficient to replenish the amount of nutrients exported in fertilized crops so farmers should use more fertiliser or other nutrient sources such as crop residues or waste and animal manure to make up the deficit.
- Some of the decisions that farmers make during harvesting and preparation of food crops can be changed so that nutrients are retained in the food gardens as much as possible. For example, some of the preparation of crops like pineapple and peanut should be done in the garden instead of at the house or market so that the waste can be applied back to the garden instead of it being lost completely from the system when they are discarded elsewhere. This might be achieved through extension efforts that put a monetary value on the crop waste in terms of purchased NPK fertilizer needed to replace the nutrients lost. This might change farmersô perception of the value of time/comfort convenience.

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Appendices

Appendix 1- Interview Questionnaire

<u>Coffee Garden Inspection</u>

Name of farmer:

Village:

Coffee garden name:

Coffee garden #:

Age of coffee garden:

Garden GPS coordinates:

<u>Coffee trees</u>

1. How often are the coffee trees pruned? Why?

2. How many branches are pruned? Why?

3. Where is it used?

4. What is done with the coffee leaves from the pruned branches?

5. What is done to the coffee leaf litter?

<u>Shade trees</u>

6. Types and number of shade trees within coffee garden.

7. How often are the shade trees pruned?

8. How many branches is pruned?

9. Where are the branches used?

10. What is done to the shade tree leaves of pruned branches?

<u>Coffee Cherry Harvest</u>

Where do you pulp your coffee?

What do you do with the coffee pulp?

i. Left at pulping site
ii. If put in coffee garden, which coffee garden?
iii. If put in food garden, which food garden

Food Garden Inspection

Date:

Name of farmer:

Village:

Food garden name:

Food garden #:

Age of food garden:

Garden GPS coordinates:

Details of food garden

1. Garden type

i. monocrop

ii, mixed cropping

2. What sort of crops/food are grown?

3. How many rounds of planting have you done and what crops were cycled?

4. Is there a fallow period and how long is it?

5. What is the dominant fallow vegetation?

i. legumes

ii. short grass

iii. tall grass

iv. other

Inputs

1. Do you apply any organic fertilizer in this garden? If yes, what type?

2. How often do you apply in garden and what is the application rate (kg/plant)?

3. Do you apply any inorganic fertilizer in this garden? If yes, what type?

4. How often do you apply in garden and what is the application rate (kg/plant)

Harvesting and selling

1. Where does the harvested food from your garden go?

a. household consumption

b. market

c. customary ceremonies

e. given to relatives

2. How often do you harvest food from this garden?

2. Where do you put the litter of your harvest?

a. left at the garden

b. put in coffee garden

c. piled at the edge of garden

3. How much food/crops do you harvest?

3. Do you sell your harvest in the market?

4. If yes, the quantity that is sold at the market?

5. How often do you sell your produce at the market?

6. If harvested for household consumption, where do you put the food peelings?

Appendix 2- Garden History

Farmer	Garden #	History
A	1	**Age**: <1 year **Vegetation prior to food crops**: *Imperata cylindrica*. **Plot 1:** Just came out of fallow and cropped with bulb onion. Fertilized with NPK (12:12:17)*@ 1.7g/plant.
	2	**Age**:>10 years **Vegetation prior to food crops**: Secondary vegetation. **Plot 1**: previously sweet potato (not fertilized) now replanted with broccoli. Broccoli fertilized with NPK (10:25:12)*@ 11g/plant. No fallow **Plot 2**: previously sweet potato (not fertilized) now replanted with cauliflower. Cauliflower fertilized with NPK (10:25:12) @ 11g/plant. No fallow **Plot 3:** previously broccoli (fertilized with NPK (10:25:12) @ 11g/plant) now planted with sweet potato (not fertilized). No fallow *The farmer makes 3 rounds of broccoli and cauliflower on separate plots in a year and rotates it with sweet potato or continues cropping for another year. The yearly NPK usage for this garden is 15kg.
	3	**Age**:>10 years **Vegetation prior to food crops**: *Imperata cylindrica*. **Plot 1**: previously sweet potato (not fertilized) now replanted with broccoli. Broccoli fertilized with NPK (10:25:12) @ 11g/plant. No fallow **Plot 2**: previously sweet potato (not fertilized) now replanted with cauliflower. Cauliflower fertilized with NPK (10:25:12) @ 11g/plant. No fallow **Plot 3:** previously broccoli (fertilized with NPK (10:25:12) @ 11g/plant) now planted with sweet potato (not fertilized). No fallow *The farmer makes 3 rounds of broccoli and cauliflower on separate plots in a year and rotates it with sweet potato or continues cropping for another year. The yearly NPK usage for this garden is 15kg.
B	1	**Age**:<2 years **Vegetation prior to food crops**: *Imperata cylindrica* **Plot 1**: previously planted with peanut (not fertilized) now replanted with bulb onion. Bulb onion fertilized with NPK (12:12:17) @ 1.7g/plant. No fallow.
	2	**Age**:>10 years **Vegetation prior to food crops**: *Imperata cylindrica* **Plot 1**: previously planted with sweet potato (not fertilized) now replanted with pineapple (not fertilized). No fallow
	3	**Age**:<4 years **Vegetation prior to food crops**: *Imperata cylindrica* and *Mimosa pudica*

		Plot 1: continuous pineapple (not fertilized). No fallow. **Plot 2**: continuous sweet potato (not fertilized). No fallow
C	1	**Age**:>10 years **Vegetation prior to food crops**: *Imperata cylindrica* **Plot 1**: Coffee intercropped with cabbage. Cabbage fertilized with NPK at a rate of 100g/plant. No fallow.
	2	**Age**:>10 years **Vegetation prior to food crops**: *Imperata cylindrica* **Plot 1**: continuous sweet potato (not fertilized). No fallow.
	3	**Age**:<5 years **Vegetation prior to food crops**: *Imperata cylindrica* and *Mimosa pudica* **Plot 1**: continuous pineapple (not fertilized). No fallow. **Plot 2**: continuous sweet potato (not fertilized). No fallow.
D	1	**Age**:<5 years **Vegetation prior to food crops**: *Imperata cylindrica* **Plot 1**: continuous sweet potato (not fertilized). No fallow. **Plot 2**: previously peanut (not fertilized) now replanted with cassava (not fertilized). No fallow.
	2	**Age**:<3 years **Vegetation prior to food crops**: *Imperata cylindrica* **Plot 1**: continuous pineapple (not fertilized). No fallow
E	1	**Age**:<3 years **Vegetation prior to food crops**: *Imperata cylindrica* and *Mimosa pudica* **Plot 1**: previously sweet potato (not fertilized) now bulb onion. Bulb onion fertilized with NPK (12:12:17) @ 1.7g/plant. No fallow. **Plot 2**: continuous sweet potato (not fertilized). No fallow.
	2	**Age**:>10 years **Vegetation prior to food crops**: *Imperata cylindrica* and *Mimosa pudica* **Plot 1**: continuous pineapple (not fertilized). No fallow **Plot 2**: continuous sweet potato (not fertilized). No fallow
F	1	**Age**: > 10 years **Vegetation prior to cultivation for food crops**: *Imperata cylindrica* **Plot 1**: continuous pineapple (not fertilized). No fallow **Plot 2**: wide ï spaced citrus intercropped with pineapples. No fertiliser but some coffee pulp applied to citrus **Plot 3**: previously pineapple for 5 years (not fertilised) now replanted with sweet potato (no fertiliser). No fallow **Plot 4**: previously pineapple for 5 years (not fertilised) now replanted with bulb onion. Bulb onion fertilized with NPK (12:12:17) @ 1.7g/plant. No fallow

*The NPK fertilizers are in the oxide form.