DEVELOPING AN INTEGRATED SOIL FERTILITY MANAGEMENT DECISION SUPPORT TOOL FOR ARABICA COFFEE (*Coffea arabica*) IN SELECTED AREAS OF NORTHERN TANZANIA

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EXTENDED ABSTRACT

Coffee is one of the major export crops in Tanzania, contributing 24% to the agricultural gross domestic product (AGDP). The crop contributes directly to the livelihoods of over 420 000 farm families and indirectly to over 2 million people employed in the coffee value-chain. The Tanzanian average coffee production is variably pegged at 45 000 – 52 000 metric tons annually, while smallholder coffee productivity per tree ranges between 250 and 300g of parchment which is low compared to the world average of 500 – 600 g per tree. In the northern zone, for instance, annual coffee production trend indicates a decline over years as from 1980. During the first coffee stakeholders' conference in 2009, soil fertility decline was pointed out by representatives of coffee growers as one of the most limiting factors for coffee productivity and sustainability. In the absence of a clear soil fertility intervention strategy in the coffee growing areas, with scanty and incoherent soil fertility data and limitations in their reliability and usability, it would seem impossible to verify the farmers' claims or devise an intervention pathway. This formed the rationale of this work, whose objective was to develop a system that will make the soil analytical data useful for coffee farming. A model was required to quantitatively translate the soil data into estimated coffee yield, and also to recommend nutrient input application for best returns. This study was undertaken in Hai and Lushoto Districts, Northern Tanzania. The two districts were picked on merit of both growing coffee (thus experiencing the problem of coffee productivity decline) and each belonging to different geological origins (volcanic and metamorphic-gneissic parent materials, respectively). The first task was to establish the farmers' perception of soil fertility decline as a problem and their attitudes towards integrated soil fertility management (ISFM) for coffee, thereby identifying the appropriate intervention strategies. Based on questionnaire data involving 126 respondents, both farmers' awareness of the problem and their attitude were highly significant (at p<0.01). Age, total land area under coffee and total off-farm income negatively affected farmers' attitude. As farmers get older, they tend to refrain from innovation. For the two districts, ISFM interventions will make a better impact to younger and more energetic farmers with enough land for coffee production and who depend largely on this crop for their livelihood. It was therefore concluded that the interviewed farmers echoed the concern that their representatives made in 2009. Another study was conducted to assess the soil fertility status against the soil fertility requirements for Arabica coffee, thus scientifically verifying the above concern. A total of 116 soil augerings and 10 soil profiles were described, and soil samples analyzed for the key soil fertility parameters. Soil fertility was assessed qualitatively, quantitatively and spatially. It proved to be considerably low in the study areas, and much lower in Lushoto than in Hai. Immediate recommendations to address the declining soil fertility were given, which include integrated farm management, adequate supply of essential nutrients and building capacity to produce high quality soil data and to interprete them in terms of coffee productivity. Following the two earlier studies, a review of existing crop models was made and a Wageningen model called QUEFTS was picked as a benchmark. It was recalibrated with the coffee crop in mind, and a new model called SAFERNAC (Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee) was developed. The model was checked for accuracy and applicability and found to be capable of reproducing the actual yields by 80-100%. The new model, tested with soils of Hai and Lushoto Districts, proved to be a useful tool for coffee land evaluation and ISFM planning. Through a screen house experiment, different organic materials were tested for nutrient release potential and the data used as inputs to the model for yield estimation under different nutrient management options. Mineral N, P and K release varied significantly (P<0.001) among the organic materials and between the two soil types representative of the study areas. The model demonstrated its potential in suggesting appropriate nutrient management options for both organic and conventional farmers, and showed that green manure plants have great potential in coffee ISFM. The model was further expanded to involve prices of inputs and outputs for the determination of net returns and coffee profitability. It was used to obtain yields from a soil of known properties receiving different levels of input N, P and K from both organic and inorganic sources (ISFM). The costs of inputs were derived from experiences in Northern Tanzania, while coffee prices were estimated to range between 1250 and 2500 TZS kg^{-1}. The economically optimum input applications (in equivalent terms) that gave highest net returns and value: cost ratios were found to be 401, 332 and 418 kE ha^{-1} for soils of low, medium and high fertility, respectively.

The recommendations emanating from this study are outlined hereunder:

1. ISFM efforts should focus on younger and more energetic farmers with enough land and who depend largely on coffee for their livelihood. TaCRI and other coffee stakeholders should devise a programme to encourage young people to take coffee farming as a viable business.
2. Factors affecting farmers’ decisions on fertilizer use should be taken into consideration in devising an ISFM strategy for the coffee farmers.
3. TaCRI and the coffee extension machinery at district level should continue to promote the right kind of nutrient management strategy to the farmers. Also, promotion of the improved coffee varieties among farmers should continue.
4. Farmers should be encouraged to come forward and pre-test the model under TaCRI guidance. The pre-testing should include interested organic and conventional farmers around Lyamungu and Yoghoi, specifically to test the target yield and respective ISFM options suggested.

The following activities are envisaged for future perfection of this work:

1. To continue research on the four green manure plants (*Mucuna, Lupine, Canavalia* and *Crotalaria*) as to their appropriate application methods in a farm, and notify coffee farmers as soon as the results becomes available.
2. To include in the coffee ISFM programme other plants with nutritive value, such as “tughutu” (*Adhatoda engleriana*), wild sunflower (*Tithonia diversifolia*) and fishbean (*Tephrosia vogelii*).
3. To carry out more research on the applicability of the model to all categories of coffee growers, with issues of shade-grown coffee, intercropped with staple food crops, etc.
4. To integrate the model to more generic agrometeorological models as climate change becomes more and more important in the coffee growing areas.
5. To establish the appropriate entry points in the inclusion of secondary macronutrients and micronutrients to the model and the way they influence the availability of N, P and K to coffee.
6. To collaborate with computer programming specialists and develop a full-fledged software for SAFERNAC.

DECLARATION

I, **GODSTEVEN PETER MARO**, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

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The above declaration is confirmed

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DEDICATION

This thesis is dedicated to my first wife Beatrice, who bravely started the work with me, but could not live to see it a reality; and to my mother, Eliaichanasia, who always inspired me to study hard and aim higher, but the Almighty God needed her earlier than she could see this success. May the two souls rest in peace, Amen.

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LIST OF ABBREVIATIONS AND SYMBOLS

α	Symbol Alpha (representing attitude towards ISFM)
A	Availability (of a certain nutrient) for plant uptake
a	Short form of PhEA or PhEmin
ANOVA	Analysis of variance
aP	Symbol representing awareness of soil fertility problems
APSIM	Agricultural production systems simulator (a crop model)
CBD	Coffee berry disease
CERES	Crop environment resource synthesis (a crop model)
CI	Confidence interval
CLR	Coffee leaf rust
CPU	Central pulping unit (usually owned by farmer groups)
CRS	Coffee Research Station, Lyamungu (later became TaCRI headquarters)
CV	Coefficient of variability
d	Short form of PhED or PhEmax
DSSAT	Decision support system for agro-technology transfer (a crop model)
ESRI	Environmental Systems Research Institute
EU	European Union
FAO	Food and Agricultural Organization of the United Nations
FC	Field capacity (of a soil)
FYM	Farmyard manure (in the context of this work: cattle manure)
GDP	Gross domestic product
GIS	Geographic Information System
GPS	Global Positioning System
HCx	Handling cost of fertilizer input

HCy	Handling cost of yield (harvesting, processing, storage etc)
I_i	Input of nutrients in inorganic nutrient sources
I_o	Input of nutrients in organic nutrient sources
IA	Available input nutrients
ICO	International Coffee Organization
ICRAF	International Centre for Research on Agroforestry
IDW	Inverse distance weighting (a GIS spatial interpolator)
INPUT	Model component dealing with application of nutrients
IPM	Integrated pest management
ISFM	Integrated soil fertility management
ITC	International Trade Centre
ITK	Indigenous technical knowledge
IUSS	International Union of Soil Sciences
K	Potassium
kE	Nutrient equivalent (same effect on yield as 1kg N)
KNCU	Kilimanjaro Native Cooperative Union
LUTs	Land utilization types
MARI	Mlingano Agricultural Research Institute
MOP	Muriate of Potash
MRF	Maximum recovery fraction
N	Nitrogen
Nmin	Mineral nitrogen (usually mineralized from organic forms)
NGO	Non-governmental organization
(S)OC	(Soil) organic carbon
P	Phosphorus

PhE	Physiological (or internal utilization) efficiency
PhEA	Physiological efficiency at accumulation
PhED	Physiological efficiency at dilution
PhEM	Physiological efficiency at balanced nutrition
pH	Negative logarithm of hydrogen ion concentration
PLANT	Model component dealing with plant properties like density
QUEFTS	Quantitative Evaluation of the Fertility of Tropical Soils
r	Parameter describing minimum uptake required for yield (not used for coffee in Northern Tanzania)
R	Rating for the questionnaire information
RE	Relative effectiveness of nutrients in organic sources
RPP	Radiation-thermal Production Potential
RUSLE	Revised universal soil loss equation
SA	Amount of available nutrients from soil alone (natural fertility)
SAFERNAC	Soil analysis for fertility evaluation and recommendation on nutrient application to coffee
SAP	Strategic action plan of TaCRI (usually of 5 years)
SECAP	Soil erosion control and agroforestry project
SOIL	Model component dealing with soil properties of interest
SOP	Sulphate of potash
SOTER	Soil and terrain database
SPSS	Statistical package for social sciences
SSA	Sub-Saharan Africa
SV	Substitution value (same as RE)
TA	Target amount of available nutrients

TaCRI	Tanzania Coffee Research Institute
TCA	Tanzania Coffee Association
TCB	Tanzania Coffee Board
TCCCo	Tanganyika Coffee Curing Company
TCGA	Tanganyika Coffee Growers Association
TRIT	Tea Research Institute of Tanzania
TSA	Total soil available nutrients (N, P and K) in equivalent terms
TSBF	Tropical Soil Biology and Fertility
TU	Target uptake (for a target yield)
TY	Target yield
TZS	Tanzanian Shilling
U	Uptake
USD	United States Dollar
UTM	Universal Transverse Mercator
VPU	Vegetative Propagation Unit
WPP	Water-limited production potential
Y_{act}	Actual yields from experimental sites
YE	Yield estimated by the model
YKA	Yield associated with the uptake of potassium at accumulation
YKD	Yield associated with the uptake of potassium at dilution
Ymax	Maximum attainable yield under salient phenological set-up
YNA	Yield associated with the uptake of nitrogen at accumulation
YND	Yield associated with the uptake of nitrogen at dilution
YPA	Yield associated with the uptake of phosphorus at accumulation
YPD	Yield associated with the uptake of phosphorus at dilution

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Importance of Coffee

1.1.1 Global importance as a traded commodity

Coffee is an important commodity in the world economy, accounting for trade worth approximately USD 16.5 billion in 2010/11 (TCB, 2012). World production is estimated to reach over 130 million 60-kg bags. A total of 70 countries produce coffee globally. Of these, 45 which are exporting members of the International Coffee Organization (ICO, 2011) are responsible for over 97% of world output (ITC, 2002). Brazil and Vietnam lead the production, while Africa's share is about 12% and Tanzania's is 0.6% from the 2011 statistics (TCB, 2012). The share of coffee in total exports by value in 2000, was over 50% in Burundi, Ethiopia, Uganda and Rwanda, while in Tanzania and Kenya it was 15% and 12%, respectively (ITC, 2002).

Coffee is important to the livelihoods of more than 25 million people and their families, and it is one of the most valuable commodities in the world. Every day, about 1.5 billion cups of coffee are consumed globally, of which one-fifth are drunk in the United States (Luttinger and Dicum, 2006).

1.1.2 Importance of coffee in the Tanzanian economy

1.1.2.1 Coffee trade in Tanzania

Coffee is the second major export crop in Tanzania after tobacco, contributing 24% to the annual agricultural export earnings, generating an average of USD 100 million annually (TCB, 2012). Coffee supports the livelihoods of over 420 000 farm families directly and over 2 million people employed in its value-chain indirectly (Carr *et al.*, 2003). Arabica coffee contributes 65% of the Tanzanian total coffee export, while the rest is Robusta. The Tanzanian coffee, especially the washed Arabica, is one of the best in the world, ranked among the rare category of “Colombian Milds”. Due to its distinct body and flavour, it is normally used to blend with other inferior coffees like ordinary milds, hard Arabicas and Robustas, thus the demand for the Tanzanian coffee is always higher than the supply.

1.1.2.2 Coffee stakeholders

Coffee attracts a lot of players along its value chain. Such players are collectively known as stakeholders. Coffee stakeholders are well defined in the TaCRI Memorandum and Articles of Association, and are also recognized, individually or in groups, by the Crops Act of 2006 which formed the crop stakeholder forums, and also the Coffee Industry Act of 2010 (TCB 2011) and the Coffee Industry Development Strategy (TCB, 2012). The stakeholders are categorized as:

i. **Smallholder coffee producers**: This group is comprised of farmers owning less than two hectares of coffee land. These produce over 95% of Tanzania’s coffee.

ii. **Large scale producers and estates**: This includes farmers owning land between 2 and 20 ha (large scale farmers) and above 20 ha (estates). They contribute about 5% of total annual coffee produce, most of them located in the Northern Zone.

iii. **Primary and secondary processors**: This include firms owning primary processing plants (like group-owned CPUs) and the curing plants like Tanganyika Coffee Curing Company Ltd (TCCCo), Mbinga Coffee Curing, Mbozi Coffee Curing, Rafiki Coffee Mills and Amimza Ltd.

iv. **Coffee exporters**: These are agents of some coffee traders overseas who buy coffee, store it in their warehouses and ship it to its final destination. They are the active players in the Moshi Coffee Auction, while they also oversee the process of direct coffee export.

v. **Local roasters, coffee shops and vendors**: This is a complex group of coffee stakeholders. There are people who are involved in the coffee roasting as a business of its own, coffee shops which also do the roasting, and the street coffee vendors in major cities.

vi. **The Tanzania Coffee Board**: This is a government organ established by the Tanzania Coffee Industry Act No. 23 of 2001. Its main function is to regulate the coffee industry in Tanzania and advise the Government on all matters related to coffee (TCB, 2012).

1.2 Coffee Growing in Tanzania

1.2.1 History of Arabica coffee

Arabica coffee is said to have originated in Ethiopia, and was first discovered in the Kaffa area. A goat herder by the name of Kaldi found that when the goats ate berries and leaves of a certain wild bush they became more active. He picked some berries and showed them to a monk, who dismissively threw them away, some falling into open fire. Upon roasting, that typical aroma and fragrance recaptured the monk's attention. He took the beans from the ashes and put them in water to cool. He then drank that water (the first cup of coffee), and played a key role in the promotion of the berries (Millinga *et al.*, 2008; Luttinger and Dicum, 2006).

Coffee was first grown commercially in Yemen, in the Arabian Peninsula; and this can explain the name *Coffea arabica* coined by the Swedish taxonomist, Carolus Linnaeus (1707-1778). It was introduced to Tanzania in 1893 from the Reunion Island by the French Roman Catholic missionaries, and was first planted at the missionary stations of

Morogoro and Kilema in Kilimanjaro. It was first grown commercially by European settlers on the slopes of Mt. Kilimanjaro. TCB (2012) gave an estimated total of 178 500 ha currently growing Arabica coffee in five zones, namely Northern, Mbinga, Mbeya, Tarime and Kigoma.

Coffee belongs to the genus Coffea, family Rubiaceae, class Angiospermae and phylum Spermatophyta in the Plant Kingdom. Three other commercial species exist, namely Robusta coffee (*Coffea canephora*), *Coffea liberica* and *Coffea excelsa*. A number of other wild species have been discovered in the wilderness of East Africa and are being harnessed to enrich the available coffee germplasm, the latest one being *Coffea kihansiensis* discovered in the Udzungwa Mountains (Millinga *et al.*, 2008).

1.2.2 Characteristics and requirements of Arabica coffee

Arabica coffee is a shrub or small tree, usually 2.0–7.5 m tall (Smith *et al.*, 2011), with wild coffee trees growing up to 12 m and cultivated trees pruned conveniently for harvesting (DaMatta *et al.*, 2012). Plants have vertical and lateral branches. The first shoot growing from the seed becomes a vertical branch, and two lateral branches grow from buds produced at each node. Leaves are opposite, shiny deep green, oval, pointed 7–20 cm long and 3–7 cm wide (Smith *et al.*, 2011). Flowers are white, fragrant, massed in thick clusters at leaf axils along the branches; corolla has 5 narrow lobes, longer than the tube, which is about 1 cm long (Luttinger and Dicum, 2006). The fruit is dark red, yellow, or pink when ripe, drying to brown, ovoid, fleshy berry about 1.2–1.6 cm long, 1.0–1.2 cm in diameter, usually containing two seeds although occasionally only one seed called “peaberry” develops. Fruits are borne on 1-year-old lateral wood. Once a node has produced fruits, it usually will not produce again.

Arabica coffee (*Coffea arabica*) prefers a tropical highland climate with rainfall of over 1200 mm spread over eight months (Collet *et al.*, 2012). For good coffee growth and yields, the dry season should not be longer than 3 months. The ideal temperature for *C. arabica* ranges from 15-25^{o}C, while absolute minimum temperatures should not be lower than 4-5^{o}C and absolute maximum temperature should not exceed 30-31^{o}C (Maro and Mbogoni, 2009). It prefers very deep (usually more than 1.5 m), well drained friable loamy and clay soils. Soils with high available water holding capacities and a pH in the range of 5-7, the ideal range being 5.8-6.2 (Smith *et al.*, 2011) with high nutrient retention capacities are suitable for coffee production. Such soils may be in the soil groups Luvisol, Nitisol, Andosol and Vertisol (IUSS Working Group, 2006). As a perennial crop coffee removes on the average 135 kg of N, 35 kg of P_2O_5 (= 15.3 kg P) and 145 kg of K_2O (= 121.2 kg K) per ha per season (Sys *et al.*, 1993).

1.2.3 General cultural practices

General cultural practices for Arabica coffee are well described in Pohlan *et al.* (2012), Smith *et al.* (2011), TaCRI (2011), Wintgens (2012) and Wrigley (1988). The important agronomic practices for Arabica coffee include:

i. Land preparation (clearing, ploughing, harrowing and field layout)
ii. Nursery practices (raising of seedlings from seeds or vegetative clones)
iii. Planting
iv. Weeding
v. Control of pests and diseases
vi. Shade tree and canopy management (including pruning of both coffee and the shade trees, and removal of vertical non-productive suckers)
vii. Soil fertility and nutrient management
viii. Irrigation (where rain is inadequate and irrigation water is available)

1.2.4 Coffee harvesting and primary processing

There are two types of coffee harvesting as described by Wintgens (2012), namely selective hand picking and stripping. Selective harvesting consists of picking the ripe cherries only (Plate 1.1). This is the ideal procedure which ensures that 100% of red-ripe cherries are harvested with the least damage to the tree; and is practised by all smallholder coffee growers in Tanzania. Stripping, which is very famous in Brazil, consists of removing berries of all ages (immature, ripe and over-ripe) at once. It is impractical with wet processing unless supported by mechanical sorters.

Ripe cherries are pulped the very day they are harvested, and farmers should be trained and insisted to observe quality during harvesting so as to minimize the inspection and sorting time.

Plate 1:1 Coffee should be harvested while red-ripe.

Wet parchment should be washed with all remaining pulp removed, and then fermented for 24 hours (this is usually not needed if ecological pulpers with demucilagers are used). This is followed by washing and further under-water soaking to remove mucilage from the centre-cut, and finally drying in raised beds.

1.2.5 History of coffee research in Tanzania

By the end of the 19th Century, coffee had been established as a commercial crop by the colonial settlers in Kilimanjaro (Teri *et al*., 2004). It was therefore considered important to have a coffee research centre to address the coffee production challenges. The Coffee Research Station (now TaCRI Headquarters) at Lyamungu was established in the 1920s and became operational in 1934.

Initially coffee research during the colonial period concentrated on breeding for higher yields and quality, and related agronomic practices. Coffee leaf rust, caused by the fungus *Hemileia vastatrix,* was not an issue for research until 1952 though it was reported in Kilimanjaro in 1894 (Kilambo *et al.*, 2004). Coffee berry disease (CBD) caused by *Colletotrichum kahawae* was reported much later, in the 1940s, but it soon became an issue for research. By independence (1961), coffee research was already tuned to breeding for resistance to the two devastating diseases and some promising lines had been selected (Teri *et al.*, 2004).

After independence, all private crop-oriented research stations were nationalized and made into Agricultural Research Institutes; dealing with a variety of crops and even livestock. The post-independence coffee research was characterized by inefficiency due to meagre funding of diverse programmes and the sector suffered even more with the historical coffee crisis of 1980s to 1990s. However, some efforts, specific to the coffee crop, were still being done through the EU-funded Coffee and Stabex Management Unit (Agrisystems, 1998).

Following the limitations cited above, coffee stakeholders (especially growers) realized that they were not getting their rightful service from the coffee research programme.

They organized lobbying sessions with the aim of regaining ownership of coffee research. Borrowing a leaf from Tea Research Institute (TRIT) which had been formed earlier, TaCRI was legally constituted in 2000 and became operational in September, 2001 as a stakeholder-led, demand-driven coffee research institute.

1.2.6 Coffee production trends

A thorough review of the performance of the coffee industry in Tanzania was done by Agrisystems (1998), Baffes (2003) and Hella *et al.* (2005), who noted that the Tanzanian average annual coffee production was variably pegged at 45 000 – 52 000 metric tons. The smallholder coffee productivity per tree ranges between 250 and 300 g of parchment which is very low compared to the potential yield of over 1 kg per tree (Baffes, 2003). In the northern zone, for instance, annual coffee production trends indicate a decline over years whereby Kilimanjaro, once a giant coffee producer, appears to have suffered most, with annual production declining from about 20 000 tons in 1981/82 to less than 5000 tons by 2005/06 (Maro *et al.,* 2010a).

A number of constraints have previously been pointed out as the cause of this decline, like unreliable marketing and low prices (Baffes, 2003; Envirocare, 2004; Chimilila *et al.*, 2008) and high production costs, especially due to the high prices of the fungicides for CBD and rust control (Teri *et al.*, 2004). Currently, however, these limitations have been addressed through quality improvement by putting emphasis on central pulpers (Maro *et al.*, 2010b), breeding for disease-resistant varieties and adoption of IPM practices (Kilambo *et al.*, 2004, Magina, 2011). As reflected during the coffee stakeholders’ forum (TCB, 2009), soil fertility decline has emerged as one of the most limiting factors.

1.3 Soil Fertility in Coffee Growing Areas

Soil fertility is defined as the capacity of soil to support (plant) life (Brady and Weil, 2002). It is measured by the presence in the soil of plant-available forms of nutrients (primary and secondary macronutrients, and micronutrients), in sufficient amounts and in proper balance; coupled with ideal physical conditions that ensure effective uptake and utilization by the plants.

Soil reaction (pH), cation exchange capacity (CEC) and organic matter content are determinants of the availability of most nutrients to coffee (Cordingley, 2010). Coffee grows well at the pH range of 5.2 to 6.5. Low pH increases aluminium toxicity, which is associated with deficiency of basic cations (calcium and magnesium). Trace elements like iron, manganese, zinc, copper, etc, become more mobile at low pH values, while some microbial activity is inhibited. High pH induces micronutrient deficiency, and is mostly associated with sodicity. CEC represents the amount of negative charge at the surface of soil particles which attract (adsorb) cations. Such cations can be exchanged between the colloidal particle surface and the soil solution, allowing cations applied in the field as fertilizers to be retained (against leaching) and taken up by plant roots (Brady and Weil, 2002). Expressed as Organic Carbon (OC), organic matter represents reserve nutrients which need time and favourable environment (including availability of micro-organisms) for decomposition so as to become available to plants.

Plate 1.2: Healthy coffee trees (left), malnourished ones (right)

Nitrogen is the most limiting of all the essential plant nutrients, required by the coffee plant for vegetative growth, flowering and bearing capacity, protein formation and enhancement of leaf:crop ratio. Plate 1.2 compares a healthy coffee field with another one showing nitrogen deficiency. N deficiency results into lack of bearing wood, reduced flowering points, reduces fruits per cluster and reduction in leaf size and leaf life (reduced photosynthetic potential) (Cordingley, 2010; Wintgens, 2012).

Phosphorus is essential for root growth, wood formation, sound fruit formation and early maturity of berries. P deficiency is often associated with purple lower leaves with faint yellow veins, while young leaves remain dark green. Necrosis of older leaves occur at advanced stages (Cordingley, 2010). Soil P levels should be > 30 mg kg^{-1} for maintaining profitable yields in coffee (Obethur *et al*., 2012). Phosphorus availability is inhibited by fixation at low pH values (Brady and Weil, 2002).

Potassium is essential in coffee plants for metabolism, yield formation (development and ripening of cherry) and efficient water utilization. A soil K level of 200 mg kg^{-1} (or 0.5 $cmol_c.kg^{-1}$) K is considered the minimum desirable level for coffee (Cordingley, 2010). Coffee removes almost as much of K per ton of yield as N (Janssen, 2005). Therefore in low K soils, where natural supply of K is inadequate, it is essential to apply as close to a 1:1 ratio of N: K as possible.

Maro *et al.* (2006) attempted to characterize the soil fertility status of coffee growing areas in Tanzania. From the earlier work by Van Oosterom *et al.* (1998), who produced a coffee suitability map of Tanzania at a scale of 1:2 000 000, it was noted that, for both Arabica and Robusta, the ideal condition that requires no nutrient input does not exist, and the current coffee growing areas range from suitable (S2) to marginally suitable (S3) and even unsuitable with possibility of improvement (N1). Generally, 86% of coffee land was found to be of moderate to very low natural soil fertility. With coffee as a perennial crop which has specific nutrient demands, the situations of low natural soil fertility are aggravated by continuous mining of specific nutrients.

1.4 Soil Fertility Decline in the Coffee Growing Areas

1.4.1 Causes of soil fertility decline in coffee areas

Janssen (2005), Semoka *et al.* (2005) and Maro *et al.* (2006) noted the following possible causes of soil fertility decline: (a) The soil conditions in the coffee growing areas, related to the type and age of the parent material and factors of soil formation. For instance, soils derived from sandstone (Kagera), the red, highly weathered soils (Mbozi and Mbinga) and the more recent volcanic soils (Moshi and Arusha) differ in their natural fertility; (b) climate and terrain features which influence the nature and direction of nutrient flows (e.g. washing away of cationic nutrients by rain in upper slopes, which lowers soil pH); (c) the life span of a coffee tree which is perennial, therefore having to be in place for over 30 years and continuously mining specific nutrients from the soil, and (d) improper soil fertility management by the coffee growers (inability/reluctance to invest in soil fertility replenishment, improper farming practices that encourage leaching and erosion).

1.4.2 Extent of the soil fertility decline problem

Soil fertility decline has become an issue of concern throughout the Sub-Saharan Africa, cutting across many different soils and crops (Buresh *et al.*, 1997; Kumwenda *et al.*, 1996; Blackie, 1994). The problem covers all coffee growing zones of Tanzania and all types of coffee growers, namely small, middle and large scale farmers (Agrisystems, 1998).

1.4.3 Efforts in addressing the soil fertility problem

1.4.3.1 Collection and analysis of available soil fertility information

Since SAP I (2003-2008), TaCRI appreciated the importance of soil fertility in coffee and the need for having soil fertility records for gauging the present and future decisions in soil fertility management. In 2004/05, two consultancies were launched to evaluate the soil fertility database in the Tanzanian coffee growing areas (Semoka *et al.*, 2005) and to evaluate the performance of the then Crop Nutrition Department (Janssen, 2005). Knowledge gained from the two consultancies provided a convenient starting point in devising appropriate ISFM research for coffee.

1.4.3.2 Establishment of a soil fertility laboratory

From recommendations made by Semoka *et al.* (2005) and Janssen (2005), TaCRI embarked on establishing a coffee soils laboratory on the platform of an old wooden building, and the laboratory was inaugurated in February, 2008. The analytical capacity of the laboratory has been gradually increasing with the acquisition of modern equipment and as of now, it can handle all routine soil, water and plant tissue analysis.

1.4.3.3 Fertilizer trials

For many years and in different crops, field trials on crop response to fertilizers have been the standard source of information for charting out fertilizer recommendations. For a number of reasons including the nature of coffee as a perennial crop, only a limited number of such trials have been conducted, as noted by Kullaya (2002) and Janssen (2005). The trials were location-specific and usually not reproducible in different ecological settings. This, coupled with the global move towards precision agriculture (Bruce, 2007), underscore the need to establish a system of fertilizer recommendation that will be both simple and generic, but applicable in multiple coffee growing areas.

1.4.3.4 Fertilizer recommendations based on soil characteristics

Fertilizer recommendation on the basis of soil characteristics and target yields is a rather new discipline, meant to complement fertilizer response trials (Kullaya, 2002). TaCRI has adopted this in its campaign “Know your farm” started in 2006 with the objective of sensitizing farmers to make informed decisions on nutrient input usage in their farms based on soil characteristics. The campaign seemed to work more with large farms (which could afford the cost of soil analysis) than the resource-poor smallholders. A follow-up campaign, which is still on-going, is to generate “global” district level databases which will guide the District Coffee Subject-Matter Specialists (DCSMS) to address the location-specific needs of smallholders.

1.4.4 Information gap

1.4.4.1 Lack of clear soil fertility intervention strategy

Since the first TaCRI’s Strategic Action Plan (SAP I, 2003-08), and even in the second SAP (2008-13), proper soil fertility intervention, and particularly integrated soil fertility management (ISFM), has been identified as key to improved and sustainable coffee productivity. Gumbo (2006) and Raab (2002) cited ISFM as the key in raising productivity levels in agricultural systems while maintaining the natural resource base. It aims at replenishing soil nutrient pools, maximizing on-farm recycling of nutrients, reducing nutrient losses to the environment and improving the use efficiency of external inputs. So far, however, there has not been a clear soil fertility intervention strategy in the coffee areas (Semoka *et al.*, 2005). There is therefore a need to put efforts towards such a strategy.

1.4.4.2 Scanty and incoherent soil fertility database

The consultancy reports by Semoka *et al.* (2005) and Janssen (2005) noted that soil fertility information for coffee growing areas in Tanzania is scanty and incoherent. They reported a general lack of long term comprehensive soil fertility data, with the available data being of limited coverage and not having been updated for nearly 30 years. Despite the establishment of a coffee soil laboratory (Janssen, 2007), the recently started and on-going campaign of district level soil fertility surveys and compilation of zonal soil fertility database, the information is of limited use to a farmer unless properly interpreted. An easy-to-use system of soil data interpretation for coffee farmers is therefore desirable.

1.4.4.3 Use and misuse of organic litter at farm level

Farmers have varying levels of appreciation of soil fertility as a problem and the role of integrated soil fertility management in sustainable coffee productivity. The farmers have been using organic manures for ages in their coffee farms. Some are even reluctant to apply inorganic fertilizers to coffee (Maro *et al.*, 2006), believing that, as originally a forest crop (Wrigley, 1988) coffee can survive naturally and yield well with organic manure alone. Most farmers, however, refer to organic matter as farmyard manure (FYM) alone, which in most cases is applied raw to the field. Such manure is usually subjected to nutrient losses through leaching and volatilization, which results into reduced efficacy as a nutrient source.

The coffee agro-ecosystems contain a lot of materials which can be very useful in plant nutrition if properly harnessed. One important material is pulp, which has been extensively studied. In India for instance, Korikanthimath and Hosmani (1998) rated coffee pulp higher than FYM in terms of nutrient content, having 2.38, 0.53 and 4.21% of N, P and K, respectively compared to respective figures in FYM of 0.3-0.4, 0.1-0.2 and 0.1-0.3%. Chemura *et al.* (2008) noted that composted pulp alone or in combination with husks, flocculent and pruned material gave higher coffee yields and financial returns when applied together with NPK fertilizer (20:10:20). In Tanzania however, coffee pulp, for the farmers who still process their coffee at home, is mostly applied raw to the fields, thus reducing its value as a nutrient source.

Oberthur *et al.* (2012) noted that the N_2-fixing leguminous shade trees are a major source of nutrients on both conventional and organic farms. Litter from shade trees (such as *Albizzia spp*) can contribute 0.5-1.5 tons (dry weight) organic matter annually to one ha of coffee depending on the climate, soil quality and external input of fertilizer (Van der Vossen, 2005). In many Tanzanian coffee producing areas, litter from shade trees and coffee prunings are collected and burnt (Maro and Mbogoni, 2009). Florentin *et al.* (2011) gave a list of green manure cover crops, together with their properties and potential contribution to soil fertility improvement. Information is therefore needed on the importance of the organic materials that farmers take for granted, the best ways to handle them and their potential in improving farm productivity and profitability.

1.5 Objectives of the Study

1.5.1 Overall objective

The overall objective of this study was to develop a model for integrated soil fertility management in order to enhance profitability and sustainability of coffee production in Northern Tanzania.

1.5.2 Specific objectives

The specific objectives were as follows:

i. Establishing the farmers' perception on soil fertility and local experience in soil fertility management in the Northern zone.
ii. Generating spatial soil fertility data for selected coffee-growing districts in Northern Tanzania and map the important soil fertility parameters.
iii. Developing a baseline coffee yield model on the basis of the accrued soil fertility data to be used in mapping the estimated yields.
iv. Exploring the contribution of various organic substrates to coffee ISFM and their relevance to the coffee yield model, and
v. Developing a cost-effective and appropriate ISFM system for coffee through the integration of ISFM to the model and economic analyses of various model scenarios.

1.5.3 Research hypotheses

The research hypotheses for this study were as follows:

i. The soil fertility declining trend in the Northern Coffee Zone of Tanzania could be mitigated by application of appropriate ISFM measures.
ii. Appropriate ISFM measures depend on the availability of sufficient soil fertility database and a crop model for yield prediction based on the soils' database.

1.6 Conceptual Framework Adopted in the Current Study

1.6.1 Understanding the soil fertility problem in the farmers' perspective

During the first coffee stakeholders' meeting (TCB, 2009), farmers' representatives voiced their concerns that soil fertility decline is an important production constraint. This is in agreement with the observations made by Condliffe *et al.* (2008). But effective research into an environmental problem facing farmers should start with the farmers themselves, as D'Emden *et al.* (2005) noted that awareness of a problem is a motivator in devising or adopting problem-solving techniques. This has been addressed in Chapter 2 of this thesis.

1.6.2 Soil fertility surveys and mapping

The first step in soil fertility intervention for coffee is to conduct soil fertility evaluation surveys in coffee growing districts so as to determine the baseline soil fertility situation. With the use of Geographic Information Systems (GIS), spatial interpolation can give proxy soil fertility status outside the actual survey sites. This has been comprehensively addressed in Chapter 3.

1.6.3 Crop modelling

Coffee yield modelling forms the centre-piece of this thesis, featuring in Chapters 4 to 6. For a crop like coffee, which is grown in diverse locations and therefore diverse soil types, harmonization of fertilizer application rates and ISFM packages requires a kind of simplified model; whereby empirical relationships are worked out so as to identify a benchmark yield level, calibrate the crop physiological parameters and leave the soil parameters variable. That way, location-specific fertilizer rates required for a known crop yield level can be derived.

Agricultural models consist of a set of equations that represent the reactions that occur within a plant and the interactions between the plant and its environment. With the complexity of the agricultural systems, universal models do not exist; and models are built for specific purposes and the level of complexity is accordingly adopted. Examples include the work by Rojas (2010), Irmak (2001), Maro (2004) and Tixier *et al.* (2008) for yield modelling, Maro *et al.* (2010a) for land degradation vulnerability, and Lopez (2009) for climate change prediction.

1.6.3.1 Types of crop models

Thornley and Johnson (1990) and Cheeroo-Nayamuth (1999) have given a detailed account of crop models, their usage, potentials and limitations. Models were categorized as either:

i. *Empirical* or *mechanistic* depending on fineness of detail (with the latter going into finer detail). Most crop models start as empirical and evolve into mechanistic as more information is gained.

ii. *Static* or *dynamic* depending on whether a component of time is included. A dynamic model is one in which the change in the behavior of the system can be quantified within short periods of time (such as, on daily basis).

iii. *Deterministic* or *stochastic* depending on the level of probability allowed. Deterministic models make definite predictions and are inadequate where the system is uncertain. Stochastic models give mean values and associated variance.

iv. *Simulating* or *optimizing* depending on the intended use. Simulating models are interested in the behavior of the system, whereas optimizing models are interested in devising the best management option for practical operation of the system.

1.6.3.2 The model quantitative evaluation of the fertility of tropical soils brief description

The Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS), described in detail by Janssen *et al.* (1990) and used by Janssen and de Willigen (2006), Mowo *et al.* (2006) and Tabi *et al.* (2007) among others, is one of the series called the Wageningen Crop Models. The model can be categorized as empirical, static and deterministic. It uses yields of unfertilized maize as a yardstick, and is applicable to well drained, deep soils, that have a pH(H_2O) in the range 4.5-7.0, and values for organic carbon, Olsen's P and exchangeable K below 70 g kg^{-1}, 30 mg kg^{-1} and 30 $mmol_c$ kg^{-1}, respectively (0-20 cm). Soil fertility is interpreted as the capacity of a soil to provide plants with nitrogen, phosphorus and potassium, but the methodology allows for inclusion of other nutrients.

The framework on which the model was built (with the assumptions cited above) appears to be in synchrony with the physiographic requirements of Arabica coffee. Janssen (2005; 2007), in his mission reports to TaCRI, recommended this model as the best fit for coffee yield modelling since it requires minimum adjustment. Part of this study was to establish the required adjustments, apply them and observe the model behaviour over a range of soil types before recommending it for application. This is covered in Chapter 4.

1.6.4 Exploration of the nutritional potential of organic material

Kikafunda *et al.* (2001) and Mureithi *et al.* (2003), in their adaptability studies of several green manure plants, ranked *Mucuna pruriens*, *Lupinus albus*, *Canavalia ensiformis* and *Crotalaria ochroleuca* highly among farmers in Ethiopia, Kenya, Tanzania and Uganda. It is important to determine the nutritional potential of these, compared with farmyard manure (FYM) and coffee ecosystem by-products. This can be done through incubation studies like those used by Conant *et al.* (2008), Khalil *et al.* (2005) and Gunapala *et al.* (1998). This is covered in Chapter 5.

1.6.5 Economic consideration

The bottom-line of all this effort is whether a farmer decides to apply ISFM measures or not. Only those measures that would ensure substantial returns to farmers' effort and sustainably profitable coffee production are likely to be adopted. It is therefore important to not only consider the yields, but also include some economic factors like prices of coffee and those of nutrient inputs. This is covered in Chapter 6.

1.7 Study Areas

The Northern coffee zone consists of Arusha, Kilimanjaro, Manyara and Tanga Regions. As noted earlier, the zone was the first to grow coffee on a commercial scale. However, due to various constraints, including soil fertility decline, it has of recent been overtaken by other newer coffee zones such as Mbinga and Mbozi. A brief description of the two selected representative districts is given below.

1.7.1 Hai district, Kilimanjaro region

The present-day Hai (after recent seclusion of Siha) comprises three divisions – Lyamungo, Machame and Masama. The area starts broadly at the southern foot of Mt. Kilimanjaro (Rundugai) and tends to taper northwards and upwards. It is bordered to the south and west by Arusha Region, to the north and northwest by Siha District, and to the east by Moshi Rural and Rombo Districts. Annual rainfall ranges from 1000 to 2000 mm. Soils are deep, well drained brown to red sandy loam to sandy clay loam. The major soil group in the study area is the Nitisol, though other groups such as Histosols (upper levels) and Cambisols (lower levels) do occur as well.

Farmers in the district own farms in two distinct zones: the highlands, where they live in permanent homesteads, and the lowland zone where they raise annual crops. The highland zone (represented in Fig.1.1) has relatively more rainfall and the cropping pattern is complex, with coffee and bananas as main crops, usually intercropped with annual crops (maize and beans), root/tuber crops and some vegetables. The lowland zone is cropped with maize and beans, either as pure stands or intercropped. While coffee is the main cash crop in the district, production has been declining in recent years due to the high incidence of coffee berry disease. Falling production coupled with declining real producer prices have resulted in a growing tendency towards diversification and even total abandonment of coffee (Maro *et al.*, 2010a).

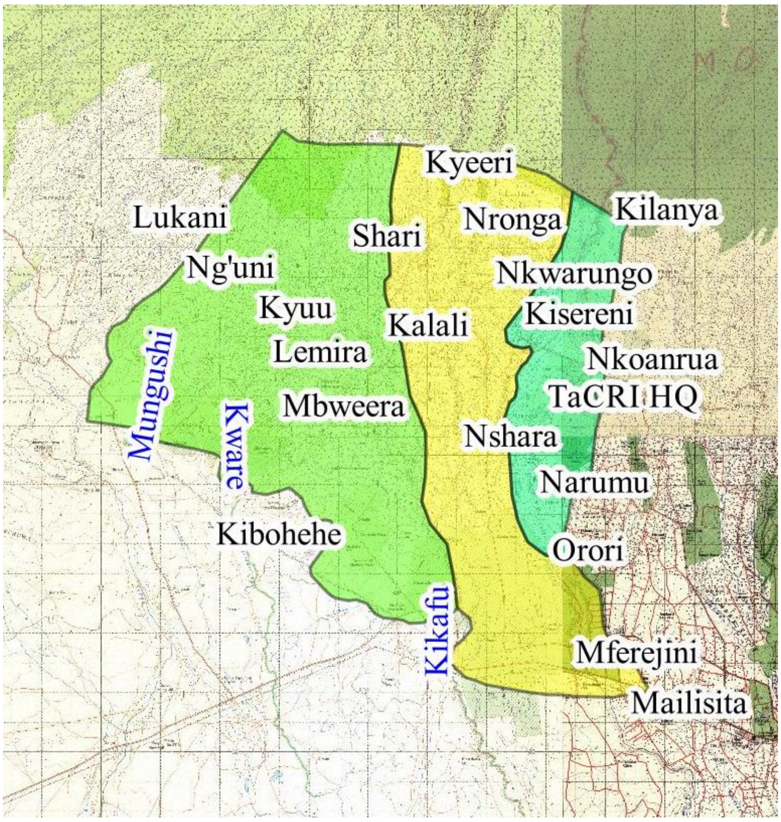

Figure 1.1: The coffee growing areas in Hai District

Livestock production is an integral part of the farming system in the district. Land scarcity has contributed significantly to the high degree of interdependence between the crop and livestock sub-systems. Stall feeding is the rule, and crop by-products are extensively used as feed, while the manure from the livestock is, in turn, used on the banana/coffee plots to add nutrients to the soil.

1.7.2 Lushoto district, Tanga region

Lushoto is one of the eight districts of Tanga Region. It is bordered to the northeast by Kenya, to the east by the Muheza District, to the northwest by the Same District and to the south by the Korogwe District. The study area, which represents the West Usambaras, is shown in Fig.1.2.

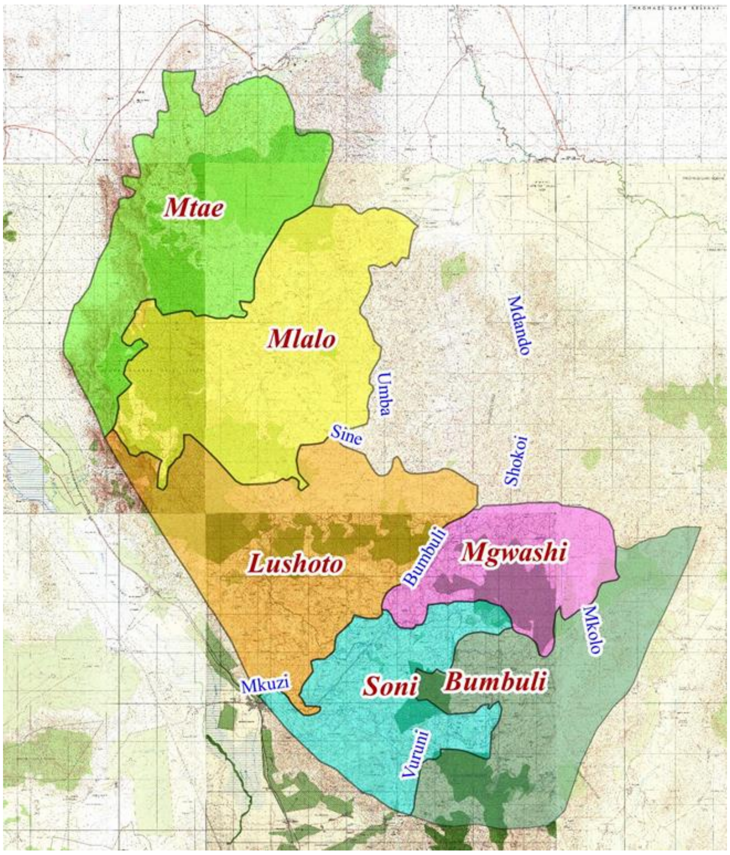

Figure 1.2: The coffee growing divisions of Lushoto District

Annual rainfall ranges from 800 to 1700 mm and the soils are deep, well drained, brown, red and yellow sandy clay loam to clay. The major soil group is Acrisol (medium to high altitude) and Fluvisol (valley bottoms). The farming system is a mixed crop-livestock system, with high value trees and crops being the primary sources of income. Hillside cultivation is the most traditional form of land use, where staple crops like maize, beans and banana; and perennial cash crops like tea and coffee are grown. Valley bottoms are of economic importance and are utilized for market oriented vegetable production systems.

Due to its mountainous location, Lushoto District has enjoyed a substantial amount of research. It suffers from continuous land degradation threats (including soil erosion), and the Soil Erosion Control and Agroforestry Project (SECAP) launched demonstration trials on agroforestry as a strategy which would eventually control land degradation (Johansson, 2001). Another example of avenues for research/extension directed to the district is the African Highlands Initiative under the auspices of ICRAF World Agroforestry Centre (Masuki *et al.*, 2010). Most of these researches were inclined to soil conservation (erosion control structures, tree planting) without much emphasis on soil fertility.

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CHAPTER TWO

2.0 FARMERS' PERCEPTION OF SOIL FERTILITY PROBLEMS AND THEIR ATTITUDES TOWARDS INTEGRATED SOIL FERTILITY MANAGEMENT FOR COFFEE IN NORTHERN TANZANIA

2.1 Abstract

In response to the concern on soil fertility decline, pointed out during the 2009 Coffee Stakeholders' Conference, a study was conducted in Hai and Lushoto Districts, Northern Tanzania to establish a wider farmers' perception of the problem and their attitudes towards integrated soil fertility management (ISFM) for coffee. A structured questionnaire on aspects of coffee production was administered to a total of 126 respondents, and the information processed using Statistical Package for Social Sciences (SPSS) Version 16. Household size and adoption of improved coffee varieties affected farmers' awareness significantly ($p<0.05$). As for farmers' attitudes, six of the eight predictors were significant ($p<0.05$). Age, household size, adoption of new varieties and total farm income were highly significant ($p<0.01$). Age, total land under coffee and total off-farm income negatively affected farmers' attitudes. As farmers get older, they tend to refrain from taking up new innovations. Larger farms are likely to exert more pressure on the available organic resources. With multiple farms, distant farms are likely to receive less attention. When off-farm income was considered, multiple ventures compete for the farmers' time, resources and attention. For the two districts, ISFM interventions will make a better impact to younger and more energetic farmers and the coffee industry should strive to take young people on board. This study has proved the farmers' concern of 2009, and has also provided important socio-economic information for use in devising a comprehensive ISFM strategy for coffee.

Key words**:** *Soil fertility; farmers' perception; ISFM; coffee; Tanzania*

2.2 Introduction

Coffee is one of the major export crops in Tanzania, contributing 24% to the agricultural GDP (TCB, 2009). It contributes directly to the livelihoods of over 420 000 farm families and indirectly to over 2 million people employed in the coffee value-chain industry (Carr *et al.*, 2003). Arabica coffee contributes 65% of the Tanzanian total coffee export. The Tanzanian coffee, especially the washed Arabica, is one of the best in the world, ranked among the rare category of “Colombian Milds” used to blend other inferior coffees.

Coffee is also grown in many countries in East and Central Africa. Other important coffee producers are Ethiopia, Uganda, Kenya, Rwanda and Burundi. According to statistics from the International Coffee Organization (ICO, 2011), total production for the six countries was 10.6, 11.4 and 12.9 million bags (equivalent to 530 000, 570 000 and 645 000 tons) for 2008, 2009 and 2010, respectively. Tanzania’s share was 11.14%, 6.2% and 7.08%, while Kenya’s share was 5.08%, 5.51% and 6.56%. Ethiopia and Uganda together commanded over 70% of the share for all the three years.

The Tanzanian average smallholder coffee productivity per hectare ranges between 250 and 300 kg of parchment which is very low compared to the potential yield of over 1000 kg (Baffes, 2003; Hella *et al.*, 2005). In Kenya, coffee yields were reported to have fallen from 892 kg ha^{-1} in 1980 to 284 kg ha^{-1} in 2006, much lower than average yields for Arabica coffee worldwide of 698 kg ha^{-1} and yields of 1160 kg ha^{-1} in Rwanda and 995 kg ha^{-1} in Ethiopia.

Soil fertility decline is one of the major problems facing coffee productivity in Tanzania. It is defined by Stocking and Murnaghan (2000) as the loss of soil physical and nutritional qualities. It has been an issue of concern throughout the Sub-Saharan Africa (SSA), and cuts across many different soils and crops (Okalebo *et al.*, 2007). In Tanzania, the problem covers all coffee growing zones and all types of coffee growers (Envirocare, 2004). Reports from Kenya indicate that decline in coffee yields were caused by farmers' reluctance to invest in fertilizers (Condliffe *et al.*, 2008), which translated to low soil fertility.

Integrated soil fertility management (ISFM) has been cited by many authors, including Okalebo *et al.* (2007); Gumbo (2006) and Raab (2002), as the key approach in raising productivity levels in agricultural systems while maintaining the natural resource base. It is described by Vanlauwe and Zingore (2011) as a set of soil fertility management principles, strategies and practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. Because of the pressing need for global food security, many articles have been published which relate ISFM to the production of annual food crops like maize (Ikerra *et al.*, 2007; Kimani *et al.*, 2007), and rice (Kaizzi *et al.*, 2007), giving lesser attention to perennial crops like coffee. It is no wonder then that the role of ISFM for coffee in Tanzania and the socio-economic perception of it have not been studied to any significant detail.

The coffee producing zone of Northern Tanzania comprises four regions, namely Arusha, Kilimanjaro, Manyara and Tanga with a total of 12 districts. Coffee production is both historical and traditional, especially in Kilimanjaro region which was the first to grow coffee as a commercial crop (Maro *et al.*, 2010). Annual coffee production trends for the zone indicate a decline over the years. A number of constraints have been pointed out as the cause of this decline. Currently, as reflected during the coffee stakeholders' forum (TCB, 2009), soil fertility degradation has emerged as the most limiting factor. This is, however, a very generic perception which needs to be studied in detail, by targeting specific locations and farming communities.

The current study was therefore conducted in Hai and Lushoto districts to establish the magnitude of soil fertility problem as perceived by farmers in the two districts, and to establish the baseline farmers' attitudes towards ISFM, thereby identifying the appropriate intervention strategies.

2.3 Materials and Methods

2.3.1 Data collection

A structured questionnaire (Appendix 2.1) was administered to farmers in Hai and Lushoto districts to solicit the farmers' opinion on soil fertility and coffee productivity. The two districts were selected as representative of coffee growing areas of Northern Tanzania, and also representative of soils with contrasting geological backgrounds; originating from volcanic and gneissic parent material respectively. The coffee areas in the districts were categorized on the basis of altitude; namely low (900-1100), medium (1100-1400) and high (>1400) metres above mean sea level and respondents were randomly selected on the basis of having at least 50 coffee trees. A total of 60 respondents were interviewed in Lushoto and 66 in Hai, making a total of 126 respondents. Generic questions included personal details (gender, age, level of education, position in the household, household size and sources of coffee management information) and farm details (size, number of trees and varieties). Additionally, respondents were requested to give an account of their knowledge of soil problems, source of ISFM knowledge if any, experience in industrial fertilizer use with coffee and negative effects if any, usage of organics (manure, coffee processing by-products, mulches, green manure plants), major and subsidiary income sources and income ranges in the 2009-10 season. The data were processed and analyzed by using the Statistical Package for Social Sciences (SPSS version 16). The analysis involved computations of means and frequencies, together with two linear regressions: one on farmers' appreciation of soil fertility problem and the other on farmers' attitude towards ISFM.

2.3.2 Defining the variables

The degree of appreciation of soil fertility deterioration as a problem (aP) was described as a mean of two ratings, one qualifying the farmers' knowledge of their soils (0, 1 and 2 for no, slight and basic knowledge, respectively) and the other qualifying farmers' understanding of soil related problems (0 = no idea, 1 = could identify other problems, 2 = could identify crop-related problems and 3 = was able to identify nutritional disorders). The ratings were categorized as 0, 0.5, 1.0, 1.5 and 2.0 for unaware, slightly aware, moderately aware, sufficiently aware and fully aware, respectively. The assumption was that, as noted by D'Emden *et al.* (2005), awareness of a problem is a motivator in devising (or adopting) problem-solving techniques.

Attitude towards ISFM (α) was described as a mean of eight ratings including the two stated above (R_{soil} and R_{prob}) and six others. The ratings R_{ind}, R_{f} and R_{b} are dummy variables qualifying whether a farmer uses (1) or does not use (0) industrial fertilizers, farmyard manures or coffee by-products, respectively. R_{fp} and R_{bp} at the scale of 0, 1, 2 and 3, are the ratings qualifying farmers who have nothing to process because they do not use farmyard manure or pulp, those who use the organics raw without any processing, those who just heap the material to stabilize in the open, and those who compost the material in a pit. R_{train} is a rating that qualifies whether and how many times in 2010 a farmer received training on ISFM (an aggregate of four topics – soils, ISFM, identification of nutritional problems and making of organic composts): 0 = no training, 1 = trained once, 2 = trained twice and 3 = trained more than twice. The resultant ratings varied between 0 and 2, and were clustered at maximum values in terms of likelihood of adopting ISFM interventions as shown in Table 2.1 below:

Table 2.1: Description of clustered ratings

Cluster	Maximum value	Description
0	0.0	Very low likelihood of adoption
0.1-0.5	0.5	Low likelihood of adoption
0.6-1.0	1.0	Moderate likelihood of adoption
1.1-1.5	1.5	High likelihood of adoption
1.5-2.0	2.0	Very high likelihood of adoption

2.3.3 Descriptive statistics

The two variables aP and α were subjected to descriptive statistics following the models of Nkamleu (2007) and Zhou *et al.* (2008), which involved physical counts and percentage frequency, and these were compared per district.

2.3.4 Regression modelling

The defined variables aP and α were separately subjected to a linear regression model as functions of demographic predictors (age and level of education of the household head, the size of the household, farm and non-farm income) as defined by Doss (2003) and farm related predictors (such as land size and types of coffee trees). Both models used the same predictors as shown in the example below which represents aP.

$$aP = b_0 + b_1A + b_2ED + b_3HS + b_4FEX + b_5LS + b_6CV + b_7FI + b_8NFI + \ell$$

Where:

b_0 represent the constant,

b_1A = coefficient related to age,

b_2ED = coefficient related to level of education,

b_3HS = coefficient related to household size,

b_4FEX = coefficient related to coffee farming experience in years,

b_5LS = coefficient related to total coffee land size,

b_6CV = coefficient related to coffee varieties (whether improved varieties are adopted),

b_7FI = coefficient related to farm income 2009/10,

b_8NFI = coefficient related to non-farm income 2009/10, and

l= random error of prediction.

Each of the eight predictors were then assessed in terms of the significance level at which it influences the farmers' awareness of soil fertility decline as a problem on one hand, and the farmers' readiness to adopt ISFM interventions on the other.

2.4 Results and Discussion

2.4.1 The significance of predictors per district

The eight selected predictors were compared per district (t-test) and were all highly significant ($p < 0.01$). Means and their 95% confidence intervals are shown in Table 2.2. Average age of respondents was around 60 years, implying that coffee is still held by old people. This observation was in line with Morris and Venkatesh (2000); Mateos-Planas (2003) and Tiamiyu *et al.* (2009). Two schools of thought exist here; that of old people clinging to their coffee farms as their only source of income (and power), and that of disinterested youths who opt out for quick money in urban centres (even as street vendors!). Education level was mainly primary, with fewer cases of post-primary education. The majority of households have 2-8 persons, which is average for many Tanzanian households (ILFS, 2001; Kamuzora, 2001).

Table 2.2: A comparison of the selected predictors per district

Predictor	Unit	Means	95% C.I		Notes
			Lower	Upper	
A	Years	60.83	58.37	63.29	Coffee is a crop for old people
ED	Rating	1.23	1.09	1.37	Majority primary, fewer ordinary
HS	Rating	2.37	2.21	2.54	2 to 8 persons per household
FEX	Years	30.08	27.3	32.86	People with immense coffee exp.
LS	Ha	0.8	0.68	0.92	Typical smallholders
CV	0=no, 1=yes	0.33	0.24	0.41	Adoption of 24-41%
FI	Rating	9.13	8.39	9.86	600 000 to 900 000 TZS
NFI	rating	1.83	1.05	2.6	Maximum of 200 000 TZS

With the mean coffee farming experience of 30 years, it implies that most of the coffee farmers in the study districts have immense experience in their business, and their perception of soil problems and best ways to manage soil fertility should be considered in devising appropriate ISFM packages (Douthwaite *et al.*, 2002). Land size of mean 0.8 ha (CI 0.68-0.92) implies that the sampled households are truly smallholders who are resource-poor, and therefore, the ISFM packages should have that in mind. An average of 33% of the respondents have adopted the new improved varieties released by TaCRI, a situation attributed to age (with its implied reluctance to change) and/or fear of income security during the transition time. There is therefore an uphill task for TaCRI and other coffee stakeholders to promote these varieties and the process of gradual farm transition. The distribution of farm and off-farm incomes in 2009/10 is given in Table 2.3. Farm income appears to be fairly normally distributed with the majority ranging between

0.3m and 2m Tanzania Shillings (equivalent to USD 190-1250 at the current exchange rate of TZS 1600 per USD).

Table 2.3: A summary of farm and off-farm incomes in 2009/10

Income range (TZS)	From coffee farm (%)	From off-farm ventures (%)
None	0.0	74.6
<0.3m	14.4	11.0
0.3 – 2.0m	76.0	9.6
>2.0m	9.6	4.8

With off-farm income, 74.6% of the respondents reported to have none, thus depending entirely on the farm for their livelihood. Those who have subsidiary off-farm incomes (25.4%) may portray variable pictures as regards farm attention. For some it may be a deterrent factor, keeping the farmer busy with the off-farm ventures at the expense of the farm. For elite farmers however, a subsidiary off-farm income can act as a buffer against fluctuating coffee prices, and/or a stimulant in adopting good agricultural practices (Karki and Bauer, 2004).

2.4.2 The distribution of variables per district

The frequency of farmers’ awareness of soil fertility decline as a problem is shown in Fig. 2.1. The majority of respondents from Lushoto are either unaware (25%) or slightly aware (60%). On the other hand, 9% had sufficient awareness and 0% fully aware. In Hai, the unaware and slightly aware groups were 13.6% and 45.4%, respectively while 3.0% are fully aware, 10.6% moderately aware and 27.3% sufficiently aware. The results appear to correlate well with the respondents’ levels of education, whereby 6.67% in Lushoto and 25.53% in Hai had post-primary education. As for likelihood to adopt ISFM (Fig.2.2), the distribution of respondents in Hai was fairly normal, with a peak at 50% for moderately likely group, tailing at very low (1.5%) and very high (7.6%). The Lushoto distribution was rather irregular, with only one interesting feature, that the percentages that have moderate and high likelihood are equal at 40% each, therefore constituting the bulk of the sample. The reason for this observation could be that, by coincidence, many of the respondents had been involved in previous soil management projects such as SECAP (Johansson, 2001). The percentage of respondents with moderate to very high positive attitude was 84% for Hai and 92% for Lushoto, implying that ISFM intervention will be adopted more easily in the latter.

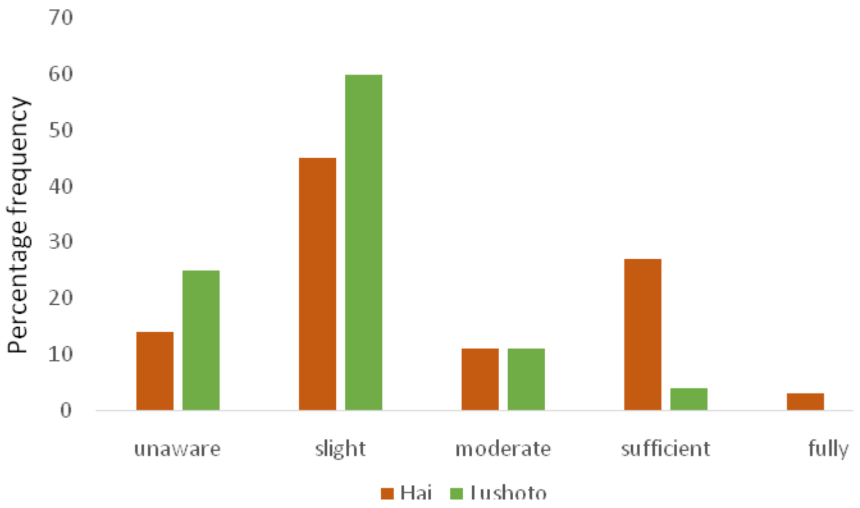

Figure 2.1: Distribution of awareness of soil fertility decline as a problem

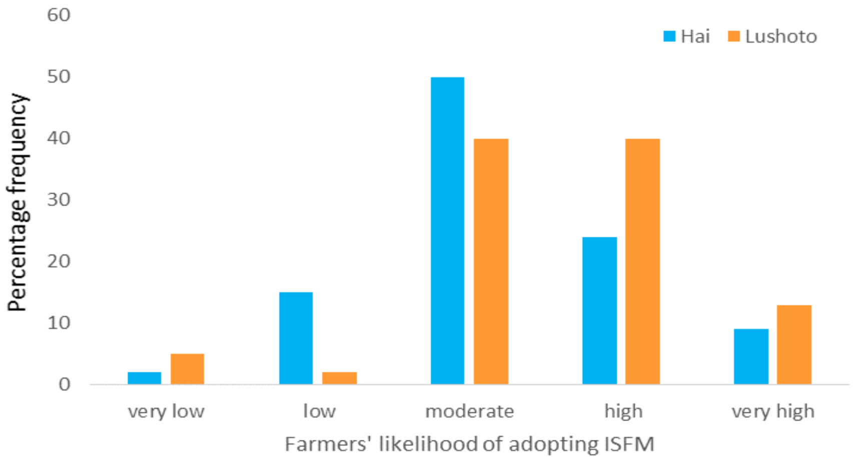

Figure 2.2: Distribution of attitudes of farmers towards soil fertility management

2.4.3 Analysis of regression models

A summary of the regression models for problem appreciation and attitude towards ISFM is given in Table 2.4.

Table 2.4: Model summaries for problem appreciation and attitude towards ISFM

Predictors	Problem appreciation			Attitude towards ISFM		
	β	t	Sign	β	t	Sign
Age	-0.163	-1.597	0.113	-0.350	-3.103	0.002
Level of education	0.041	0.447	0.656	0.113	1.319	0.190
Household size	0.251	2.761	0.007	0.235	2.785	0.006
Years growing coffee	0.079	0.763	0.447	0.288	2.530	0.013
Coffee land size	0.165	1.743	0.084	-0.185	-2.083	0.039
New varieties adoption	0.228	2.553	0.012	0.422	5.022	0.000
Farm income 2009/10	0.087	0.956	0.341	0.227	2.659	0.009
Off-farm income 2009/10	-0.110	-1.159	0.249	-0.145	-1.654	0.101
(Constant)		1.747	0.083		3.953	0.000

β = Standardized coefficient; t = statistic for predictor effect; sign = significance level

2.4.3.1 Problem appreciation

The regression model for problem appreciation (aP) was highly significant (at $p<0.01$) even though there was a rather poor correlation (Adjusted R^2 of 0.133) among the parameters entered. Only household size and adoption of improved coffee varieties were significant ($p<0.01$). Age was seen to negatively affect the farmers' awareness of soil fertility problem as older people tend to become more passive about what happens in their farms (Truong and Yamada, 2002). The rest did not show any statistical significance; including level of education. The relationship between household size and problem appreciation is not very clear. However, if family members are trained in diagnosing unusual characteristics in the field, the bigger the hosehold size, the more likely it is for problems to be identified.

During the survey in Lushoto, the 75% of respondents who had slight to sufficient awareness about soil fertility degradation, also had considerable information about soil fertility management. Similar observations had been noted at Makueni District, Eastern Kenya by Kimiti *et al.* (2007). Their indigenous technical knowledge (ITK) showed that “mishai” trees (*Albizzia maranguensis)* contribute in restoration/maintenance of soil fertility. Other ITKs noted during the survey include the “tugutu” bush (*Adhatoda engleriana* Lindau, family Acanthaceae) which is also medicinal (Moshi *et al.*, 2005). It has been tested with other crops and found to have high nutrient release potential. A formulation for making liquid fertilizer from their leaf extract was described. This opens an avenue for further research on the nutrient content of the “tugutu” leaves and ways in which this, where present, can be integrated in the local ISFM packages for coffee.

2.4.3.2 Attitude towards ISFM

The regression model was also highly significant (at $p<0.01$). Of the 8 parameters used in predicting α (attitude towards ISFM), 4 were highly significant (Age, household size, adoption of new varieties and total farm income) and 2 were significant at $p<0.05$ (land size and coffee farming experience). These observations are partly in agreement with those of Jamala *et al.* (2011). Level of education showed positive but insignificant influence on farmers’ attitudes. The significance of education level in the adoption of ISFM was reported by Tiamiyu *et al.* (2009); Barungi and Maonga (2011); Ono (2006) and Ani *et al.* (2004), which does not appear to be true in the current study areas. This could be explained by the fact that most of the elite farmers in the areas (who had post-primary education) are retirees from public service, their behaviour is influenced partly by their positions during active age and are somehow difficult to convince.

Age, total land under coffee and total off-farm income had negative B, β and t values. Age showed to negatively influence the capacity and willingness to adopt new approaches including ISFM. This is in line with the observations by Nzomoi *et al.* (2007). Total coffee land showed negative relationship with likelihood of adopting ISFM contrary to the observation by Karki and Bauer (2004). Explanations could be that larger farms exert more pressure on the limited amounts of available organic sources of nutrients like FYM; and/or farmers have multiple farms, others a distance away from their households and rarely getting the bulky organic sources (Nkamleu, 2007; Vanlauwe and Giller, 2006). Off-farm income showed negative influence on farmers' attitudes, observations that are in agreement with those of Adolwa *et al.* (2010). If this source of income contributes substantially to the total family income, the farmers' attention gets skewed from coffee towards the other ventures.

2.5 Conclusions and Recommendations

The perception of soil fertility degradation as a problem in the study areas is influenced by several household and farm parameters. Among the eight predictors, only the size of the household and adoption of new improved varieties showed to be responsible for variations in perception. More than 75% of the respondents in both districts are aware of soil fertility problem. It has therefore been concluded that the sampled farmers share the concerns of their representatives in stakeholder forums that soil fertility decline is one of the key limiting factors to coffee productivity.

Attitudes towards ISFM showed to be highly influenced by age, household size, adoption of new varieties and total farm income; and moderately influenced by total land under coffee and number of years spent by the household head in coffee business. Age showed a negative relationship to adoption of ISFM, implying that older people are usually skeptical in adopting new approaches. The percentage of respondents with moderate to very high likelihood of adoption generally exceeded 82%, being higher in Lushoto than Hai district.

In the two districts, ISFM interventions will make a better impact to younger and more energetic farmers with enough land for coffee production and who depend largely on coffee for their livelihood. These are the ones who can easily adopt improved varieties and good agricultural practices, including ISFM practices like mulching, composting of farmyard manure, use of coffee pulp and other field residues as sources of plant nutrients.

This study puts forward the following recommendations to the coffee industry, and specifically to TaCRI:

(i) To encourage younger people to take up the coffee farming business,

(ii) To build the capacity to monitor the soil fertility regularly and give quick, site-specific recommendations.

(iii) To continue promotion of the improved coffee varieties among farmers, and

(iv) To continue promoting appropriate ISFM practices in coffee.

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CHAPTER THREE

3.0 SOIL FERTILITY EVALUATION FOR COFFEE (*Coffea arabica*) IN HAI AND LUSHOTO DISTRICTS, NORTHERN TANZANIA

3.1 Abstract

The aim of this study was to evaluate the soil fertility status of selected coffee growing districts of Northern Tanzania and recommend immediate and long term soil management intervention strategies. The study was conducted in Hai and Lushoto Districts, between May and September, 2011. A total of 116 soil augerings and 10 soil profiles were described, and soil samples analyzed for the key soil fertility parameters. These were evaluated qualitatively by assigning scores against the requirements of Arabica coffee, and quantitatively by calculating the total soil-available N, P and K. Spatial assessment of the total soil-available nutrients was done using ArcView GIS 3.2 and ArcGIS 9.3. Soil fertility was found to be considerably low in the study areas, much lower in Lushoto than in Hai. Common limitations are low P and micronutrients, while the additional limitations for Lushoto are low CEC and exchangeable K. Spatial interpretation revealed interesting trends, which could be explained from the topography of the areas and/or the farming practices common in the areas. The results are discussed in this paper, and recommendations on appropriate ISFM strategies are put forward.

Keywords: *Soil fertility evaluation, Arabica coffee, ISFM, Northern Tanzania*

3.2 Introduction

The importance of coffee in the Tanzanian economy is well documented by TCB (2012); Carr *et al.* (2003); Hella *et al.* (2005); Smith and Ndunguru (2007) among others. Coffee is a perennial crop whose average nutrient removal from 1 ha soil per growing cycle is 135 kg of N, 35 kg of P_2O_5 and 145 kg of K_2O (Sys *et al.*, 1993). Considerable amounts of nutrients are also lost through leaching under a heavy rainfall and as a result of fixation and immobilization of nutrients in the soil. Such depletion may lead to the impoverishment of the soil. It is thus essential to plan for replacement of the lost nutrients (Semoka *et al.,* 2005; Maro *et al.*, 2006).

Soil fertility is defined as the capacity of soil to supply plants with enough available nutrients and moisture to produce crops. It is expressed in terms of the presence of the right quantities and forms of essential nutrients in the soil (Brady and Weil, 2002). Other indirect factors of soil fertility are moisture availability and stability, soil aeration, texture, structure and pH. Soil fertility is influenced by factors of soil formation such as climate, parent material, natural and cultivated plants, and topography. Other factors are related to the way the soil is used (the type of crop grown –monocrops/intercrops, annual/perennial) and managed (fertilization, nutrient cycling, etc).

Chemical soil fertility involves such parameters as pH, CEC, OC, N, P, K, Ca, Mg, S and micronutrients, whose methods of analysis are detailed in various manuals including NSS (1990), Van Ranst *et al.* (1999). Soil fertility is indirectly inferred from the analytical data, either qualitatively by rating the data as compared to specific requirements of a crop (Sys *et al.*, 1993) or quantitatively by using soil fertility models (Van Ranst *et al.*, 2002; Maro, 2004). Information thus accrued can be used in appropriate ISFM planning and implementation.

Soils of Northern zone were described by De Pauw (1984) as originating from volcanic rocks, ash and lava (Kilimanjaro and Meru) and metamorphic rocks (the Pare-Usambara Fold Mountains). Addressing the problem of soil fertility decline in such diverse soils requires a baseline soil fertility evaluation, to determine location-based soil fertility status and appropriate ISFM intervention for sustainable coffee production. The first study (Chapter 2) described farmers' perception of soil fertility decline as a problem and their attitude towards ISFM. The current study was therefore meant to complement the information gained during the earlier study, by assessing the soil fertility status, performing spatial soil fertility evaluation for coffee and recommending appropriate soil management options.

3.3 Materials and Methods

3.3.1 Study area

This study was conducted in Hai District, Kilimanjaro Region and in Lushoto District, Tanga Region. These represent the historical and traditional coffee growing areas of Northern Tanzania (Maro *et al.*, 2010), but they fall into two different agro-ecological zones (MARI, 2006), namely volcanic and rift areas (N series) and high plateaus and plains of gneissic origin (H series), respectively.

3.3.1.1 Hai district

The study area was confined to the coffee growing areas in Masama, Machame and Lyamungo divisions, exclusively north of the Moshi-Arusha Highway, extending to the Kilimanjaro Mountain Forest border. It ranges in altitude from 988 to 1873 m. above mean sea level. The landform is mainly plateau, gently sloping to undulating, and the soil is moderately to well drained with slight to moderate risk of sheet and rill erosion (FAO, 1990). Few people (one in every four) use industrial fertilizers, common brands being CAN, NPK (20:10:10), Urea (46%N), MRP and DAP in a decreasing order of importance. By contrast, almost every farmer uses farmyard manure, and at the recommended rate of one tin (approximately 10 kg) per tree.

3.3.1.2 Lushoto district

The study area in Lushoto was also confined to the coffee growing areas, along the West Usambara Mountains, and included Lushoto, Soni, Bumbuli, Mgwashi, Mtae and Mlalo divisions. It varies in altitude from 1157 to 1961 m above mean sea level. Landform is plateau to mountainous, gently sloping through undulating, rolling to very steep, and the soil is moderately to well drained with moderate to high risk of sheet and rill erosion. Very few people (one in every six) use industrial fertilizers, common brands being Urea (46%N), NPK (20:10:10), DAP, SA and MRP in a decreasing order of importance. Even here, almost every farmer uses farmyard manure, and at the recommended rate of one tin per tree.

3.3.2 Field sampling and soil characterization

A total of 58 auger sites were drilled and 5 pit profiles opened per district to represent the coffee growing areas in Hai and Lushoto. Sampling was done in altitudinal clusters as in the earlier study (Chapter 2) while sampling within clusters was random due mainly to terrain structure. All profiles and augerings were geo-referenced by using a GPS (with coordinates converted to UTM), and later geocoded into the GIS database for the areas. In situ soil characterization was done and soil properties such as depth, drainage, colour, texture, structure, consistence, porosity and root distribution were recorded (Appendix 3.1). One profile per district was accorded a Class 1 description for purposes of soil classification, while the description for the other four profiles was of Class 2 for verifying the established SOTER database for the districts as noted in MARI (2006). Augerings were accorded a Class 4 description and used for soil fertility evaluation.

Bulk soil samples were collected with hand-auger from depths of 0-30cm, 30-60cm and 60-90cm, and from natural pedogenetic horizons in the representative soil profiles. Undisturbed core samples were also taken for determination of bulk density and soil moisture characteristics.

3.3.3 Soil analysis

The bulk soil samples were air-dried, ground, sieved through a 2 mm sieve and analyzed for pH-water and pH-KCl (1:2.5) (Van Ranst *et al.*, 1999), organic carbon by Walkley-Black wet digestion method (Nelson and Sommers, 1982), total Nitrogen by semi micro-Kjeldahl method (Bremner and Mulvaney, 1982), available Phosphorus by Bray 1 extraction followed by quantification with UV-Vis spectrophotometer (NSS, 1990). The CEC was determined by using the ammonium acetate ($C_2H_7NO_2$) extraction method at pH 7 (Thomas, 1982). Exchangeable cations were determined from the ($C_2H_7NO_2$) extracts by using flame atomic absorption spectroscopy. Texture was analyzed by using the Bouyoucos Hydrometer method (NSS, 1990). The micronutrients iron (Fe), copper (Cu), manganese (Mn) and zinc (Zn) were determined by the method of digestion with nitric-perchloric acid followed by quantification by atomic absorption (Ryan *et al*., 2001). Sulphur was determined by extraction with ($C_2H_7NO_2$) and $BaCl_2$; while Boron was extracted with Azomethine H in hot water. Both extracts were quantified with a UV-Vis spectrophotometer at 420 nm (NSS, 1990; Van Ranst *et al.*, 1999; Ryan *et al.*, 2001). Other routine data for pedological characterization of the representative pedons of the study sites were analyzed following Moberg's manual (Moberg, 2001).

3.3.4 Soil classification

Using field and laboratory data (summarized in Appendix 3.1), the representative pedons of the study sites were classified to the Tier-2 of the World Reference Base for Soil Resources scheme of soil classification (IUSS, 2006).

3.3.5 Soil fertility evaluation

Soil fertility was evaluated qualitatively and quantitatively. In the qualitative approach, fertility scores were assigned according to the soil fertility requirement of coffee (Sys *et al.*, 1993) as shown in Appendix 3.2. Separate parameters were scored and total scores re-rated. Final scores ranged from 0 (very poor) to 4 (very fertile) with descriptions shown in Appendix 3.3. All the analyzed parameters were involved in the scoring.

In the quantitative approach, only a few selected parameters were involved: pH and OC as fertility drivers, and N, P and K as primary macronutrients, as in Tsirulev (2010). These were picked because they are required by plants in amounts large enough to be quantifiable. Soil pH was used to establish the correction factors for available N, P and K (fN, fP and fK). Then relationships were empirically worked out between the correction factors, OC and the amount of total N, available P and exchangeable K to get the total available forms of each in kg ha^{-1} (Janssen *et al.*, 1990). The nutrient equivalent factors of 1, 0.175 and 0.875 were worked out for coffee following Janssen (2011) and used to make the amount of nutrients uniform, and therefore additive. Soil fertility was measured in terms of the total number of nutrient equivalents that one ha of soil can make available to plants.

3.3.6 Mapping of soil fertility status

ArcView GIS Version 3.2 was used to build shapefile database from the original Excel spreadsheets. Base map layers such as boundaries, rivers and road networks were digitized from mosaics of 4 map sheets for Kilimanjaro and 9 for Lushoto, and edited by using the field GPS data. Attribute data generated during the fieldwork and laboratory analysis were geocoded into GIS-compatible format and loaded into the attribute tables. The shapefiles were then exported to ArcGIS 9.3 for spatial interpolation of important fertility attributes. The inverse distance weighting (IDW) interpolator was used, with the option “nearest neighbours” set to 12, the power set to 2.0. The interpolated attribute was the calculated total soil-available nutrients (TSA) in kE ha^{-1}.

3.4 Results and Discussion

3.4.1 Pertinent pedological and related soil properties of study areas

A summary of the detailed description of soil profiles representative of the two districts is given in Table 3.1. The other profiles in Hai District were located at Nkwarungo Foo, Machame Division (1514 m ASL), categorized as high-altitude coffee belt. Soils are shallow, well drained reddish brown to dark olive sandy loams, with thin dark reddish brown sandy loam topsoils. This upper belt is transitional into either a Fibric Histosol or a Humi-Umbric Nitisol (MARI, 2006).

Two other profiles were located at Tema Mboreni, Masama Division (1371 m ASL) and APK Farm, Lyamungo Division (1254 m ASL), both categorized as medium altitude belt. Soils are fairly deep, well drained with colours ranging from dark reddish brown to brown sandy clay loam topsoils, and dark reddish brown sandy to silty clay loam subsoils. These are mainly Eutric and Haplic Nitisols. The last one was at Narumu Orori, Lyamungo Division (1049 m ASL), representing the low-altitude coffee belt. Soils are very deep, fairly well drained reddish brown to dark reddish brown sandy loams, with thick dark brown sandy loam topsoils. They are transitional to Eutric Cambisols further south (MARI, 2006).

Table 3.1: Some pertinent attributes of the representative soil profiles of the study areas

Site	**Hai**	**Lushoto**
Profile location	TaCRI Field 46 (37°14’546" E/ 03°13'587" S; 1336 m ASL.)	Yoghoi Prisons Farm (38°16.246 E/ 04°48.166 S; 1408 m ASL.).
Parent material	Colluvial / alluvial derived from volcanic debris.	Colluvial and alluvial derived from metamorphic – gneissic rocks.
Soil properties	Ustic, isohyperthermic, very deep, well drained RB to DRB, SC to SCL, with thin brown clay loam topsoils.	Ustic, hyperthermic, very deep, well drained R to DRB clay to SCL, with thick red to dark red loam topsoils.
Diagnostic properties	AB/SAB subsoil breaking to fine shiny peds. gradual/diffuse and smooth boundary.	Medium and coarse AB and SAB, with clay and sesquioxide cutans in the subsoil.
Analytical indicators	Low CEC (≤ 22 cmol(+) kg^{-1}) and BS of average 32.88% topsoil and 24.09% subsoil	Low CEC (≤ 22 cmol(+) kg^{-1}) and BS of average 23.7% topsoil and 15.65% subsoil
Soil name	Haplic Nitisol (Humic, Dystric).	Cutanic Acrisol (Humic, Hyperdystric, Profondic)

Colours: R=red, RB=reddish brown, DRB=dark reddish brown. Texture: SCL=sandy clay loam; SC=sandy clay. Structure: AB=angular blocky, SAB=subangular blocky.

The other profiles in Lushoto District were located at Nkongoi village, Mgwashi Division (1385 m ASL) and Ngazi village, Mlalo Division (1396 m ASL) comparable to the medium coffee belt of Hai. The other two were located at Mbelei village, Soni Division (1517 m ASL), and Sunga village, Mtae Division (1834 m ASL) representing the high-altitude coffee belt. Soils are generally very deep and well drained. Soil colour varies from dark brown through red to orange. Textures are clay to silty clay loams, with loam to clay loam topsoils. These, coupled with the evidence of illuviation of low-activity clays, confirm the SOTER database (MARI, 2006) which classifies the study area as having Humi-Umbric and Cutanic Acrisols (IUSS, 2006).

3.4.2 Important soil fertility parameters

The comparative assessment of soil data followed Nunez *et al.* (2011), and a summary is given in Appendix 3.4. Soil texture varied with locations. Of the Hai soils, 38.37% were predominantly sandy clay loams, 37.21% were sandy loams. Clays and clay loams were 8.72% each while 5.23% were silty loams, and 1.75% were sandy clays. Lushoto soil texture is dominated by sandy loams (36.9%) followed by sandy clay loams (22.62%), silty loams (11.9%), sandy clays and silty clay loams (8.93% each), loams (5.36%), silty clays (2.98%), clays (1.13%) and coarser textures (loamy sand to sand, 1.79%). Soil reaction (pH-water) had an overall mean of 6.09 for Hai and 5.85 for Lushoto, both considered ideal for Arabica coffee (Cordingley, 2010).

Soil organic carbon of 1.37 to 11.34% (average of 3.96%) for Hai is considered normal for coffee, with a minimum above 1%. As for Lushoto, the average of 2.02% is considered normal, though the minimum was far below 1%. Some areas, namely Wema, Kibandai, Ruvu, Kianga, Tiku and Mwangoi, showed remarkably low OC, (<0.5%), calling for efforts in organic matter enrichment. The mean total N was 0.17% for Hai and 0.08% for Lushoto; while the respective values of available P were 37.9 and 11.52 mg kg^{-1} and those of exchangeable potassium (K) were 0.98 and 0.41 $cmol_c$ kg^{-1}. The mean content of extractable Fe, Cu, Zn and B were higher in Hai than Lushoto, while those of Mn and S were lower. The effective cation exchange capacity (ECEC) was more or less the same in both districts. Ca/Mg ratios for Hai were between 1 and 90, very similar to the Mg/K ratios in the range of 1 to 80). The (Ca+Mg)/K ratios had a very wide range of 1.91 to 558.03). As for Lushoto, Ca/Mg ratios were between 1 and 116, lower than the Mg/K ratios in the range of 1 to 280). The (Ca+Mg)/K ratios had a very wide range of 2.68 to 1030).

3.4.3 Qualitative fertility evaluation

From Fig. 3.1, only four categories were distinguished in Hai: Low (1 site, 1.72% of total sites surveyed), moderately low, moderate and moderately high (10, 43 and 4 sites; 17.24, 74.14 and 6.9% respectively).

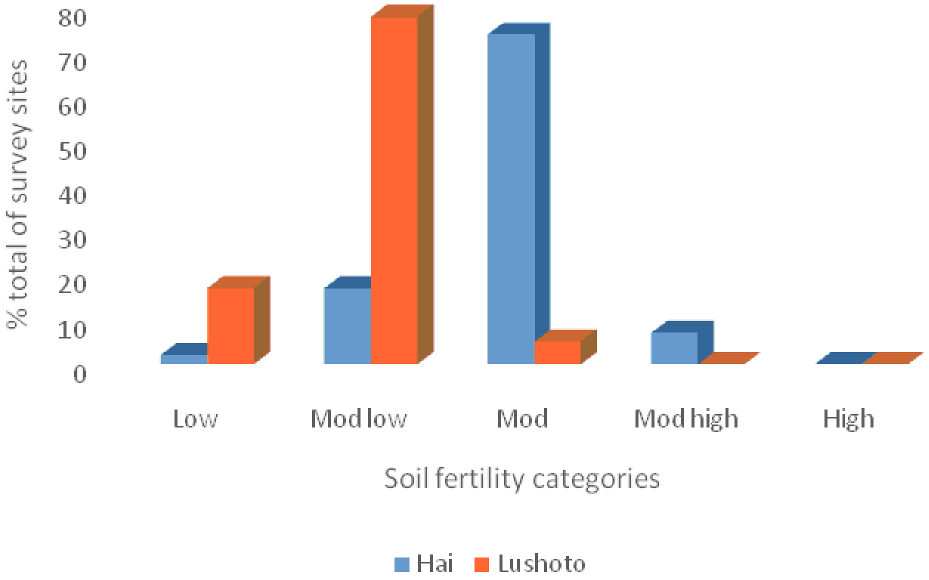

Figure 3.1: Summary results of qualitative fertility evaluation, Hai and Lushoto Districts

None of the surveyed locations in Hai belonged to the high fertility category (the most ideal soil for coffee production). The implication is that the whole coffee growing area in Hai requires ISFM intervention of varying magnitude for coffee to grow well and yield optimally.

Fewer categories (three) were distinguished in Lushoto: Low (10 sites, 17.24%), moderately low (45 sites, 77.59%) and moderate (3 sites, 5.17%). Dominant limitations are low CEC, K, B, Fe, Cu and Zn. This implies that soils of Lushoto are less fertile than those of Hai, and therefore will require more effort in ISFM.

3.4.4 Quantitative fertility evaluation

The calculated total soil-available units (TSA) of N, P and K for Hai ranged from 72.02-617.69 kE ha^{-1} (average 216.21 kE ha^{-1}). Lower figures (<100 kE ha^{-1}) were found in Shari Mamba, limited by low N and K; and also in Masama Kyuu, limited by low pH, N and P. If the soil can only supply a sum of primary macronutrients less than 100 kE ha^{-1}, it is considered of low fertility, which requires substantial ISFM efforts to grow coffee. At the other extreme, Masama Sawe, Narumu Orori, Nkwarungo and Nshara are all capable of supplying over 400 kE ha^{-1}. In Lushoto, TSA ranged from 26.78 to 585.29 kE ha^{-1} (average 152.0 kE ha^{-1}). Lower figures were noted in Galamba, Wema, Dulle, Yeriko, Kwekitui, Kidenya-Mgongo, Kianga, Ludende, Emau, Tiku and Kituja; the most prominent limitation being low K (also noted by Cordingley, 2010), followed by N, OC and P, in a decreasing order of importance. The low K levels could be explained by low CEC (typical of Acrisols) and the terrain structure which encourages K leaching and downstream flow (Brady and Weil, 2002). At the other end only one site (Mlalo-Mwangoi) showed to be capable of supplying over 400 kE ha^{-1}. This quantitative approach simply confirms the findings of the qualitative approach, that the soils of Lushoto are less fertile than those of Hai District.

3.4.5 Spatial data interpretation

The spatial variation in total soil-available N, P and K (TSA) in kE ha^{-1} for Hai is given in Figure 3.2. Soil fertility is high at Orori-Nshara-Sawe, followed by Shari-Kyeeri-Kilanya. Lowest soil fertility is at the west (Mbosho-Lemira and Lukani-Mashua). The relatively higher TSA values to the south than north could be explained by the terrain structure whereby nutrients tend to be washed from higher levels and enriched at lower levels. The Shari-Kyeeri and Nkwarungo-Kilanya areas have higher TSA values than their surroundings, and this can be related to organic matter enrichment resulting from the integrated crop-livestock farming system common in those areas. Smallholder farmers run dairy cattle projects as a way of income diversification (Staal *et al.*, 2003) and import maize crop residues from lowland farms for feed, whereby manure and feed remains find their way into the soil.

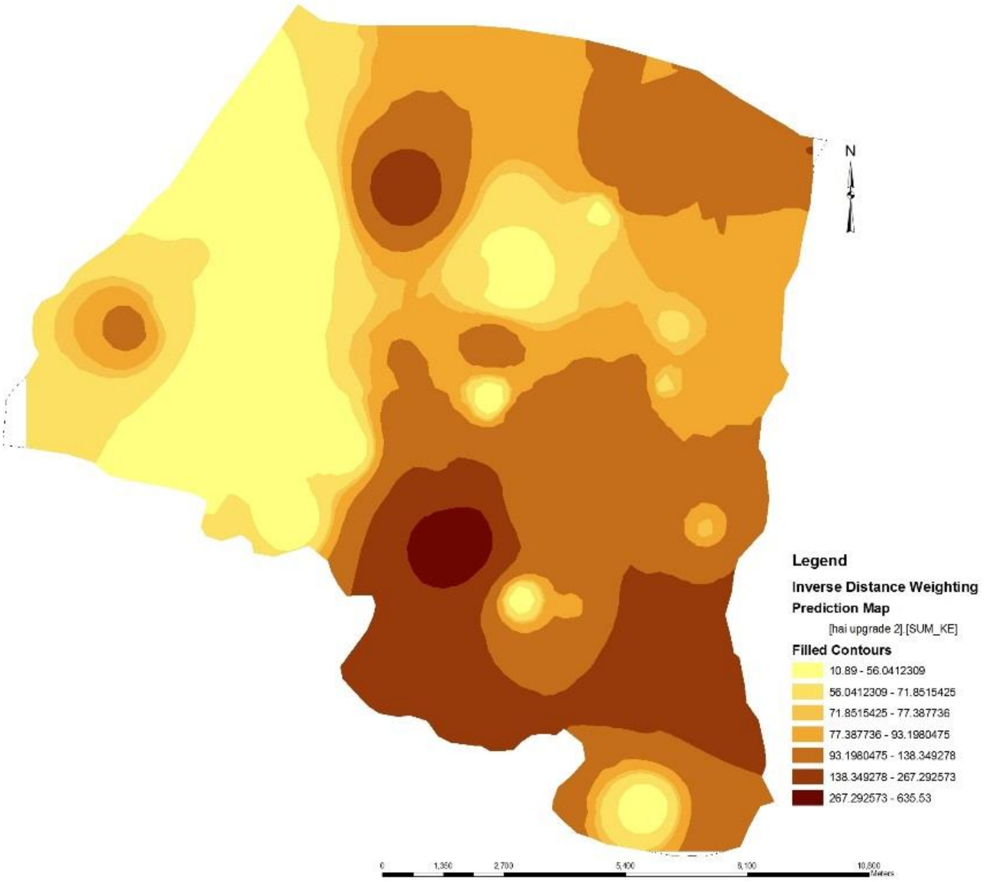

Figure 3.2: Calculated soil available nutrients, Hai District

The observed west-east soil fertility gradient is rather difficult to explain. The low fertility to the west (Lukani, Mashua, Mbosho and Lemira) could only be related to the farmers' crop management practices, as noted by Samake *et al.* (2005). During the baseline survey (Chapter 2), coffee farms in these areas were almost at a total state of neglect (due probably to low and unstable coffee prices, ageing household heads and/or disinterested youths), while in some areas coffee had been replaced by intensive bananas and, specifically for Lukani, Irish potatoes. None of the contacted farmers indicated having used industrial fertilizers in coffee, a practice more common with farmers to the east (Machame and Lyamungo). It seems as if the fertilizers used in Machame and Lyamungo have had positive impact on nutrient balance (countering the effect of nutrient mining in perennial cropping systems).

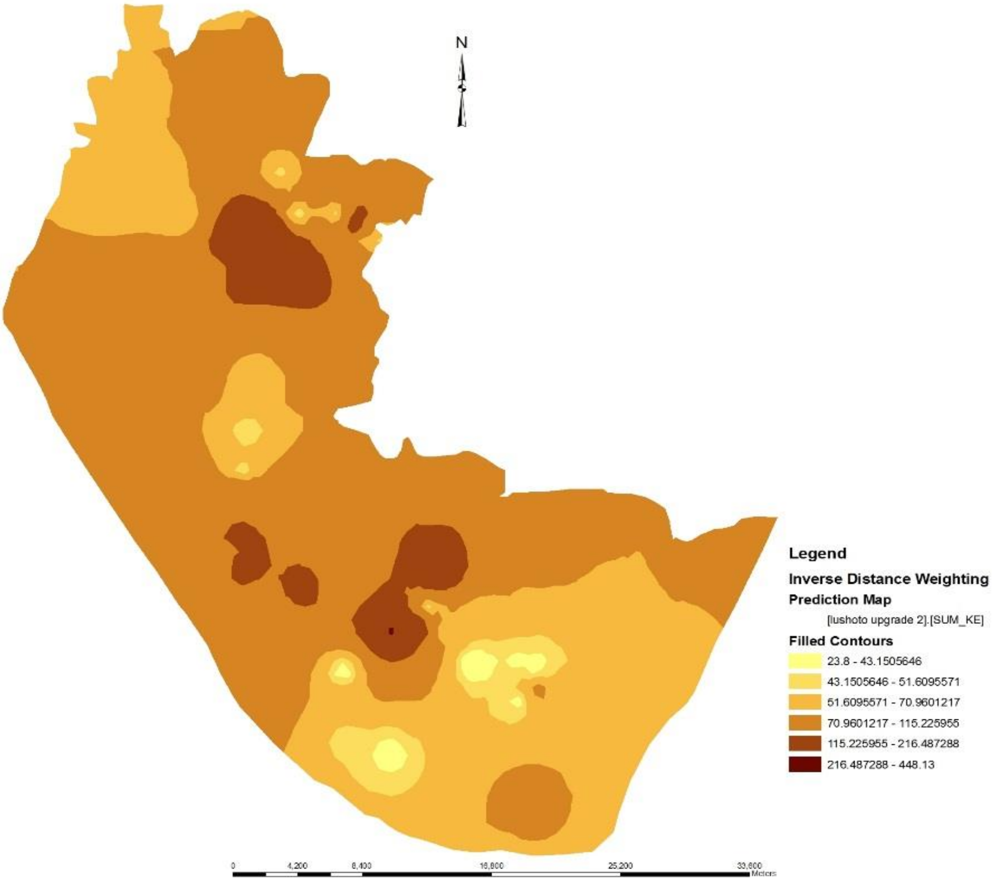

Figure 3.3: Calculated total soil available nutrients, Lushoto District

The spatial variation in total soil-available N, P and K (TSA) in kE.ha^{-1} for Lushoto is given in Fig. 3.3. The moderate to high fertility areas included most of Soni, Lushoto and Mlalo, characterized by steep but terraced land (thanks to SECAP Project –Johansson, 2001) intensively used for annual field crops like maize and beans; and high-value horticultural crops (vegetables and fruits). Lower soil fertility areas covered most of

Bumbuli, Mgwashi and about half of Mtae, which are mostly high-altitude areas where bracken ferns are common, indicating low pH of the soils.

3.4.6 Discussion

Soil fertility surveys, of the type used in this study, have been reported by several research scientists including Gachimbi (2002); Maria and Yost (2006); Belachew and Abera (2010); Kimani and Njoroge (2001); Belurka and Yadawe (2011), at varying details. Some have made use of remote sensing and GIS (Tsirulev, 2010; Grealish *et al.*, 2008); while others used statistical tools (Nunez *et al.*, 2011). The bottom-line is the applicability of the results to the intended users. The approaches used in this work could be termed as hybrid – statistical assessment per division, comparison with the soil fertility requirements of coffee (Sys *et al.*, 1993), nutrient availability modelling and spatial interpretation. All these approaches agree in principle that soil fertility is on the decline in the coffee growing areas of Northern Tanzania, and call for ISFM intervention. They also agree that the Hai soils are more fertile than those of Lushoto.

Both this work and the earlier one have helped to confirm the stakeholders' observation (TCB, 2009) that soil fertility decline is an important limitation to coffee productivity. It was noted in the earlier study that few people (about 25% of the sampled farmers in Hai and about 16.67% in Lushoto) use industrial fertilizers. There is, therefore, an uphill task for TaCRI and the coffee extension staff at district level to promote the right kind of nutrient management strategies to the farmers. Fertilizers commonly used are CAN, NPK (20:10:10), Urea (46%N), MRP and DAP in Hai District, and Urea (46%N), NPK (20:10:10), DAP, SA and MRP in Lushoto District. With the exception of NPK, which TaCRI recommends at onset of flowering, it appears that farmers are used to apply N and P, but not K. By contrast, almost every farmer uses farmyard manure, and at the recommended rate of one tin (approximately 10 kg) per tree. Factors affecting farmers' decision on fertilizer use have been reported by several researchers including Adesanwo *et al.* (2009); Coorbels *et al.* (2000); Norbu and Floyd (2001); Matsumoto and Yamano (2009). Their observations should be taken into consideration in devising an ISFM strategy for the coffee farmers of Hai and Lushoto districts. The database created in this work can be very useful in that regard.

Soil fertility is not a distinct soil property, it is rather a combination of many soil properties and therefore, measuring soil fertility requires knowledge about the interactions of those soil properties. Unfortunately, there is no unique technique for studying such interactions (Mulder, 2000). Soil productivity, which is defined as the capacity of a soil to support crop yield (Brady and Weil, 2002), is more meaningful to a farmer than soil fertility, though the two have mutual cause-and-effect relationship. To express one in terms of another (and particularly soil productivity in terms of the soil fertility data accrued from soil analysis), crop models become quite useful. It is therefore recommended that future soil fertility evaluation tasks be expanded through modelling to soil productivity evaluation.

3.5 Conclusions and Recommendations

This study has proved that soil fertility is considerably low in the study areas. The qualitative assessment revealed major limitations as low P and micronutrients for both districts, with additional limitations of low CEC, exchangeable K and boron for Lushoto only. The calculated TSA for N, P and K have shown that soils of Lushoto are less fertile than those of Hai, and therefore will require more effort in ISFM. The spatial variation in soil fertility for the two districts is related to the topography of the areas and/or the farming practices common in those areas. A decision support tool for ISFM in coffee will therefore be helpful to farmers in Hai and Lushoto districts and other coffee growing areas in Northern Tanzania.

From this study, the following recommendations are made:

i. TaCRI and the District Coffee Subject Matter Specialists (DCSMSs) should continue promoting the knowledge on the right kind of nutrient management strategies (including fertilizer types, rates and timing of application) to the coffee farmers.

ii. Stockists should consider having some straight K fertilizers (such as muriate of potash) for sale to coffee growers, especially in Lushoto where low K levels have been noted.

iii. "Integrated Farm Management" strategy which involves keeping livestock should be encouraged among farmers for both income diversification and nutrient cycling.

iv. Soils which showed remarkably low OC, (<0.5%), call for efforts in organic matter enrichment such as mulching, application of manures and composts.

v. In areas of low soil pH and low CEC, a programme involving lime and organic matter application is desirable because lime alone is not effective in soils of low CEC.

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CHAPTER FOUR

4.0 DEVELOPING A COFFEE YIELD PREDICTION AND INTEGRATED SOIL FERTILITY MANAGEMENT RECOMMENDATION MODEL FOR NORTHERN TANZANIA

4.1 Abstract

A study was conducted between 2010 and 2013 at TaCRI Lyamungu, to develop a simple and quantitative system for coffee yield estimation and nutrient input advice, so as to address the problem of declining annual coffee production in Tanzania, particularly in its Northern coffee zone, which is related to declining soil fertility. Source data were taken from Hai and Lushoto Districts, Northern Tanzania. An earlier model QUEFTS, developed for maize but under similar conditions as those of Arabica coffee (*Coffea arabica*) in the study areas, was used as a benchmark. Secondary fertilizer trial data were used in model calibration for coffee, while adding two more steps related to balanced nutrition and the economics of integrated soil fertility management (ISFM). The result was a new model SAFERNAC (Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee). The model consists of three modules: SOIL (the soil properties of interest), PLANT (all the crop and crop management parameters such as physiological nutrient use efficiency, plant density, maximum yields per tree) and INPUT (nutrient inputs – organic and inorganic). It consists of two subsequent parts – a baseline approach (no input) for coffee land evaluation; and an integrated soil fertility management (ISFM) approach that involves application of nutrient inputs, for ISFM planning and design of fertilizer experiments. The model was checked for accuracy of the adjusted equations, and found to be capable of reproducing the actual yields by 80-100%. The new model is a useful tool for use in coffee farms.

Key words: Coffee yield model, nutrient use efficiency, QUEFTS, SAFERNAC.

4.2 Introduction

The importance of coffee in the Tanzanian economy is well documented by Baffes (2003); Carr *et al.* (2003); Hella *et al.* (2005) among others. Coffee prefers very deep (usually more than 1.5 m), well drained friable loam and clay soils. Soils with high available water holding capacity, a pH in the range of 5-7 and a high nutrient retention capacity are most suitable (Wintgens, 2012). The coffee plants' average nutrient removal from 1 ha soil per growing cycle is 135 kg of N, 35 kg of P_2O_5 and 145 kg of K_2O (Sys *et al.*, 1993). With a substantial part also getting lost through leaching, downstream flow in the soil and fixation into insoluble complex compounds, it is essential to replace the mined and lost nutrients by having a well-planned nutrient management programme (Maro *et al.*, 2006).

In Tanzania, coffee is grown in a wide variety of agro-ecological zones. Mlingano Agricultural Research Institute (MARI, 2006), following the system developed by De Pauw (1984) and adopted by van Oosterom *et al.* (1998), categorized the coffee zones as Eastern Plateaus (E12-E15), High Plateaus and Plains (H1, H2, H3, H5), Volcanoes and Rift Depressions (N4, N10), Central Plateaus (P6) and Western Highlands (W1-W4). These include an altitudinal range of 500 – 3500 metres above mean sea level, and rainfall range of 500 – 3500 mm (mostly over 1000 mm). According to the fundamental growth conditions for coffee (Wintgens, 2012; Wrigley, 1988; Oberthur *et al.*, 2012), water availability in these zones does not pose a serious limitation to coffee; neither does irradiance or temperature in this tropical Tanzanian situation. This statement, however, does not take into account the imminent threat of climate change. This leaves soil condition as a major factor of coffee productivity in the Tanzanian coffee growing zones (Van Ranst *et al.*, 2002). In the Northern coffee zone, which fits into agro-ecological zones E, H and N, and is dedicated exclusively to the production of mild Arabica coffee, annual production is on the decline (Maro *et al.*, 2010) and soil fertility degradation has been pointed out as an important contributing factor.

Soil fertility is a manifestation of many soil properties and, therefore, measuring soil fertility requires knowledge about the interactions of those soil properties. Unfortunately, there is no unique technique for studying such interactions (Mulder, 2000). Ultimately, farmers are not interested in the soil properties themselves, but how they affect agricultural production. Crop models, such as the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) (Janssen *et al.*, 1990), become useful in explaining the effects on yields of individual soil properties that are measured by soil analysis. The predicted yield can then be used as an integrative indicator of soil fertility.

QUEFTS belongs to the series called the Wageningen Crop Models. It uses yields of unfertilized maize as a yardstick, and interpretes soil fertility as the capacity of a soil to provide plants with the primary macronutrients. Four successive steps are involved: calculation of the potential supplies of N, P and K, actual uptake of each nutrient, yield ranges depending on the actual uptakes, and lastly, pairwise combination of yield ranges and the yields estimated for pairs of nutrients are averaged to obtain an ultimate yield estimate. QUEFFS was described by Janssen *et al.* (1990) as a useful tool in quantitative land evaluation, whose principles may be applied to other crops, soils, nutrients and agro-ecological regions. The framework on which the model was built is in synchrony with the physiographic requirements of Arabica coffee.

One of the important thrusts of Tanzania Coffee Research Institute (TaCRI) is in the area of integrated soil fertility management (ISFM). Considering the diverse environments under which coffee is grown, crop yield and fertilizer modelling becomes quite useful.

With many coffee yield modelling attempts so far based on the crop and its physiological processes (Camargo *et al.*, 2008), this work focused on the land and its capacity to support coffee. Its objective was to make a coffee ISFM decision support tool based on soil properties, organic and inorganic nutrient inputs; calibrated for the northern coffee zone of Tanzania, with a prospect of scaling up and out.

4.3 Materials and Methods

4.3.1 Background

Efforts to collect and collate the available soil data for purposes of gauging the TaCRI recommendations on soil fertility management started in 2005. Soil data from various places in Kilimanjaro, results from NPK reference trials at TaCRI Usagara C farm, and fertilizer x tree density trial, Lyamungu (unpublished TaCRI records) were collected. These data were used between 2007 and 2010 in calibrating an earlier developed fertilizer advice model QUEFTS (Janssen *et al.*, 1990; Janssen and Guiking, 1990; Janssen and de Willigen, 2006; Mowo *et al.*, 2006; Tabi *et al.*, 2007) to coffee.

4.3.1.1 Estimation of physiological nutrient use efficiency by coffee

In the trials whose data were used in this work, crops had not been analyzed. The uptake of nutrients was, therefore, estimated by dividing the yield by the physiological nutrient use efficiency (PhE), which relates agronomic yield with nutrient uptake in all crop components (Janssen and de Willigen, 2006). Unfortunately there has been no real data on PhE for coffee in Tanzania. The PhE values were therefore derived from the literature (Cannell and Kimeu, 1971; Snoeck and Lambot, 2004; Van der Vossen, 2005), and adjusted to the results of TaCRI fertilizer trials (Table 4.1). It was assumed that those PhE values are averages. The medium physiological nutrient use efficiency (PhEM) was then found by dividing dry matter production of parchment coffee by gross uptake of nutrients.

It should be noted that in Table 4.1, dry matter production of pulp and vegetative growth refers to the annual production going together with an annual dry parchment coffee production of one ton. This results in 1000/70 (=14), 1000/12.5 (=80), 1000/63 (=16) for N, P and K.

Table 4.1: Rounded-up indicative values of dry matter production and average nutrient contents in various components of the coffee tree*

Component	Dry matter (DM)	N	P	K
Parchment coffee	1000	20	2.3	18
Pulp	875	16	6.0	17
Vegetative growth	2000	34	4.2	28
Total DM; Gross uptake	3875	70	12.5	63

N = Nitrogen; P= Phosphorus; K = Potassium
*Adapted fromCannell and Kimeu (1971)

4.3.1.2 Experimental data for model calibration

In the calibration of QUEFTS, coffee-based data from two TaCRI's on-station field trials (NPK reference and fertilizer x tree density trials) were used to establish relationships between soil fertility indices and nutrient uptake by coffee (Appendix 4.4 and 4.5). The NPK reference trial had been superimposed on established coffee in 1983. The design was a 4^2 factorial with N and K both applied at rates of 0, 80, 160 and 240 kg per ha per year while all units received 60 kg P per ha per year. N and K were applied in three rounds and P in two rounds. Two extra experimental treatments were included as well: $N_2P_0K_2$, $N_2P_2K_2$, where N_2 and K_2 stand for 160 and P_2 for 120 kg ha^{-1} year^{-1}. The fertilizer x tree density trial was started at Lyamungu in 1994. It had a split-plot design with tree density (1330, 2660, 3200 and 5000 trees ha^{-1}) as the main treatment, and N application as a sub-treatment (0, 90, 180 and 270 kg N ha^{-1} year^{-1}, split-applied in three rounds). Only yields of the best year were used in order to minimize the risk that other factors than soil fertility and NPK had influenced yields. Some soil analytical data of both trials were available (Table 4.2). Starting with the parameter values of the original

QUEFTS model, a trial-and-error procedure was followed until the fit could not be improved further.

Table 4.2: Soil analytical data for the two on-station trials

Location	SOC* g/kg	SON* g/kg	$P_{Bray\ 1}$ mg/kg	K_{exch} mmol/kg	pH_{water}
			NPK reference trial		
Usagara C	18	2.8	67	19	5.7
			Fertilizer x tree density trial		
Trees per ha					
1330	22	2.2	86	22.1	5.7
2660	24	2.4	109	21.1	5.8
3200	21	2.1	65	17.3	5.6
5000	18	1.8	119	18.2	5.3

*SOC= soil organic carbon; SON = soil organic nitrogen (= Total nitrogen)
Adapted from TaCRI fertilizer trial records

4.3.2 Adaptation of QUEFTS to coffee

The first task in adapting QUEFTS to coffee was to review, with the coffee crop in mind, its various steps. These steps dealt with the assessment of available nutrients from soil and inputs (A), the calculation of actual uptake (U) of nutrients as a function of the amounts of available nutrients (A), and the estimation of yield (Y) as a function of the nutrients taken up (U). While QUEFTS assessed available nutrients in unfertilized soils (Janssen *et al.,* 1990) and in chemical fertilizers (Janssen and Guiking, 1990), there was a need to consider in Step 1 organic nutrient inputs as ISFM components.

The calculation of actual uptake of nutrients (Step 2) was adopted as in QUEFTS, as it mainly involved theoretical concepts. The actual uptake of Nutrient 1 (U_1) is calculated twice: $U_{1,2}$ is a function of A_1 and A_2 being the available amounts of Nutrients 1 and 2, $U_{1,3}$ is a function of A_1 and A_3. The lower value between $U_{1,2}$ and $U_{1,3}$ is assumed to be the more realistic one in accordance with Liebig’s Law of the Minimum.

In Step 3, yield ranges between maximum and minimum limits are derived on basis of the actual nutrient uptakes. Yields at maximum accumulation of N, P and K in the crop (YNA, YPA, YKA) and at maximum dilution (YND, YPD, YKD) are calculated as the product of actual uptake (U) and physiological nutrient use efficiency (PhE) at accumulation and dilution (PhEA and PhED), respectively. PhE in this study is expressed in kg parchment coffee per kg of nutrient taken up (Appendix 4.2).

Step 4 mainly followed the QUEFTS principles. Yield ranges are combined in pairs (YNP, YNK, YPN, YPK, YKN, and YKP) taking nutrient interactions into account. The average value of those six yields is considered the final yield estimate (YE). Some restrictions are imposed to ensure that calculated YE does not surpass the maximum dilution of N, P or K (YND, YPD YKD) or the maximum yield that can be obtained in view of climate and crop properties (YMAX). For coffee, the concepts of Y_{tree}MAX and YMAX were introduced as maximum yield limits per tree and per ha, respectively.

Two additional steps were introduced to facilitate the assessment of the nutrient inputs required for a certain target yield (Janssen, 2011). Step 5 deals with the calculation of physiologically optimum nutrient proportions and the correspondingly required nutrient inputs for balanced crop nutrition. In Step 6 the economically optimum combinations of nutrient inputs are assessed as a function of target yield, soil available nutrients, and prices of input nutrients and yield.

4.3.3 Application of the model for coffee land evaluation

In its baseline approach, the new model was used to perform quantitative land evaluation for coffee by estimating yields on basis of spatial soil data from Hai and Lushoto districts. Data for OC, Total N, Bray 1 P, exchangeable K and pH were used. Those parameters whose units were percentage (OC and total N) and $\text{cmol}_c\ \text{kg}^{-1}$ (exchangeable K) had to be multiplied by ten to convert to g kg^{-1} and $\text{mmol}_c\ \text{kg}^{-1}$ respectively. Plant density was set at 2000 trees per ha (spacing of 2.0 x 2.5 m^2). Other model parameters were left as default.

Data on baseline yield for the two districts were converted to shapefiles under ArcView GIS 3.2 and then interpolated under ArcGIS 9.3. The inverse distance weighting (IDW) interpolator was used with number of nearest neighbours set to 12 and the power set to 2. Baseline yield data for the two districts was used as a yardstick to test various human intervention strategies; farmyard manure used alone, at 5 tons per ha (about 2.5 kg per tree); inorganic fertilizer N, P and K at the dosage of 160, 60 and 160 kg ha^{-1} respectively; and a combination of the two, as in Huth *et al*. (2009). Scatter diagrams were used to show the effects of farmer ISFM practices in areas of low, medium and high natural fertility.

4.4 Results and Discussion

4.4.1 The new model SAFERNAC

The calibration of QUEFTS for coffee gave rise to a new model SAFERNAC (Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee). The model is built on Excel spreadsheet which allows for flexibility. Depending on the use to which it is put, it can follow one of the two separate approaches –baseline and ISFM. The parameters that differentiate the two approaches are based on Step 1.

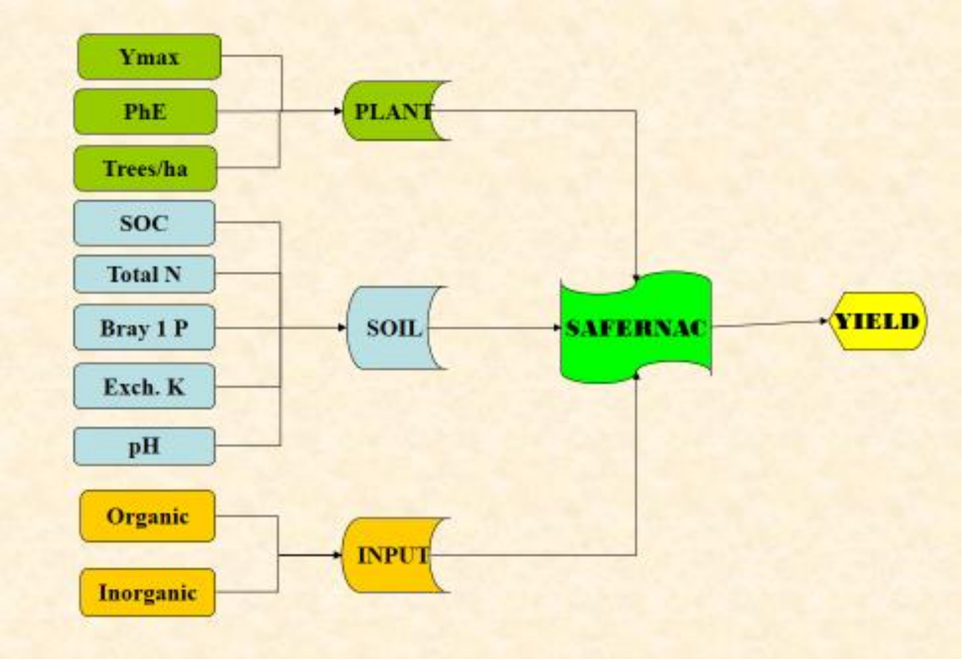

Figure 4.1: Complete structure of SAFERNAC.

Fig. 4.1 is a schematic representation of the model. The module PLANT comprises all indices related to the coffee crop (plant density, maximum yields per tree and per ha, PhEA and PhED). The module SOIL comprises five soil fertility indices (pH, organic carbon, total nitrogen, available phosphorus and exchangeable potassium), and the module INPUT comprises addition of organic and/or inorganic nutrient sources, which is the purpose of ISFM. In the spreadsheet the baseline approach is pursued by assigning zero values to all nutrient input columns. This approach simulates coffee yields under natural fertility, and is meant for use in coffee land evaluation. The ISFM approach assigns non-zero values to the nutrient input columns on spreadsheet, whereby the nutrients can be inorganic, organic or a combination of the two.

4.4.2 Model assumptions and prerequisites

The system operates under the following conditions, most of which affect Step 1 equations, with the other steps more generic:

i. Soil fertility is conceived as the capacity of a soil to provide plants with nitrogen, phosphorus and potassium as primary macronutrients. The system assumes therefore that other nutrients are far less limiting than these three.
ii. Irradiance and moisture availability are optimum,
iii. Soil is well drained (minimum of drainage class 3 – FAO, 1990),
iv. Soil is deep enough (90 cm and more),
v. $pH_{(H20)}$ is in the range 4.5-7.0,
vi. Values for SOC, $P_{Bray\ 1}$ and K_{exch} for the topsoil (0-20 cm) are below 70 g kg^{-1}, 30 mg kg^{-1} and 30 mmol kg^{-1}, respectively.

4.4.3 Calibration of model parameters of SAFERNAC

Results of model calibration are summarized in Appendix 4.1. These include a simplification of constants (as in fK, SAN, SAP and SAK), introduction of INPUT parameters IAi and IAo and an important PLANT parameter fD (a plant density correction factor downgrading land utilization by coffee whose plant density is below 3334 trees per ha) in Step 1. Another major adjustment is in Step 3, where the PhE values were recalibrated and expressed as kg parchment coffee per kg of nutrient taken up at accumulation “a” and dilution “d” as shown in Table 4.3. On the other hand, the factors rN, rP and rK subtracted from UN, UP and UK respectively for maize were removed as they do not apply in coffee growing areas in Tanzania. Step 4 follows QUEFTS principles. Additionally, limitations have been set to the model such that $YE \leq \max(YND, YPD, YKD, YMAX)$ by using two PLANT parameters $Y_{tree}MAX$ and YMAX.

Table 4.3: Physiological efficiency at maximum, medium and minimum availability of N, P and K (in kg parchment coffee)

	PhE*	Symbol	N	P	K
Maximum	PhED	D	21	120	24
Medium	PhEM	M	14	80	16
Minimum	PhEA	A	7	40	8

* Physiological efficiency at dilution (d), medium (m) and accumulation (a)

4.4.4 Balanced NPK Nutrition and crop nutrient equivalents

Some principles of balanced NPK nutrition and crop nutrient equivalents as explained by Janssen (1998) and applied in Rwanda (Bucagu *et al.*, 2013) are adopted in this work. It is assumed that the values of uptake efficiency (UE = U/A) and those of physiological efficiency (PhE = Y/U), averaged for all three nutrients N, P and K, are maximum when the available amounts and the uptakes of N, P and K have optimum proportions. In case the ratio PhED/PhEA is the same for N, P and K, the optimum proportions are equal to the ratios of the reciprocals of the medium physiological efficiencies (PhEM). This implies that in a situation of balanced nutrition, 1 kg of available N has the same effect on coffee yield as 0.175 kg of available P, or 0.875 kg of available K, and similarly does the uptake of 1 kg N have the same effect on coffee yield as the uptake of 0.175 kg P or 0.875 kg K. These values are used to define the unit of nutrient equivalents, referred to as kE.

Once “target yield” or TY and PhEM are known, the relationship Y = U * PhEM can be used in determining the target uptake (TU) and target availability (TA), the latter being the sum of SA (available nutrients from the soil) and IA (available nutrients from input). When SA is known, the amount of nutrients needed to be added to the soil (both organic and inorganic) to attain the target yield can be estimated: IA = TA-SA. For balanced crop nutrition, TAN = TAP = TAK, TAi being expressed in kE.

Balanced nutrition is the best possible situation from the environmental point of view, as it ensures maximum uptake of the available nutrients and minimum loss to the environment. Expressing quantities of nutrients in kE, and substituting $A_1 = A_2 = A_3$, $d_1 = d_2 = d_3$, $a_1 = a_2 = a_3$ and $d/a = 3$ in Step 3, it follows from that $U/A = 0.9583$. The average value of the uptake efficiencies is then maximum (being 0.96), and hence the average portion of non-utilized available nutrients is at minimum, being only 0.04.

Because soil available nutrients are usually not in optimum proportions, nutrient inputs should be managed in such a way that the sums of (SA + IA) for the three nutrients are balanced in equivalent terms. This implies that inputs should start with the most limiting nutrient. It should be applied until the available amounts of the most and the one but most limiting nutrients are in balance. Further application should be with these two nutrients according to their optimum proportions until the supplies of all three nutrients are balanced, after which all three nutrients are applied according their optimum proportions.

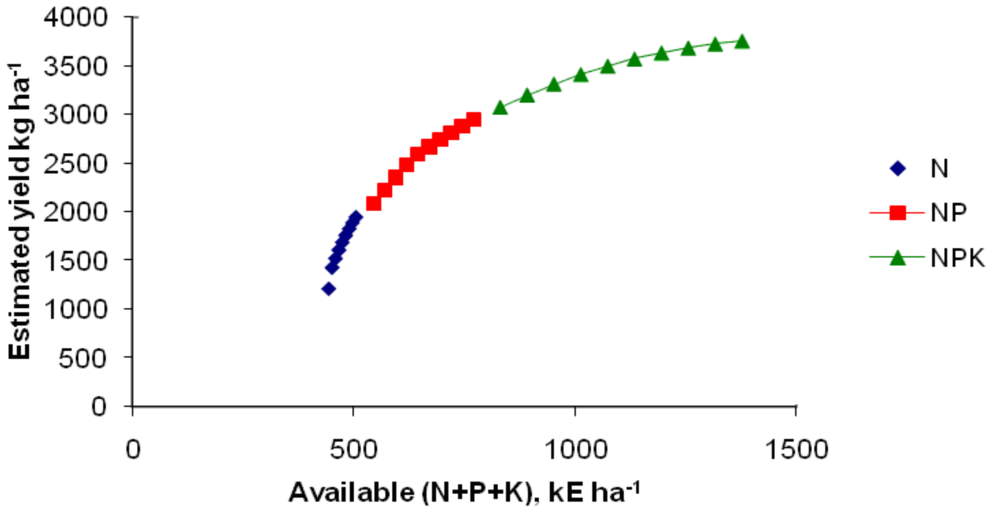

Figure 4.2: Relation between calculated coffee yields and the amount of available nutrients expressed in kE ha $^{-1}$, for three ranges of nutrient input

An example is given in Figure 4.2 representing an imaginary soil having organic C 26 g kg^{-1}, organic N 2.6 g kg^{-1}, $P_{Bray\ I}$ 52 mg kg^{-1}, exchangeable K 20 $mmol_c$ kg^{-1}, and $pH_{(water)}$ 5.2. The amounts of soil available N, P and K are then 71.5, 30.4 and 295.4 if expressed in kg ha^{-1}, and 71.5, 173.8 and 337.6 if expressed in kE ha^{-1}. The sum of soil available nutrients is 583 kE ha^{-1}. Tree density is set at 2000 and hence fD is 0.76. The calculated yield without fertilizer application is 1086 kg ha^{-1}. Because SAN is smaller than SAP and SAK (expressed in kE), inputs should start with N, followed by N+P, and finally with N+P+K. The maximum yield is 3800 kg ha^{-1}. That is why in Figure 4.2 the yield curve starts levelling off at high quantities of available nutrients.

4.4.5 Outcomes of model demonstration

In Appendix 4.3, the outcomes of the successive steps 1-4 in the basic SAFERNAC spreadsheet are shown as a two-treatment example for the on-station experiment of Usagara C: amounts of available nutrients (A), actual uptake (U) of N, P and K, yield ranges (Y_1A, Y_1D), yields as a function of nutrient pairs ($Y_{1,2}$ and $Y_{2,1}$) and the final yield estimate YE. $U_{1,2}$ stands for UN(P), UP(K), UK(N); U1,3 for UN(K), UP(N), UK(P). $Y_{1,1}$ stands for YNP, YPK, YKN; and $Y_{2,1}$ stands for YPN, YKP, YNK. The model was run using the soil analytical data in Table 4.2 as starting points. Figures 4.3a and 4.3b compare the yields simulated by SAFERNAC (YE) with actual yields (Y_{act}) for the NPK reference trial Usagara C and the fertilizer and tree density trial Lyamungu, of which soil data are given in Table 4.2.

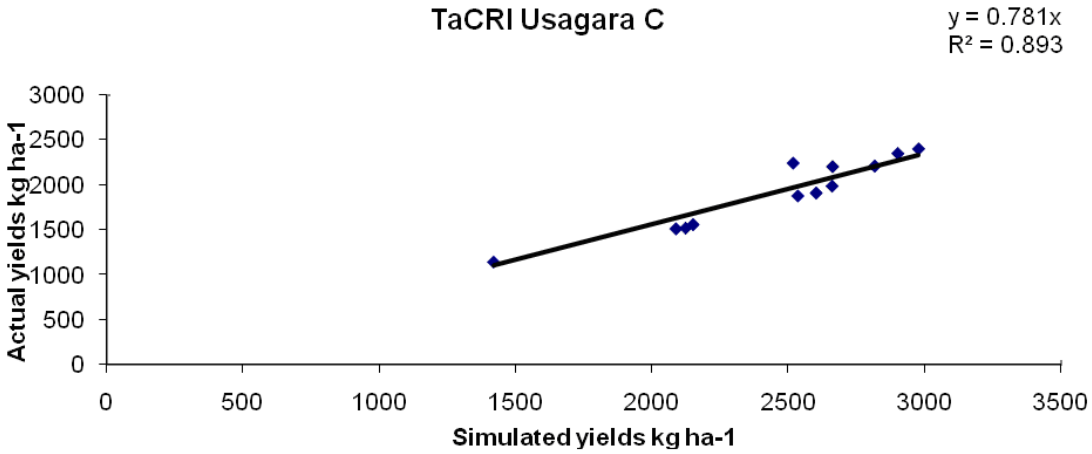

Figure 4.3a: Simulated and actual parchment yields, TaCRI Usagara C (12 points = different fertilizer combinations)

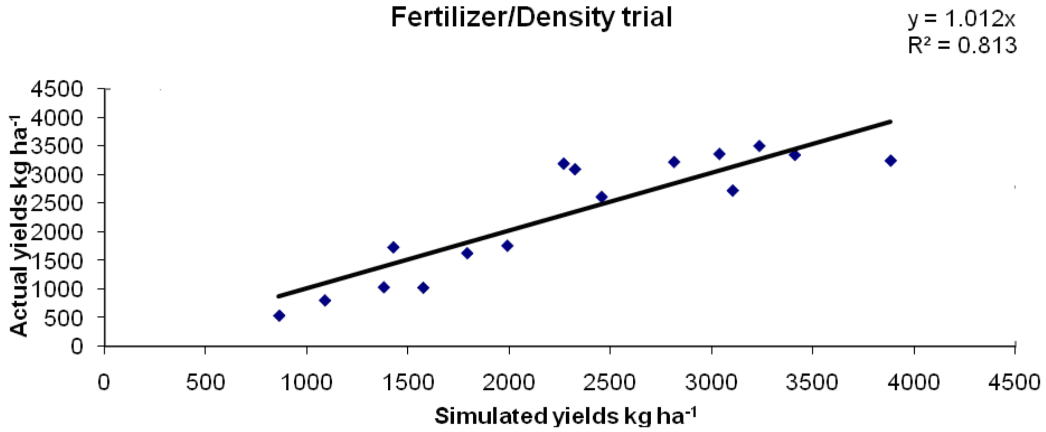

Figure 4.3b: Simulated and actual parchment yields, TaCRI fertilizer density trial (16 points = 4 plant densities x 4 fertilizer rates)

Actual yields were around 80% and 100% of the simulated yields respectively (underscoring the importance of fD which was varied in the latter trial) and the lines through the origin showed good R^2 values. The calibrated equations have therefore demonstrated their capability to reproduce the yields of the trials that had been used for their calibration to a satisfactory degree.

4.4.6 Estimated baseline yields for Hai and Lushoto Districts

Baseline yield, as estimated with SAFERNAC, is spatially represented in Fig. 4.4 (Hai) and 4.5 (Lushoto). The baseline yield map for Hai shows high spatial variation, with higher yields (>500 kg ha^{-1}) to the east (Lyamungo and Machame) and a pocket at Masama Sawe. The central part (mainly Machame) showed potential of 300 to 500 kg ha^{-1} while the western part (Masama) recorded a low potential of less than 300 kg ha^{-1}.

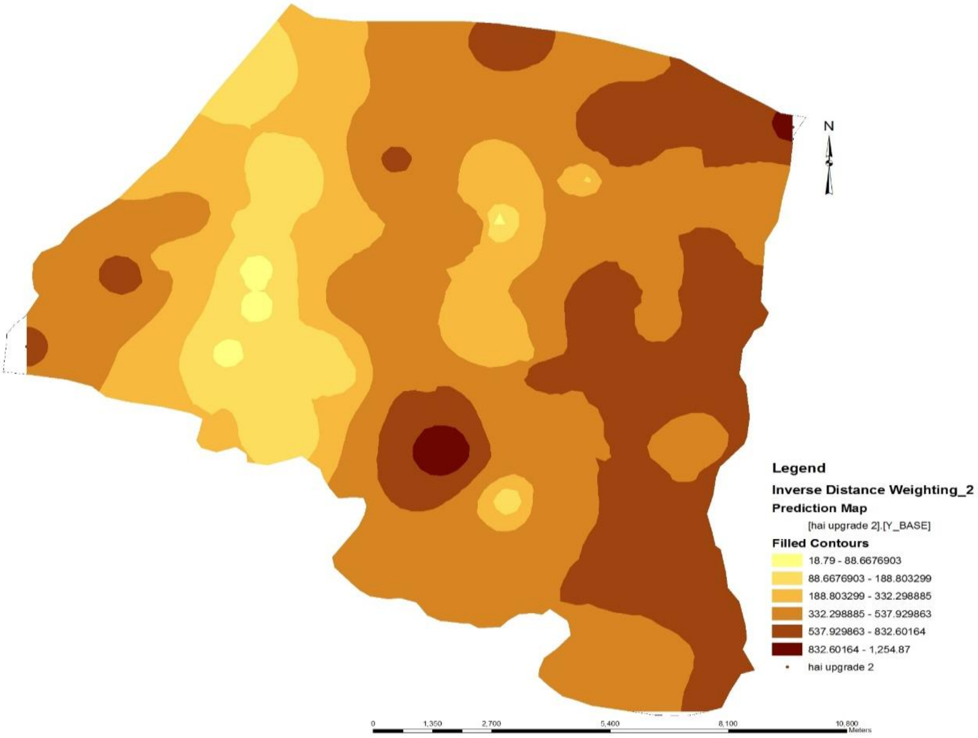

Figure 4.4: Baseline yield estimated with SAFERNAC, Hai District

The yield map for Lushoto (Figure 4.5) had lower spatial variation, with Lushoto, Soni and pockets of Mlalo recording over 350 kg parchment per ha. Mtae, the rest of Mlalo and parts of Mgwashi showed potential yield between 300 and 350 kg ha^{-1}, while lower yields (<300 kg ha^{-1}) are in most of Bumbuli, parts of Soni and northern Mlalo. Bumbuli is a traditional coffee area with traditional coffee varieties N39 and KP423, and the farmers are encouraged to continue with coffee despite the low yield potential shown in this work. On the other hand, the high potential areas of Lushoto and Mlalo have very little coffee if any, and there is enormous potential for coffee establishment despite the likely competition with the temperate fruit trees for which Lushoto District is so famous. Mtae is an upcoming coffee area with few farmers who are using the new improved coffee varieties. It is easier for farmers to adopt new varieties because doing so does not require uprooting any existing coffee trees.

Figure 4.5: Baseline yield estimated with SAFERNAC, Lushoto District

The high level of variation in coffee production potential within districts, as illustrated in Figs. 4.4 and 4.5, leads to a strong recommendation to the Tanzania Coffee Board (TCB) which is entitled to annual coffee crop estimation, to collaborate with TaCRI and devise ways to factor in SAFERNAC and soil data, thereby making their estimates more realistic.

4.4.7 Evaluation of ISFM practices

Evaluation results for farmer practices are given in Table 4.4. The slope represents the rate of change in yield from ISFM interventions with the baseline yield; the latter taken as an indicator of soil fertility. These results are comparable to those of Reid *et al.* (2002) when testing PARJIB model with maize in New Zealand.

Table 4.4: Summary of scatter-plot equations comparing ISFM interventions (manure, fertilizer and combination of the two) against baseline yields, both calculated with SAFERNAC

District	**Hai**			**Lushoto**		
Parameter	**Y-int**	**Slope**	**R^2**	**Y-int**	**Slope**	**R^2**
Manure alone	438	0.88	0.76	426	0.60	0.44
Fertilizer	1200	0.68	0.31	988	0.35	0.05
Combination	1500	0.66	0.22	1240	0.25	0.02

From the results it is noted that the effect of human intervention (with manure, fertilizer or both) tends to be felt more where baseline yield is low (the increasing Y-intercept), and diminishes progressively as baseline yield increases (the decreasing slope). In other words, response to fertilizer input is greater in soils of low fertility and vice-versa, and that the uptake of a nutrient is high in its dilution and low in its accumulation. The noted variable R^2 values are an indication that the soils, even within districts, differ in soil fertility and therefore response to ISFM interventions.

4.4.8 Description of SAFERNAC in relation to major model categories

A model is a simplified representation of a system. A system is a limited part of reality that contains interrelated elements. The totality of relations within the system is the “system structure”. Simulation is the building of mathematical models and the study of their behaviour in reference to those of the systems (Miglieta and Bindi, 1993). Models may be categorized as descriptive or explanatory, empirical or mechanistic, static or dynamic depending on whether a component of time is included, deterministic or stochastic depending on the level of probability allowed; simulating and optimizing depending on intended use (Miglieta and Bindi, 1993; Cheeroo-Nayamuth, 1999). SAFERNAC can be considered partly as a mechanistic model and partly as an empirical model. It is explanatory, but since it does not simulate changes in time it is not a dynamic model.

The major part of the model which is described in this paper (Steps 1-4), deals with simulation of (nutrient-limited) coffee yields, but as balanced nutrition and economically optimum applications of N, P and K are incorporated (Steps 5 and 6), SAFERNAC has optimizing properties as well. Like QUEFTS, it is meant as a useful tool in quantitative land evaluation and in decisions regarding integrated soil fertility management (ISFM). The yield predicted by SAFERNAC in its baseline module (with no nutrient inputs) can be used as an integrative indicator of soil fertility, which is one of the land qualities used in land evaluation. The principle of balanced NPK nutrition can be applied to arrive at target yields in the most profitable and environmentally friendly way.

4.4.9 Nutrient limited, water limited and potential yields of coffee

In many crop growth models, it is a usual practice to distinguish between potential, water limited, nutrient limited and actual yields (Van Ranst *et al.*, 2002; Van Ittersum and Rabbinge, 1997). SAFERNAC and QUEFTS simulate nutrient-limited yields, with the assumption that soil nutrient supplies in the agro-ecological zones that grow coffee in Tanzania would limit crop growth more severely than water availability (the determinant of water-limited yields –WPP), and certainly more than irradiance or temperature (which, together with the crop characteristics, govern the potential yield – RPP). It may be necessary in the future to include an agro-meteorological component (like the one suggested by Camargo *et al.* (2008) as climate change becomes more and more important for coffee in the country.

So far SAFERNAC has been developed for a mono-crop of non-shaded coffee. This means that it is more useful in coffee estates (most of which prefer non-shaded coffee) than in smallholder farms. In shaded systems however, irradiance needs to be considered because it is known to be a growth-limiting factor. Integration of various levels of shade (and various intercropping regimes) could enrich the PLANT parameter in SAFERNAC. Once this is achieved, the model will expand its usability to smallholder coffee producers. Another option would be to incorporate (parts of) SAFERNAC into a general coffee growth simulation model in the similar way that QUEFTS was incorporated in TechnoGIN (Ponsioen *et al.*, 2006).

4.5 Conclusions

A new model called SAFERNAC has been developed for yield estimation and fertilizer recommendation in coffee. It can follow two separate approaches, a baseline and an ISFM approach. It uses some chemical soil characteristics (soil organic carbon and/or soil organic nitrogen, available P, exchangeable K and pH_{water}), nutrient inputs (organic and inorganic), and maximum yields per tree and per ha for predicting the parchment coffee yield. When the model is run from soil fertility alone without intervention, it acts as a coffee land evaluation tool. When it is used to guide some crop management decisions such as intensification of coffee production, both natural soil fertility and input of nutrients in the form of chemical fertilizers, organic nutrient sources or a combination of the two, play a role. Additional required model inputs are the quantity and quality of added nutrient sources and tree density. It is also possible to assess the required nutrient additions for a certain target coffee yield with the model, given tree density and the mentioned soil data. The model then becomes an ISFM decision support tool for coffee. SAFERNAC can be used in coffee yield prediction in different coffee producing areas of the world, as long as they meet the assumptions and pre-requisites set therein.

The model was checked using yields of on-station trials of TaCRI and the data for SOC, SON, $P_{\text{Bray 1}}$, exchangeable K, pH_{water}, tree density and applied fertilizer NPK whereby it was able to reproduce the trial yields by 80-100%. Model usability for coffee land evaluation and ISFM intervention was tested with soils of Hai and Lushoto Districts, Northern Tanzania, and proved to be a useful tool in both avenues. The next step will be to pre-test the model among selected smallholder coffee farmers and estates.

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CHAPTER FIVE

5.0 EXPLORING THE NUTRIENT RELEASE POTENTIAL OF ORGANIC MATERIALS AS INTEGRATED SOIL FERTILITY MANAGEMENT COMPONENTS USING SAFERNAC

5.1 Abstract

The aim of this study was to establish the nutrient release potential of different organic materials and assess their role in integrated soil fertility management for coffee using the new coffee yield model SAFERNAC. It involved an incubation experiment conducted at TaCRI Lyamungu Screenhouse for 180 days between April and September 2011. Cattle manure, coffee leaves, pulp and husks, *Albizzia* leaves and four green manure plants – *Mucuna pruriens*, *Lupinus albus*, *Canavalia ensiformis* and *Crotalaria ochroleuca* were mixed with two soil types – Haplic Nitisols from Lyamungu, Hai District and Cutanic Acrisols from Yoghoi, Lushoto District. The mixing ratio was 5% organic to soil; the mixture was moistened to FC and incubated in 10 litre plastic containers arranged in RCBD (10 treatments and 3 replications) at room temperature. Duplicate soil samples were taken at day 0, 3, 8, 15, 26, 45, 74, 112 and 180 and analyzed for NH_4^+-N, NO_3-N, available P and exchangeable K. The cumulative N_{min}, P and K values resulting from the treatments were used to estimate their relative contribution to the soil nutrient pool, and later used in the new model SAFERNAC for yield estimation under different nutrient management options (1 to 10 tons organics per ha alone on one hand, and supplemented with 160 kg N, 60 kg P and 160 kg K on the other hand). The tested organic materials differed significantly ($P<0.001$) in their $N_{min,}$ P and K release in the two soil types. They also differed in their substitution values and therefore the amounts of nutrients each one can contribute to the soil nutrient pools. Green manures showed about ten times higher potential as compared to cattle manure. Four of them (*Crotalaria*, *Mucuna*, *Canavalia* and *Lupine*) were picked as best bets for inclusion in the coffee ISFM programme. SAFERNAC recommended a number of nutrient management options involving the test organic materials and the two soil types under organic and conventional coffee farming.

Keywords: Arabica coffee, Nutrient release, Organic materials, SAFERNAC,

5.2 Introduction

Tanzania's annual coffee production is variably pegged between 45 000 and 55 000 metric tons (Baffes, 2003) which is lower than its potential of over 100 000 tons. The Northern Zone (Arusha, Kilimanjaro, Manyara and Tanga) has been experiencing a decline in annual coffee production over years (Maro *et al.*, 2010). Kilimanjaro, once a giant coffee producer, appears to have suffered most, with annual production decreasing from about 20 000 tons in 1981/82 to less than 5000 tons by 2005/06 (TCB, 2012). Several constraints have been pointed out as the cause of this decline. In the past, farmers complained of improper marketing and low prices (Baffes, 2003; Envirocare, 2004); and production costs, especially fungicides for CBD and rust control (Teri *et al.*, 2004). These have been addressed through quality improvement by putting emphasis on central pulpers, new disease-resistant varieties and IPM (Kilambo *et al.*, 2004; Magina, 2011). Currently, as reflected during the coffee stakeholders' forum (TCB, 2009), soil fertility degradation has emerged as one of the most limiting factors.

In a bid to address the farmers' concern, Tanzania Coffee Research Institute (TaCRI) puts emphasis on integrated soil fertility management (ISFM), which includes use of organic materials in the coffee ecosystems, for improved and sustainable productivity. This is clearly stated in its Strategic Action Plans, 2003-2008 (Carr *et al.*, 2003) and 2008-2013 (Smith and Ndunguru, 2007). From a practical agricultural standpoint, organic matter is important for two main reasons: first as a nutrient reserve (by itself releasing nutrients and by improving CEC); and second, as an agent to improve soil structure, maintain tilth, and minimize erosion (Brady and Weil, 2002). ISFM is described (Gumbo, 2006; Raab, 2002) as the key in raising productivity levels in agricultural systems while maintaining the natural resource base. It aims at replenishing soil nutrient pools, maximizing on-farm recycling of nutrients, reducing nutrient losses to the environment and improving the use efficiency of external inputs.

A number of efforts have been made in other countries to develop coffee ISFM by making use of organic residues around the coffee farms. In India for instance, Korikonthimath and Hosmani (1998) established the amount of various nutrients in coffee and its processing by-products (pulp and husks) in a bid to plough back some of the by-products in coffee monocrop and coffee-cardamom systems. Coffee pulp was rated higher than FYM in terms of nutritive value, having 2.38, 0.53 and 4.21% of N, P and K respectively, compared to respective figures in FYM of 0.3-0.4, 0.1-0.2 and 0.1-0.3%. In Zimbabwe, Chemura *et al.* (2008) experimented on composted coffee pulp, husks, flocculent, pruned materials and live mulch, in various combinations. It was noted that composted pulp alone or in combination with husks, flocculent and pruned material gave higher coffee yields and financial returns when applied together with fertilizer levels (NPK 20:10:20) lower than the recommended rates.

In Tanzania, however, there has not been a clear ISFM strategy in the coffee growing areas (Semoka *et al.*, 2005). The contribution of organic components of the coffee ecosystem has not been thoroughly studied. As a result, farmers apply such materials haphazardly, while others even destroy them by burning (Maro and Mbogoni, 2009). This underscores the need for a thorough study, to establish the amounts and types of nutrient these organic materials release, to develop proper preparation and application packages, and optimum combinations of organic and inorganic sources for use in coffee, which will be socially, economically and environmentally acceptable.

A study was therefore undertaken to investigate the nutrient release potential of selected types of organic materials available in a coffee farming system applied to two contrasting coffee soils of Hai and Lushoto Districts, Northern Tanzania, and to demonstrate how the new model SAFERNAC can be used in devising and implementing appropriate coffee ISFM programmes. The focus was the release of primary macronutrients nitrogen, phosphorus and potassium.

5.3 Materials and Methods

5.3.1 The experimental materials

Soils were obtained from Lyamungu, Hai District (Field 46), representing Haplic Nitisols of volcanic origin, and Yoghoi Prisons Farm, Lushoto District, representing Cutanic Acrisols of gneiss origin. In each site, a pit 1.5m x 1.5m was dug to 50 cm depth and the experimental sample taken as a vertical slice representing the 50-cm profile. Enough soil was transported to the Lyamungu Screen-house, spread on canvas to dry for 2 days with all non-soil materials removed, then stored for the experiment. Fresh cow dung was dried in a well-ventilated drying oven at 40^{o}C for 48 hours, then ground, sieved through 6 mm mesh and stored (Anderson and Ingram, 1993). Coffee leaves obtained from coffee prunings and separated from branches were spread to dry in the open. Fresh coffee pulp was hung overnight for water to drain, spread for 4 days in the open to reduce moisture, then oven-dried at 70^{o}C for 48 hours (Temminghoff and Houba, 2004). Husks (a mixture of pulp and husks from hard Arabica hulling) were collected from an open heap and spread to dry for one day. Dry *Albizzia* leaves were shaken off branches of the recently uprooted *Albizzia maranguensis* trees and spread to dry for five days in the open. Dry materials (coffee and Albizzia leaves, pulp and husks) were ground in a tissue grinder and sieved through 6 mm mesh. The green manure plants – Velvet bean (*Mucuna pruriens*), Lupine (*Lupinus albus*), Jackbean (*Canavalia ensiformis*) and Sunhemp (*Crotalaria ochroleuca*) had been grown in augmentation blocks (Plate 5.1 – left). They were harvested 3 months after planting (onset of blossoming) chopped and spread in the open to dry for about 1 week, then ground in a tissue grinder and sieved through 6 mm mesh (Plate 5.1 – right).

Plate 5.1: The bulking up plot showing Crotalaria and Canavalia (left), processed test organic materials (right)

Before the experiment, the two test soils were analyzed for routine soil fertility parameters based on the procedures outlined by Van Ranst *et al.* (1999) and NSS (1990). Organic substrates were analyzed for total and mineralizable N, P and K by following procedures of Temminghoff and Houba (2004).

5.3.2 Setting and monitoring of the experiment

The test materials were mixed with the soils at 5% organics to soil ratio to reflect, as much as possible, the average organic matter content of mineral soil, moistened to field capacity (FC) and incubated in 10 litre plastic containers arranged in RCBD (10 treatments and 3 replications) as shown below (Plate 5.2) in the screen-house at room temperature ($24^{o}C \pm 2$) (Khalil *et al.*, 2005). Moisture level was maintained around FC by covering with poly-sheet during the day and uncovering at night (Gunapala *et al.*, 1998); together with spraying twice a week with a hand sprayer.

Plate 5.2: The set-up of experiment for Yoghoi (left) and Lyamungu (right)

5.3.3 Sampling and analysis

Duplicate soil samples were taken with a soil scoop at day 0, 3, 8, 15, 26, 45, 74, 112 and 180. Fresh soils were used for the determination of mineral nitrogen as outlined by Van Ranst *et al.* (1999); Verloo and Demeyer (1997). Twenty grams of moist soils in 200 mL of 2M KCl solution were shaken for 40 minutes and filtered through Whatman filter paper no 42. NH_4^+-N and NO_3-N from soil extracts (filtrates) were measured by steam distillation procedure using MgO and Devarda's alloy. Available phosphorus and exchangeable potassium were determined by using the same samples, but after the routine drying, grinding and sieving. The former was analyzed by using the Bray 1 method, and the latter was first extracted with NH_4OAc at pH 7, and quantified by flame AAS (Anderson and Ingram, 1993; NSS, 1990).

Nutrient release patterns were descriptively assessed. N_{min} (NH_4-N + NO_3-N), P and K were calculated and values for Day 0 were subtracted from the totals to get the nutrients released only during the time of the experiment. The values for the untreated control were also subtracted to remain with the nutrients released from the treatments. These were exposed to ANOVA and means separation (Tukey's HSD) under COSTAT Software.

5.3.4 Application of the SAFERNAC model

The mineralization model developed by Yang (1996) was adopted for describing the substitution values of various organics. The basic equations are:

$$Y_t = Y_0 * e^{-K * t} \quad \ldots\ldots 1$$

$$K_9 = R_9 * f * t^{-S} \quad \ldots\ldots 2$$

Hence,

$$Y_t = Y_0 * \exp(-R_9 * (f * t)^{1-S}) \quad \ldots\ldots 3$$

Where:

Y_t = quantity (mass) of organic matter at time t, *e.g.* in kg per ha

Y_0 = quantity (mass) of organic matter at time 0, *e.g.* in kg per ha

K_9 = average relative decomposition rate (between t = 0 and t), expressed in $year^{-1}$, after application of the organic material, at an average annual temperature of 9 ^oC

R_9 = average relative decomposition rate, expressed in $year^{S-1}$, during the first year after application (so between t = 0 and 1) at an average annual temperature of 9 ^oC

S = 'rate of aging', dimensionless; values between 0 and 1.

f = temperature correction factor, between 9 and 27 ^oC, f = $2^{(T-9)/9}$ and at 22- 27 ^oC, f is set at 3.

From Eq. 2 it follows that K decreases over time. Values of parameters R_9 and S are presented in Appendix 5.1. Using the R9 and S parameters where f = 3, the remaining fractions (Y_t/Y_0), calculated with Eq. 3 are given in Appendix 5.2. After half a year, which is about 180 days, Y_t/Y_0 of cattle manure is 0.44, while those for green manure and compost are 0.25 and 0.69. So, the fraction mineralized of the organic forms of nutrients (FMO) is $1-(Y_t/Y_0) = 0.56$, 0.75 and 0.31, respectively. Then SV is calculated according to Equation 4.

$$SV_e = FMO * F_o + F_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 4$$

For cattle manure, F_o for N and P were set at 0.9 and 0.3 according to Sluysmans and Kollenbrander (1977); Gerritse and Zugec (1977), and the SVs were set at 0.6 for N and 0.87 for P. The F_o suggested here have been assumed to apply to all organics, in the apparent absence of better alternatives.

It had been noted earlier that the input available nutrients from organic sources are exposed to substitution values also called Relative Effectiveness RE (Velthof *et al.*, 1998) related to their rate of mineralization. From Appendix 5.3, it is clear that green manures excelled in the rate of decomposition and therefore nutrient release, followed by manure and compost. The study materials were therefore subdivided into the three categories: *Albizzia, Mucuna, Lupine, Canavalia* and *Crotalaria* as green manures, coffee leaves, pulp and husks as composts, and cattle manure in its own category as in Appendix 5.3.

The other organics were compared to cattle manure (which is common in the study areas and whose substitution value and recovery fraction are known (Yang and Janssen, 2000), in order to know the quantities of the other organic materials needed to match with a standard amount of cattle manure. These were entered as input into SAFERNAC whereby total N, available P, exchangeable K, OC and pH had been adjusted to the local condition where the bulk soils were collected. With the tree density maintained at 1330 per ha, two scenarios were assessed where only the organics were applied at 1, 5 and 10 tons per ha each, and same treatments plus a blanket application of inorganic fertilizer (160 kg N, 60 kg P and 160 kg K).

5.4 Results and Discussion

5.4.1 Properties of the test soils and organic materials

The properties of the test soils are given in Table 5.1. There is no significant difference in soil pH between the two soils. Both are below the low threshold of 5.2 for Arabica coffee. All other parameters showed significant differences, with CEC and OC for Lyamungu about twice that for Yoghoi, while total N was about 3 times and K about 10 times. The high clay content and low CEC at Yoghoi suggests the presence of low-activity clays, whereas the CEC for Lyamungu could have been improved by both high-activity clay and organic matter. The only parameter whereby Yoghoi was slightly better than Lyamungu is N_{min}.

Initial N_{min}, P and K for the organics before treatment indicated that *Canavalia* had highest N_{min}, followed by *Mucuna* and manure, while the rest were not significantly different. Lupine was highest in initial P, while *Albizzia* was lowest, with virtually no P. As for K, pulp was highest, followed by *Crotalaria* and *Mucuna*.

Table 5.1: Pre-treatment soil data for Lyamungu and Yoghoi (0-50 cm depth)

Parameter	Units	Lyamungu	Rating*	Yoghoi	Rating*
Sand	%	72.4	High	50.4	Medium
Silt	%	20.8	High	8.8	Low
Clay	%	6.8	Low	40.8	High
Texture	class	SL	Low	C	High
pH		4.76	Low	4.94	Low
CEC	$cmol_c\ kg^{-1}$	16	Medium	8.5	Low
OC	%	1.58	Medium	0.76	Low
Total N	%	0.06	Low	0.02	Low
Nmin	$mg\ kg^{-1}$	18.14	Medium	20.41	Medium
P	$mg\ kg^{-1}$	0.62	Low	trace	V. low
K	$cmol_c\ kg^{-1}$	1.2	Medium	0.1	Low

* Ratings by Sys *et al.* (1993)

5.4.2 Trends of N, P and K release

Peak NH_4^+-N release was attained between Day 8 and Day 45 for both Yoghoi and Lyamungu, accounting for 62-89% and 58-90% respectively of the total NH_4^+-N released. With NO_3-N, the two soil types differed in the time of peak release. Lyamungu attained peak release between Day 15 and Day 74, which accounted for 41-92%, while Yoghoi attained peak realease between Day 26 and Day 102, accounting for 34-87%. A stagger was observed in peak release time between NH_4^+-N and NO_3-N, which can be explained from the nitrogen cycle (Brady and Weil, 2002; Pidwirny, 2006). Nitrogen mineralization from organic materials starts with NH_4^+-N formation and a further transformation is needed through NO_2-N to NO_3-N, hence the delay in NO_3-N accumulation. Similar trends were observed by Vimlesh and Giri (2009) in their study on domestic sludge.

Peak P release was attained at Day 3 for Yoghoi and between Day 3 and 8 for Lyamungu. Initial P content differed more markedly among treatments at Yoghoi than at Lyamungu. The trend for cattle manure was the smoothest in both sites. These results are in conformity to those of Kaloi *et al.* (2011) who noted a progressive decrease in P release with increasing incubation time. They are also in conformity with the principle of Jalali and Zinli (2011) who described the kinetics of P release as an initial rapid rate followed by a progressively slower rate. Other authors who had similar trends are Horta and Torrent (2007) and Nafiu (2009).

In both soils, K appeared to be present in appreciable levels initially (Day 0), experiencing a readjustment which included sharp decease or increase, to Day 3; before steadying off throughout the remaining period. Crotalaria, Canavalia and Lupine had highest initial levels at Yoghoi, while manure gave highest level at Lyamungu. Not much seems to have been documented on the release of K from organic matter, though it is known (Kaur and Benipal, 2006; PDA, 2006) that K is required by most crops in equal or slightly higher amounts than N. Ako *et al.* (2003) observed similar trend but in a slightly different experiment (artificial extraction of K from plant residues). It seems as if the change between Day 1 and 3, common to both soils, is related more to the process of soil stabilization than K release per se. It also seems as if the K levels recorded over the study period were from both the soil and the substrates irrespective of the latter’s state of decomposition.

5.4.3 Cumulative release of N, P and K

Cumulative N_{min} (NH_4- and NO_3- N) over the entire incubation period showed clear distinction between high-releasing materials (in the order *Crotalaria* > *Albizzia* > *Canavalia* > *Mucuna* > *Lupine* for Yoghoi, and *Mucuna* > *Crotalaria* > *Canavalia* > *Lupine* > *Albizzia* for Lyamungu) and the rest of the organics. Results are summarized in Fig. 5.1 (a) and (b).

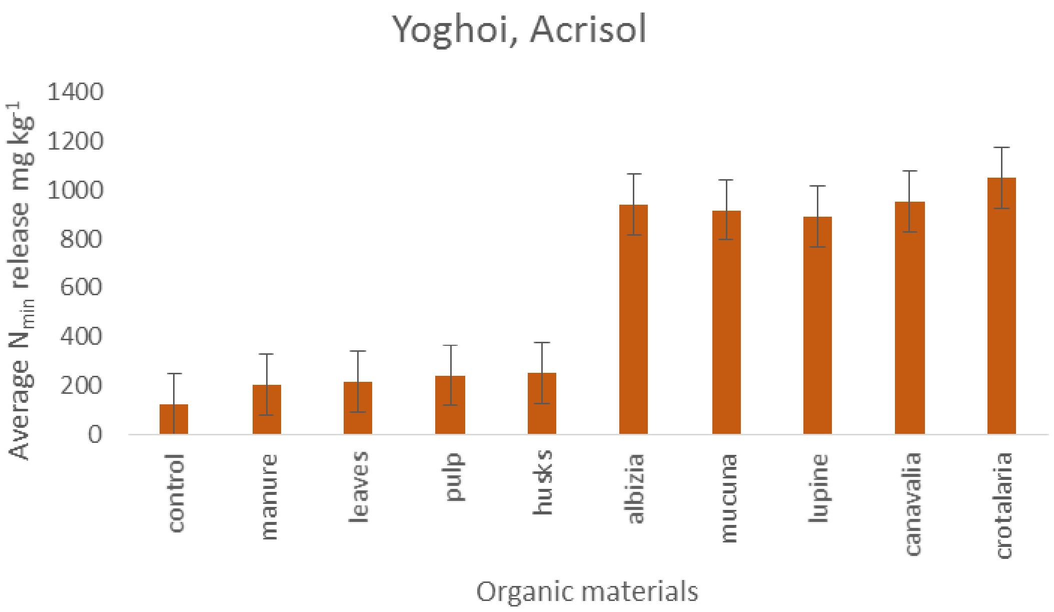

Figure 5.1(a): Cumulative N_{min} released, Yoghoi Acrisol

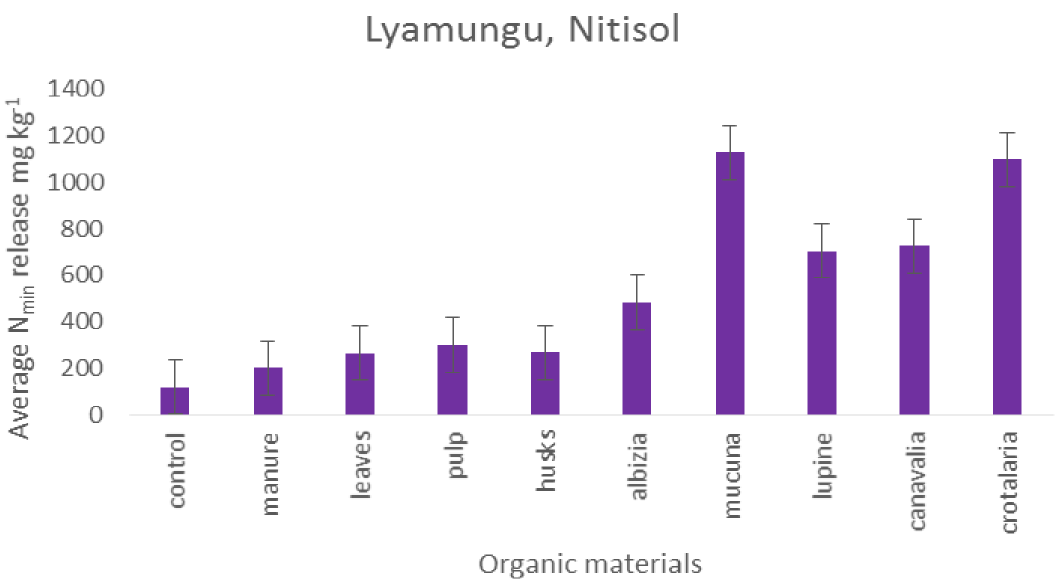

Figure 5.1(b): Cumulative N_{min} released, Lyamungu Nitisol

The N_{min} release from the tested organic materials showed highly significant variations ($P<0.001$) among the organic materials and between the two soil types. These results are in agreement with those of Kwabiah *et al.* (2001) in their work on leaf decomposition. The model was also highly significant ($p< 0.001$) with R^2 of 0.9976, RMSE of 21.3794 and CV of 4.6%.

From Tukey's HSD, the four green manure plants emerged top of the list, in the order *Crotalaria* >*Mucuna*>*Canavalia*>*Lupine*. *Albizzia* leaves came next in the list, performing better with the Acrisols than the Nitisols. There was a clear distinction between these and the last four organic materials (Pulp> Husks> Leaves > Manure), whereby *Albizzia*, the last in the upper list, was about 5 times coffee pulp, the first in the lower list. The Acrisols of Yoghoi gave average N_{min} of 488.56 mg kg^{-1}, which was higher than the average N_{min} of 440.29 mg kg^{-1} from the Nitisols of Lyamungu.

Cumulative available P behaved quite differently between the sites of Yoghoi and Lyamungu. Mean released P for Yoghoi was approximately 70 mg kg^{-1} (manure), followed by 40 mg kg^{-1} (coffee leaves) and 20-30 mg kg^{-1} (*Crotalaria, Canavalia, Mucuna* and *Albizzia*). Lyamungu soil released mean available P around 152, 148, 110 and 85 mg kg^{-1} for *Lupine, Canavalia, Albizzia, Crotalaria* and *Mucuna* respectively. The green manure plants have proved to be a slightly more dependable source of P in the soils of Lyamungu than in the Yoghoi soil. Results are summarized in Fig.5.2 (a) and (b).

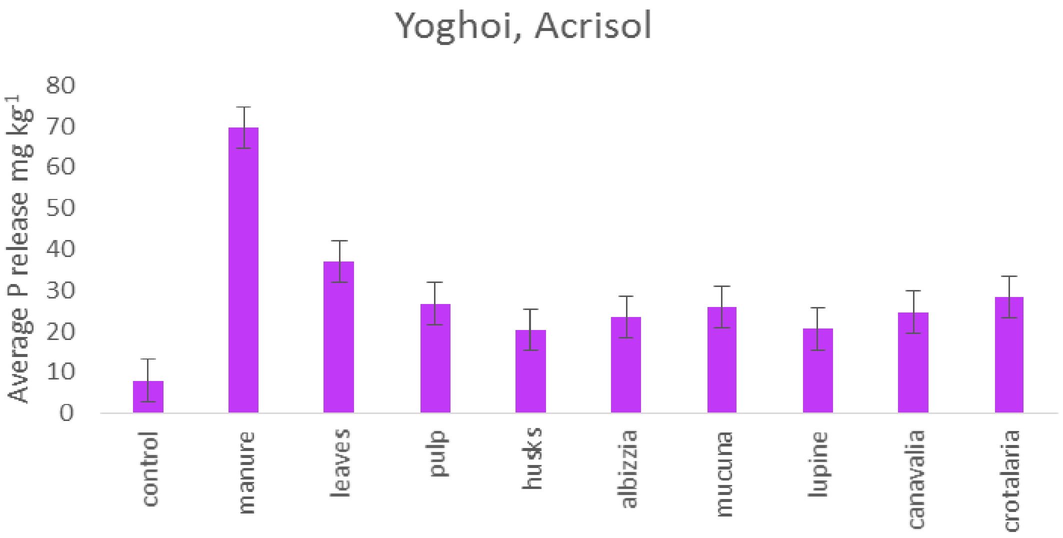

Figure 5.2(a): Cumulative available P released, Yoghoi

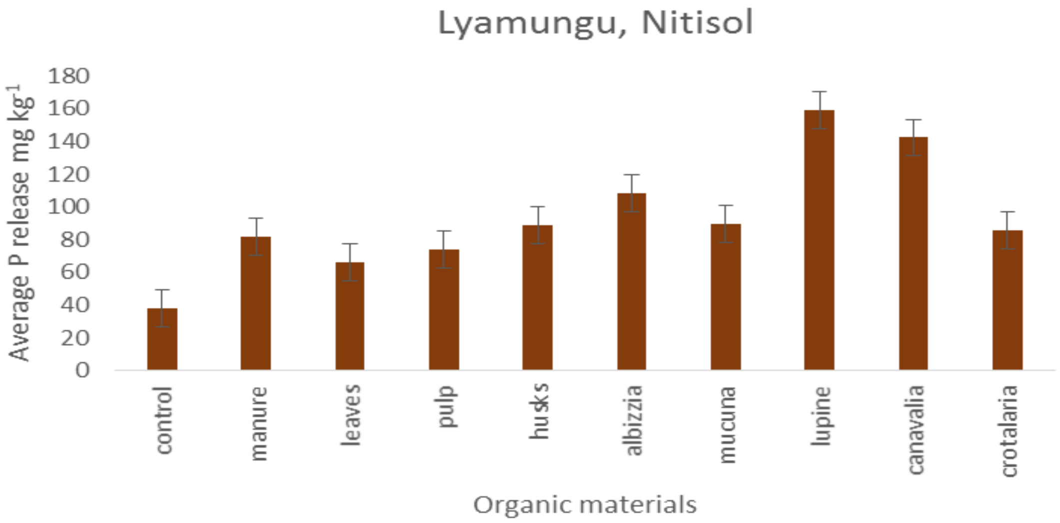

Figure 5.2(b): Cumulative available P released, Lyamungu

The P statistics distinguished two significantly different groups of organics ($p<0.05$), with the upper group in the order *Lupine*>*Canavalia*> Manure (averages of 58.5, 49.99 and 47.75 ppm respectively). The rest of the organics, ranging between 23 and 33 mg kg^{-1}, were in the order *Albizzia*>*Mucuna*> Husks >*Crotalaria*> Pulp > Leaves.

Average P release for Lyamungu Nitisols was 46.83 mg kg^{-1}, while that for Yoghoi was much lower (16.58 mg kg^{-1}). Cumulative total K release followed the same trend for Yoghoi and Lyamungu (Fig. 5.3). Highest mean release of 22 cmol$_c$ kg^{-1} was noted in *Canavalia* and manure, respectively. In both cases, coffee pulp was lowest in the list.

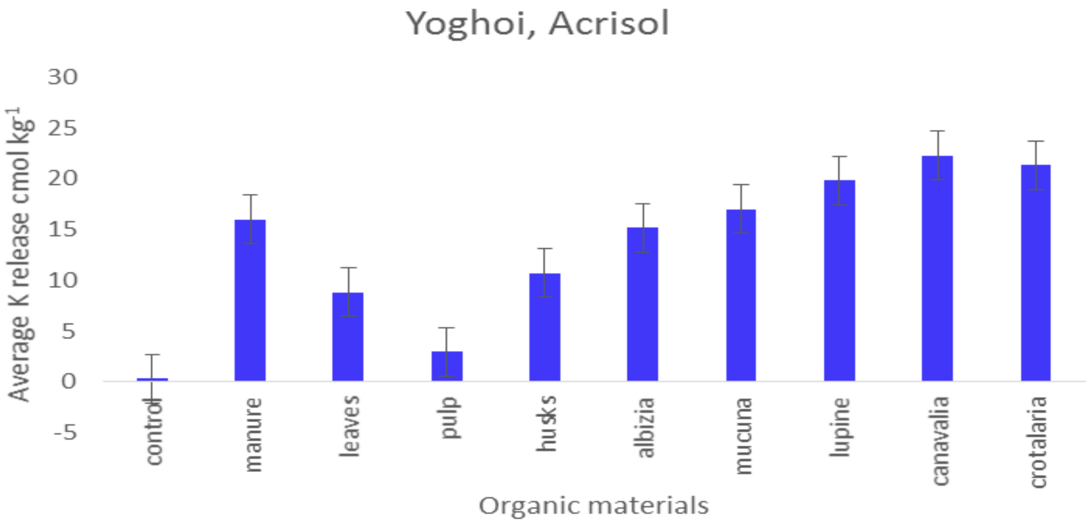

Figure 5.3(a): Cumulative exchangeable K released,Yoghoi

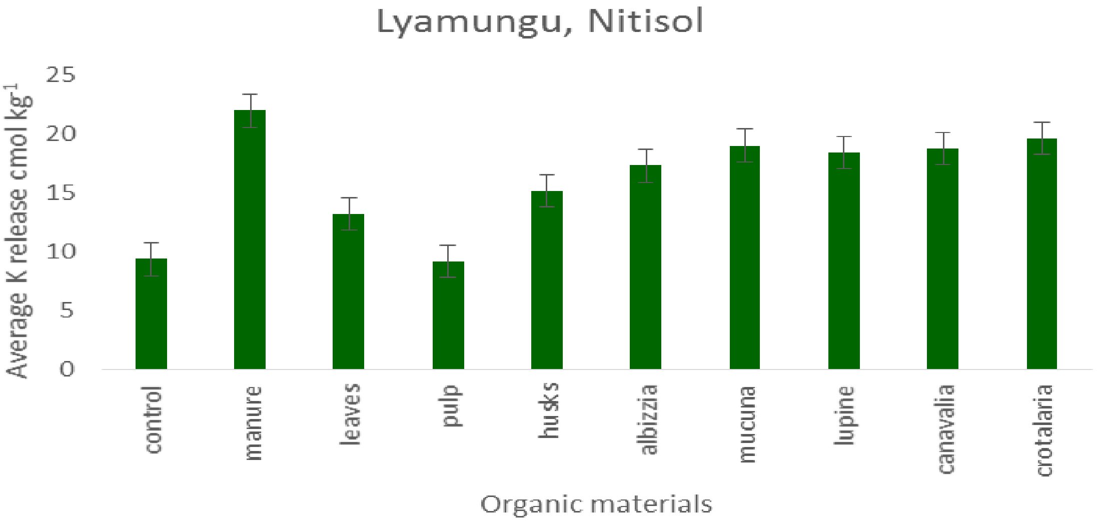

Figure 5.3(b): Cumulative exchangeable K released, Lyamungu

The K statistics showed the first five organics in the order *Canavalia* >*Crotalaria*>*Lupine*> Manure >*Mucuna* (averages of 12.86, 12.53, 11.59, 11.43 and 11.39 cmol$_c$ kg^{-1} respectively). The rest of the organics, ranging between 1.5 and 10 cmol$_c$ kg^{-1}, were in the order *Albizzia*> Husks > Leaves > Pulp. Average K release for Yoghoi was 10.97 cmol$_c$ kg^{-1}; while that for Lyamungu was much lower (5.86 cmol$_c$ kg^{-1}).

5.4.4 Results of SAFERNAC model application

The results of comparing cattle manure with other organics are shown in Table 5.2, which implies that leaves, pulp and husks can release 1.92, 2.51 and 1.98 times as much N_{min} as cattle manure, respectively with the Lyamungu Nitisol, and 1.22, 1.62 and 1.59 times with the Yoghoi Acrisol. As for P and K, the three organics can release 0.69-1.06, 0.08-0.54 times as much as manure for Lyamungu and 0.29-0.53, 0.17-0.68 times for Yoghoi. Using the figures of kg N, P and K per ton dry matter for cattle manure (13, 6 and 14 kg), the comparative nutritive potential of the test organics and the two soil types are shown in Appendix 5.4.

Table 5.2: Comparison of other organics against manure, in terms of nutrient (N, P and K) release (R_o:R_m) in 180 days

ORGANICS	LYAMUNGU NITISOL			YOGHOI ACRISOL		
	N_{min}	P	K	N_{min}	P	K
Manure	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Leaves	1.92	0.69	0.44	1.22	0.52	0.54
Pulp	2.51	0.81	0.08	1.62	0.53	0.17
Husks	1.98	1.06	0.54	1.59	0.29	0.68
Albizzia	4.93	1.32	0.74	11.44	0.39	0.96
Mucuna	14.29	1.07	0.85	11.17	0.64	1.09
Lupine	8.33	2.67	0.88	10.73	0.53	1.10
Canavalia	8.61	2.13	0.96	11.63	0.58	1.23
Crotalaria	13.63	0.82	0.94	12.77	0.68	1.20

The yield estimated with SAFERNAC are given in Fig. 5.4a and b.

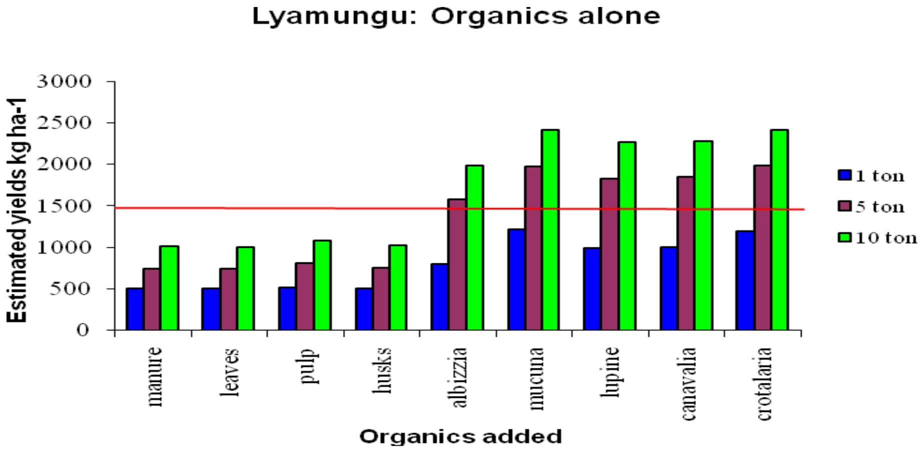

Figure 5.4a: SAFERNAC estimated yields at Lyamungu, without added inorganic fertilizer

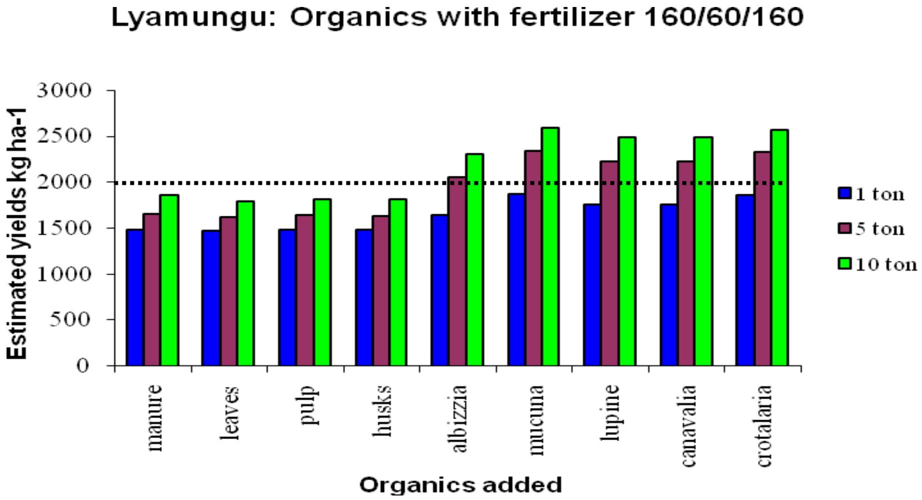

Figure 5.4b: SAFERNAC estimated yields at Lyamungu, with added inorganic fertilizer

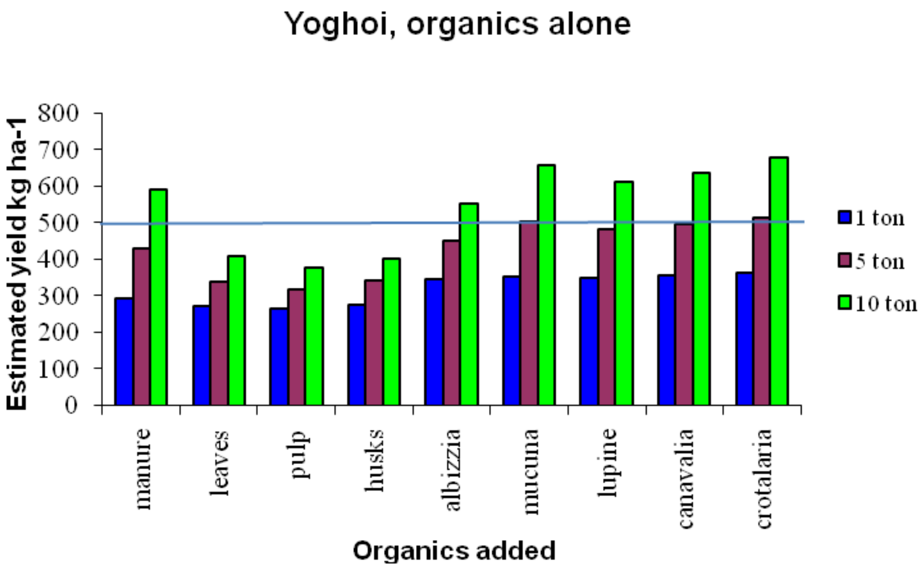

Figure 5.4c: SAFERNAC estimated yields at Yoghoi, without added inorganic fertilizer

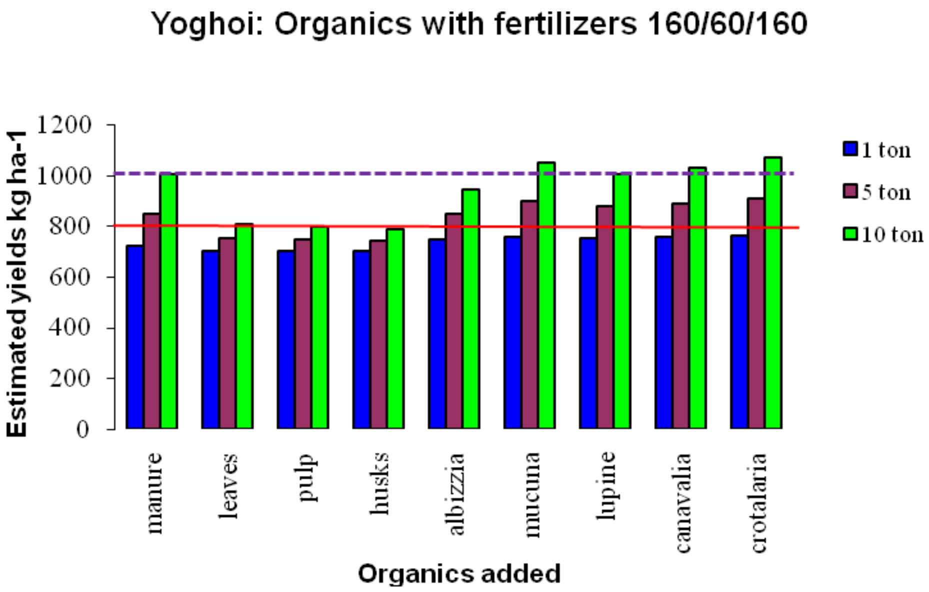

Figure 5.4d: SAFERNAC estimated yields at Yoghoi, with added inorganic fertilizer

Figure 5.4a (Lyamungu) indicates that with organics alone, there is no big difference in yield between manure, leaves, pulp and husks, whether at 1 ton, 5 tons or 10 tons, though there is a linear increase as the application rate increases. This implies some benefit in increasing the rate, at least up to 10 tons. With *Albizzia, Mucuna, Lupine, Canavalia* and *Crotalaria,* there is a more marked yield difference as rate is increased from 1 to 5 tons than from 5 to 10 tons. This suggests an optimum application of 5 tons organics per ha. With a combination of organic and inorganic nutrient sources (Fig. 5.4b), a leap in yield with manure, leaves, pulp and husks is noted, which also narrows the difference between 1, 5 and 10 tons organic per ha throughout the treatments. Since raising enough organics for supplying 10 ton dry matter per ha may be rather tedious, the ISFM or combined approach is recommended, in which case the rate of organics to apply can go as low as 1 ton per ha.

Figure 5.4c (Yoghoi) shows that the estimated yields are much lower than those for Lyamungu. Even with the addition of 10 tons of organics alone, the maximum estimated yield was around 700 kg ha^{-1}. With fertilizers, the maximum yield was raised to slightly over 1 ton ha^{-1}. This implies that coffee investment in Yoghoi requires a substantial effort in ISFM. With organics alone, manure competed well with the high nutrient releasing green manure plants at 1, 5 and 10 ton ha^{-1}, while the coffee by-products were relatively lower. The same trend was seen with the addition of inorganic fertilizers (160/60/160) (Fig. 5.4d), except that both the gaps between the coffee by-products and the rest of the organics on one hand, and between the rates of organics applied on the other, have been greatly narrowed.

From Fig. 5.4 a-d, organic farmers around Lyamungu can set target yield (horizontal cut-off point) at 1.5 tons ha^{-1} with the application of 5 tons ha^{-1} of *Albizzia, Mucuna, Lupine,* *Canavalia* or *Crotalaria*. The conventional farmers can set their target yield at 2 tons ha^{-1} with same applications and rates, combined with inorganic fertilizers. Organic farmers around Yoghoi are advised to set their target yield at 500 kg ha^{-1} and use either 10 tons manure or *Albizzia*; or alternatively 5 tons of *Mucuna, Lupine, Canavalia* or *Crotalaria*. The conventional ones can either pick a pessimistic or optimistic option. The former sets the target yield at 800 kg ha^{-1} with the application of 5 tons manure, *Albizzia*, *Mucuna*, *Lupine*, *Canavalia* or *Crotalaria* plus inorganic fertilizer. The latter option sets the target yield at 1 ton ha^{-1} with the application of 10 tons manure, *Mucuna, Lupine, Canavalia* or *Crotalaria* plus inorganic fertilizers.

5.4.5 Experience of selected organics in different crops

An appreciable amount of literature is available on *Mucuna*, *Canavalia* and *Crotalaria*; less so for *Lupine*. Most of the TSBF efforts in ISFM were based on the first three. *Mucuna* and *Canavalia* were evaluated by Okalebo *et al.* (2007) under maize and competed fairly well with other common organics *Leucaena, Tithonia* and *Calliandra*. In Uganda, a participatory demonstration plot on using different organics with maize (Tumuhairwe *et al.*, 2007) reported good farmers' ranking in the order *Canavalia*>*Crotalaria*>*Mucuna*. The choice of the four green manure plants in this work, for inclusion into the coffee ISFM programme (as an intercrop to be ploughed under at tender age), is therefore justified.

5.5 Conclusions

The nutrient release potential of nine types of organic materials available in a coffee farming system was studied in this work, as applied to two contrasting coffee soils of Northern Tanzania. It was noted that the Yoghoi Acrisols are slightly more efficient in N_{min} release than the Lyamungu Nitisols, but the reverse is true with P. There was no significant difference in K release potential in the two soil types. $N_{min,}$ P and K release varied significantly ($P<0.001$) among the organics and between the two soil types. SAFERNAC has demonstrated its potential in suggesting appropriate nutrient management options for both organic and conventional farmers, and has also confirmed the test results, that green manure plants have great potential in coffee ISFM. Four of them (*Crotalaria*, *Mucuna*, *Canavalia* and *Lupine*) were picked as best bets for inclusion in the coffee ISFM programme. The challenge remains the appropriate application techniques in coffee farms, which will be pursued in future research work.

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CHAPTER SIX

6.0 ECONOMIC OPTIMIZATION OF NUTRIENT APPLICATION TO COFFEE IN NORTHERN TANZANIA USING SAFERNAC

6.1 Abstract

The aim of this work, as an extension to SAFERNAC model, was to establish economically optimum combinations of N, P and K application to Arabica coffee in the Northern coffee zone of Tanzania. The study was conducted in Hai and Lushoto Districts between 2010 and 2012. Prices of nutrient inputs and those of parchment coffee were introduced into the original SAFERNAC model, which was used to obtain yields from a soil of known properties receiving different levels of input N, P and K from both organic and inorganic sources (ISFM). The costs of inputs were derived from experiences in Northern Tanzania, while coffee prices were estimated to range between 1250 and 2500 TZS kg^{-1}. The result was economically optimum N:P:K ratios that give highest net returns and value : cost ratios in situations of low, medium and high soil fertility. It was also shown that farmers' decision to deviate from the optimum, and the allowable level of such deviation, depend much upon the prices of nutrient inputs in equivalent terms. In the medium-fertility situation (which applies in the study districts), the highest yield increment was noted with the maximum amount of N and P. The optimum application rate was 310 kg N and 200 kg P per ha, where the profit margin (the gap between gross returns and costs) is highest. This is an indication that soil-available K is likely to suffice the needs of the crop for optimum productivity where N and P are balanced, but this is largely dependent on the K fluxes in different soil types. The optimum rates were tested with actual soil data in the two study districts, against 5 tons of farmyard manure and a combination of the two. At both the coffee prices of 1250 and 2500 TZS kg^{-1}, ISFM intervention (combination of organic and inorganic inputs) was more profitable than the other options, while coffee production showed to be more profitable in Hai than Lushoto.

Keywords: Coffee yield model, gross returns, nutrient equivalent, nutrient inputs, value cost ratio

6.2 Introduction

Coffee farming follows the principles of production as described economically by Rasmussen (2010); Beattie *et al.* (2009) and Ikerd (2001), among others. It is an entrepreneurship that involves decision making and risk taking. Application or otherwise of farm inputs, including organic and inorganic sources of plant nutrients is one such decision that a farmer has to make. The decisions are often based on previous experiences and on common sense. There are, however, scientifically sound techniques to assess the profit of nutrient applications. They require knowledge about the prices per kg coffee, fertilizer N, P and K, and the costs of other nutrient sources like animal manure and green manure. Also costs of application of the various nutrient sources and of crop husbandry measures related to the extra coffee yield must be estimated (Sadeghian, 2008). The difference between the gross financial value and the production costs of the harvested coffee represents the balance of crop production. The difference in net financial value between fertilized and non-fertilized crops represents the net return to the nutrient sources. The economic optimum is found where the net return is at maximum.

Chapter 4 described a quantitative approach to fertilizer advice and yield estimation for coffee in Northern Tanzania, and proposed a fertilizer-yield model called SAFERNAC, developed by calibrating QUEFTS for coffee. The basic structure of the model was described, where some chemical soil characteristics, nutrient inputs, and maximum yields per tree and per ha are model inputs and coffee yield is the model output. The current paper describes some additional steps to the model whereby the economics of ISFM are included.

6.3 Materials and Methods

6.3.1 Use of SAFERNAC model

The new model SAFERNAC (Soil Analysis for Fertility Evaluation and Recommendation for Nutrient Application to Coffee) was used in this work to obtain yields from a soil of known properties (baseline situation) receiving different levels of input N, P and K from both organic and inorganic sources (ISFM). The economic analysis required a price component for both input (organic and inorganic fertilizers) and output (parchment coffee sold at farm gate).

6.3.2 Estimating the costs of inputs and price of output

The costs of animal manure were estimated as follows: One truck of manure costs TZS 10 000, and contains 160 tins (estimates adopted from TaCRI). One tin corresponds to 2.5 kg dry matter. So one truck contains 400 kg dry matter. The costs of animal manure is 10 000/400 = 25 TZS per kg dry matter, or 25 000 TZS per ton dry matter. Because the substitution values of N and P in animal manure are set at 0.6 and 0.87 (Velthof *et al.*, 1998), the prices of available N and P in animal manure are roughly 70 and 115 TZS per kg. A survey of three farm input stockists in Moshi (Tanganyika Farmers Association, Rafiki Kilimo and Kibo Trading Company) was done for the period 2007/08-2010/11, and average prices for N and P sources were used for calculating the prices per kg element N, P and K. The price of K had to be calculated indirectly as no single K fertilizers were available at the time. As a result, the price of K was rather high compared to the price of N. The calculated prices of nutrients were much lower for animal manure than for chemical fertilizers (Appendix 6.1).

Table 6.1: Variations in Mild Arabica coffee prices over 10 years

Season	Price of parchment coffee in TZS kg^{-1}	Season	Price of parchment coffee in TZS kg^{-1}
1996/97	1418.70	2001/02	1453.15
1997/98	1677.35	2002/03	1671.12
1998/99	1936.00	2003/04	1800.00
1999/2000	1486.60	2004/05	2593.50
2000/01	1263.61	2005/06	3429.00

The price of coffee strongly fluctuates, as shown in the example given in Table 6.1. In this work, the minimum price was set at 1250 TZS per kg of parchment coffee, close to the lowest figure of 1263.61 TZS recorded between 1996/97 and 2005/06 seasons (URT, 2008); and the maximum was set at twice that value, that is 2500 TZS per kg.

6.3.3 Calculation of economic optimum

The mathematical expressions of production adopted in this work follow the principles of Ching and Yanagida (1985) and Webb (2010). The relation between yield (Y) and the supply (S) of a nutrient is usually described by a non-linear equation, most often by a parabola:

$$Y = a + b*S - c * S^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

with ‘a’ representing the y-intercept, which is the baseline yield obtained without the application of the given nutrient. The yield increase (ΔY) brought about by the application of a given quantity of nutrient (X) is then described by:

$$\Delta Y = b*X - c * X^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

The gross financial value of the extra yield is found by multiplying ΔY with P_Y, the price per unit of Y. Similarly, the costs of the applied nutrient are the product of X and P_X, the price per unit of X. The extra expenditures farmers have to make for the production and handling of the extra produce imply that the value of the coffee for farmers is less than P_Y. Subtracting a factor HC_Y (handling costs of Y) from P_Y, the real value per unit of Y is indicated by V_Y. The extra costs of transport, storage and application of nutrients make the costs the farmer has to incur to apply the nutrients higher than $X * P_X$; so adding a factor HC_X, the real expenses per unit of X are indicated by E_X (Moro *et al.*, 2008).

The gross return (GR) to nutrient application and the cost of nutrients are described by:

$GR = (bX – cX^2) * V_Y$, ... 3

$TC = X * E_X$. ……………………………………………………………………… 4

The net return (NR) to nutrient application is the difference between GR and TC:

$NR = (b* V_Y - E_X)*X – c * V_Y * X^2$……………………………………………….. 5

Maximum net return is obtained when the first derivative of this equation for NR is zero, so when $dNR/dX = b* V_Y - E_X – 2c * V_Y * X = 0$, the corresponding optimum quantity of applied nutrient (X_{opt}) becomes

$X_{opt} = (b* V_Y - E_X)/ (2c * V_Y)$. …………………………………… 6

The above calculations of ΔY, NR and X_{opt} are also described in Flanders (2012), and are not too difficult when only one nutrient is applied. The equations may become complicated, when two or more nutrients are applied (Colwell, 1994). This is always the case with organic manures and compound fertilizers. These problems are avoided by the use of the concepts of nutrient uptake equivalents, nutrient availability equivalents and nutrient application equivalents (Janssen, 1998). As explained in Chapter 4, in a situation of balanced nutrition, nutrient uptake equivalents of N, P and K have equal effects on yield. It was also noted that the uptake of 1 kg N has the same effect on coffee yield as the uptake of 0.175 kg P or of 0.875 kg K.

A theoretical example was run for demonstration purposes, with prices set at 1250 TZS kg^{-1} of parchment coffee, and at 1000, 2500 and 2500 TZS kg^{-1} N, P and K, respectively. A zero baseline situation was assumed, and the yield data (which also represent ΔY), and the nutrient availability data referring to input nutrients, were calculated. For convenience, HC_Y and HC_X were not considered. Yields and net returns related to the availability equivalents which vary by 30 units were calculated and optimum input ratios established for NP and NPK.

For the calculation of the economically optimum application, soil properties shown in Table 6.2 were used to represent low, medium and high soil fertility. The regression lines of the response to the most limiting, the most and the next most limiting, and three most limiting nutrients were determined, and for each of them the optimum application rate was calculated. ΔY was plotted against total E_a to fit in Equation 2 within the 3 ranges, and the resulting regression coefficients used to fit in Equation 6 for the optimum rates.

Table 6.2: SAFERNAC parameters used to define low, medium and high fertility

Parameter	**SOC** g kg^{-1}	**SON** g kg^{-1}	**P Bray** mg kg^{-1}	**K exch** mmol kg^{-1}	**pH water**
low	10	1	2	6	4.6
medium	26	2.6	52	20	5.2
high	46	4.6	120	80	6.5

6.3.4 Application to actual soil data, Hai and Lushoto districts

Average soil data for 9 divisions in Hai and Lushoto districts were adopted from the soil fertility evaluation work done earlier (Chapter 3) and used in testing the model. Comparing the data used in the examples (Table 6.2) and real data from Hai district, soil pH and OC (average 6.09 and 39.7 g kg^{-1} respectively) showed to be close to the high fertility category, while the rest of the parameters were close to the low category.

As for Lushoto, only pH was close to high category with the average of 5.93. The rest of the parameters were low, thus confirming once again that soils of Lushoto are less fertile than those of Hai. As none of the combinations was perfect enough for infinite categorization of the real-time fields as of low, medium or high fertility, the medium fertility scenario was used with the economically optimum rates of nutrient inputs adapted from the theoretical example. SAFERNAC was run four times using the average soil data for the three divisions (Hai) and six divisions (Lushoto) (Appendix 6.4). The two approaches were tested: the baseline approach (soil nutrients alone) and ISFM approach, the latter run three times; with fertilizer alone (optimum rates from the example), manure alone (5 tons) and a combination of the two.

6.4 Results and Discussion

6.4.1 The SAFERNAC model with economics

Figure 6.1 is a schematic representation of the model, with economic loops added. The modules SOIL and PLANT have been summarized from Chapter 4, because they both constitute the baseline (no-input) approach. The module INPUT which constitutes the ISFM approach has been further expounded to include organic and inorganic inputs and prices of each.

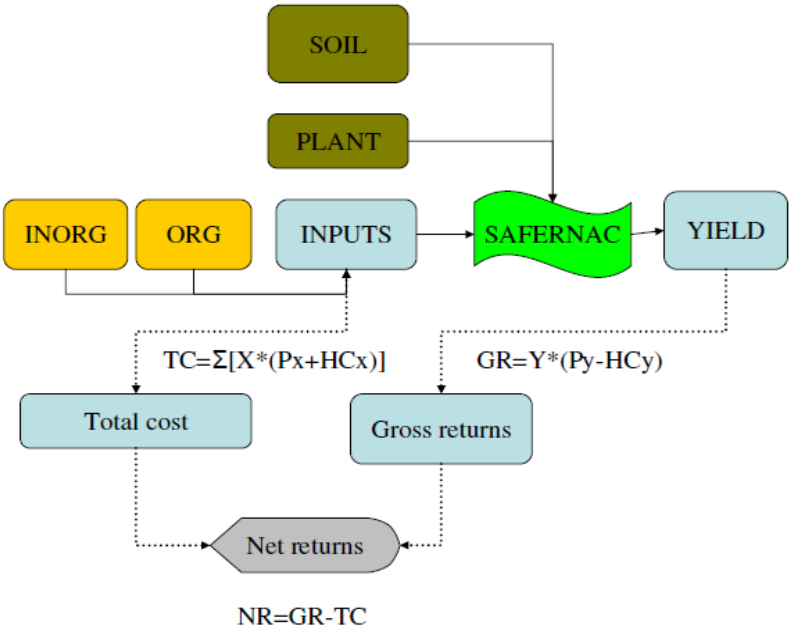


Figure 6.1: SAFERNAC model with economic loops (costs and returns)

6.4.2 Yields and net returns in relation to nutrient availability equivalents

A summary of the calculated yields and net returns is given in Appendix 6.2 which shows yields as a function of the optimum N : P ratios at each of the six levels of K, with optimum N : P : K ratios in bold underlined. The yields at optimum ratios are always higher than the other yields with the same total quantity of availability equivalents. Appendix 6.2 also shows the corresponding net return (NR) to nutrient application which is the difference between gross financial value of the extra yield (ΔY) and costs (again optimum NPK ratios in bold underlined). The net returns at the optimum ratios are always higher than the net returns obtained with other N, P and K combinations with the same total quantity of availability equivalents.

The yield calculations gave an implication that inputs deviating from the balanced situation by the same quantity of availability equivalents result in equal yields (regardless of which nutrient deviates), but those of net returns did not give similar implication.

The reason is that the prices per availability equivalent of N, P and K are not equal. They are the product of kg N, P and K per application equivalent (1.429 N, 1.75 P, 1.25 K) and the price per kg N, P and K (1000 N, 2500 P, 2500 K). The prices per application equivalent of N, P and K are 1429, 4375 and 3125 TZS, respectively.

Appendix 6.3 compares yields and net returns for different combinations of N, P and K, summing up to 360 availability equivalents. Balanced nutrition gives the highest yields as well as the highest net returns and value/cost ratios. Combinations deviating from the balanced situation by 30 availability equivalents have higher yields, net returns and value/cost ratios than combinations deviating from the balanced situation by 60 availability equivalents. The fertilizer costs are relatively low when N is higher or P is lower than in the balanced NPK-combination and relatively high when N is lower or P is higher than in the balanced situation. They reflect the differences in prices per application equivalent of N, P and K. In the case of extreme differences in fertilizer prices like, for example, by a factor of four, it may be profitable to apply more of the cheapest fertilizer than in the balanced situation. Otherwise balanced nutrition is to be preferred.

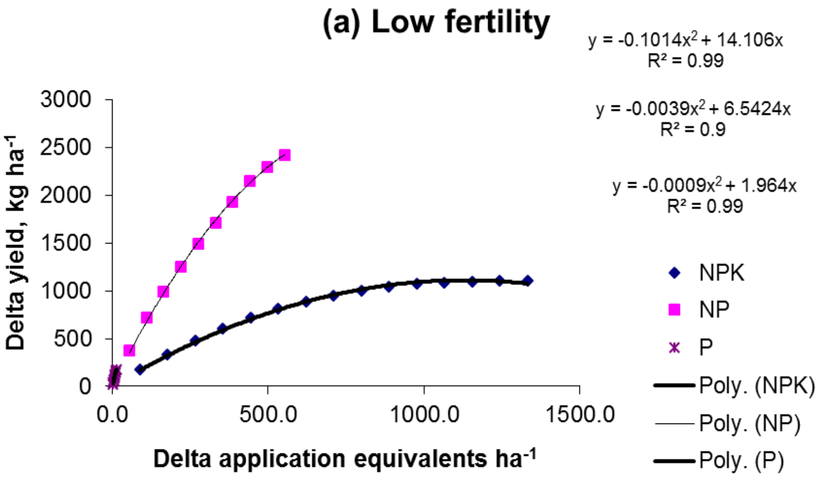
6.4.3 Economics of nutrient inputs in relation to soil data

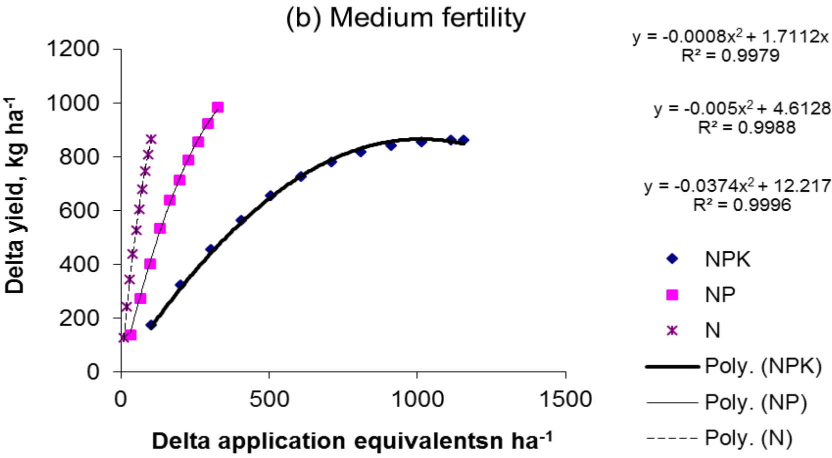
The soil nutrient supplies are rarely balanced, and one of the aims of ISFM intervention is to correct the imbalance. From Chapter 4, and also noted by Nafziger (2004), N is the most limiting nutrient, and should first be applied, then NP according to their optimum proportions, and finally NPK (at low fertility levels however, P showed to be most limiting, as it gets fixed to unavailable forms at low soil pH). It was shown in the above sections that economically optimum application of one nutrient (X_{opt}) can be calculated with: $X_{opt} = (b * V_Y - E_X) / (2c * V_Y)$. The coefficients of the three equations in Fig. 6.2 substituted “b” and “c” in the equation.

The nutrient applications and calculated ∆Y have different reference points. In the case whereby only the most limiting nutrient is applied, the baseline yield of 1086 kg is the reference. Where N and P are applied, the reference yield is 1952, obtained at the starting point of NP balance. Where N, P and K are applied, the reference yield is 2937, obtained at the starting point of NPK balance.

In the case of medium soil fertility and only N application, the optimum lies above the maximum application rate, while in the case N, P and K are applied, the optimum has a negative value. The soil is so rich in K that application of K would be a waste of money. The best application rate is found in the part where N and P are applied. The same rule seems to apply even in soils of low and high fertility status, but somewhat less clearly.

In Fig.6.3, costs and gross returns for the total applied fertilizers is shown. Also the optimum application rate is indicated; at that point the distance between gross return and costs is at maximum. The optimum rate is 332 application equivalents, of which 217 (65%) are spent on N and 115 (35%) on P. The corresponding rates expressed in kg are 310 kg N and 200 kg P per ha. This seems to be the absolute optimum rate because it is lower than the corresponding optima of 401 and 418 at low and high soil fertility, respectively.





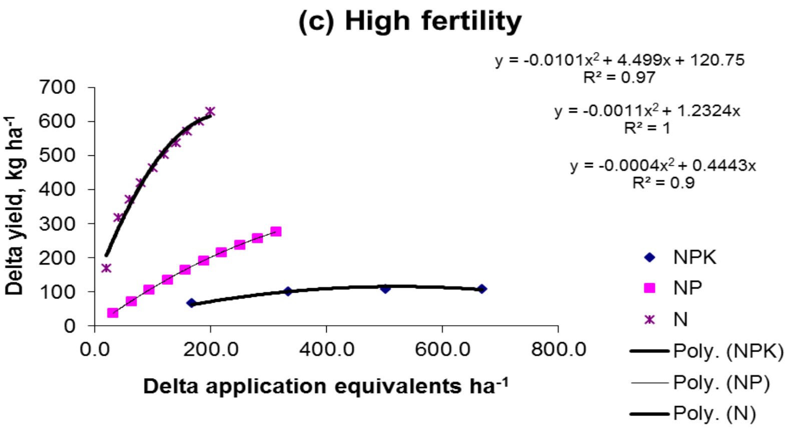
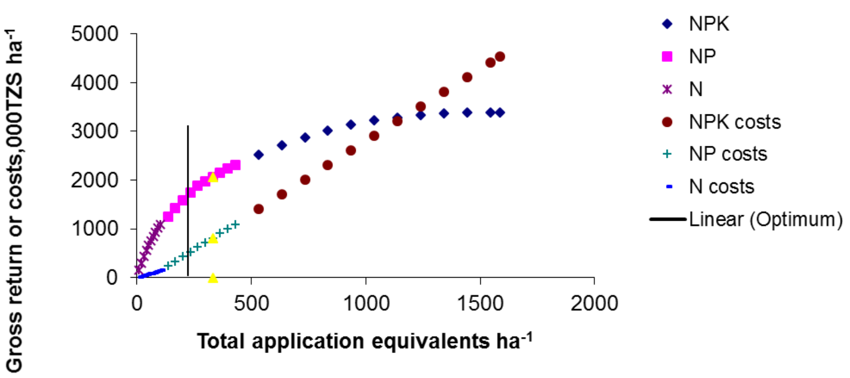
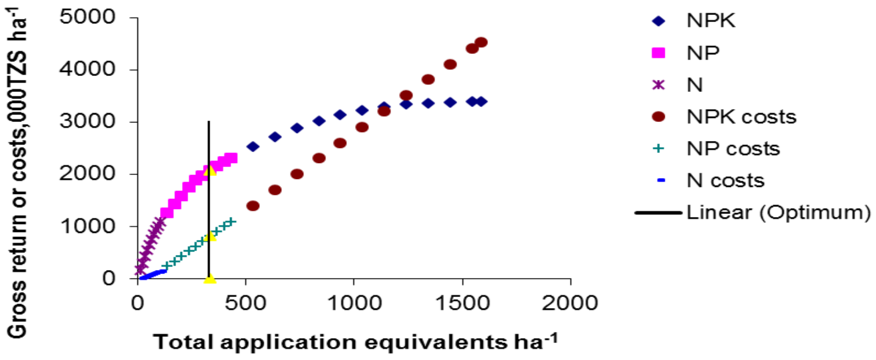


Figure 6.2: **Relation between calculated Δ coffee yields and Δ application equivalents for low, medium and high fertility, and the three input ranges (N/P, NP and NPK).**

(a) Low fertility



(b) Medium fertility



(c) High fertility

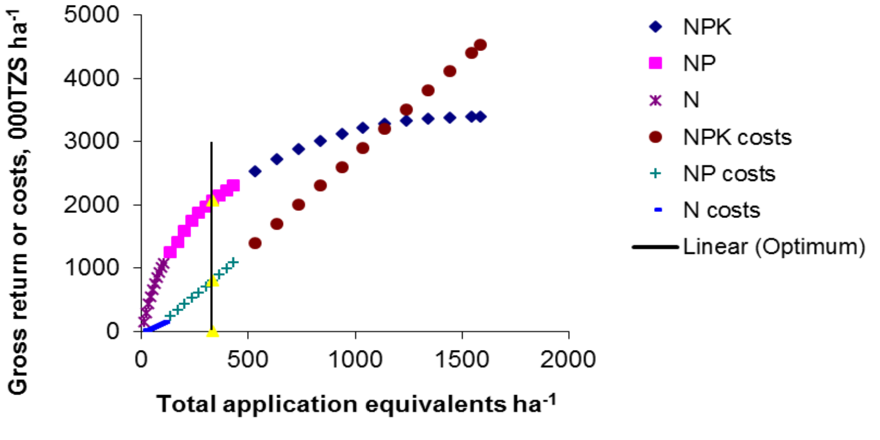


Figure 6.3: Relation between gross return to and costs of nutrient application for soils of low, medium and high fertility and three nutrient input ranges

6.4.4 Results from actual soil data, Hai and Lushoto

Figures 6.4a and b give the estimated yields and delta yields respectively for the nine divisions studied. Baseline yields showed a clear difference between soils of Hai and Lushoto, the former yielding well over 500 kg ha^{-1} and the latter hardly reaching it. With the exception of Bumbuli, where response to manure and fertilizer is practically the same, all other divisions showed a stepwise increase in the order FYM<NP<Combination.

In Fig.6.4b, response to manure steadied at around 270-300 kg ha^{-1} throughout the study areas. N and P changed the yield difference at least two-fold, with an average around 700 kg ha^{-1}. As expected, the combination of manure and fertilizers excelled the list, oscillating around the 1200 kg line. Similar results were obtained in Chapter 5.

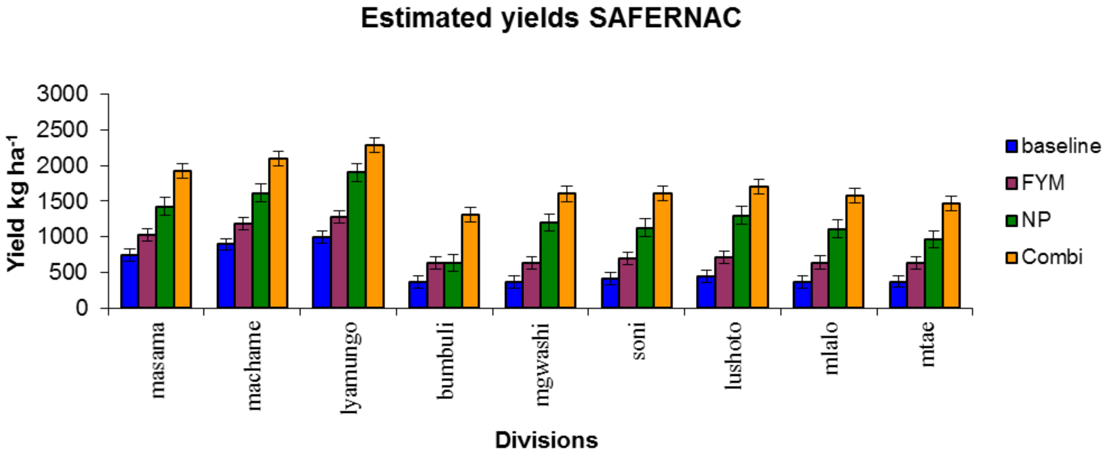


Figure 6.4(a): The estimated yields for the nine divisions

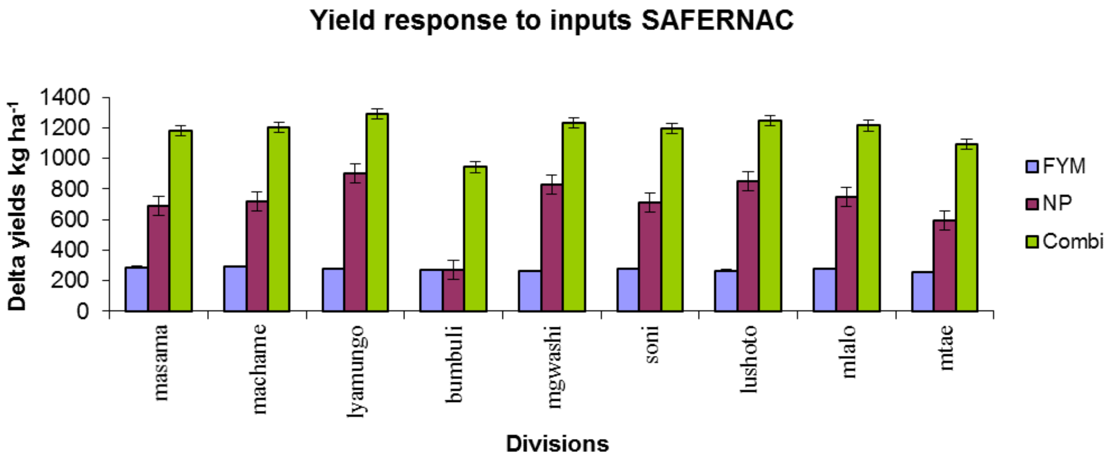


Figure 6.4(b): The estimated delta yields for the nine divisions

The value-cost ratios for the 9 divisions at coffee prices of 1250 and 2500 TZS per kg of parchment are shown in Appendix 6.5 and in Fig.6.5a and b, respectively as calculated from SAFERNAC. Mean value-cost ratios for Hai, with the application of manure alone, NP fertilizer alone and a combination of the two were 10.7, 3.1 and 2.1 at 1250 TZS kg^{-1} and 22.3, 9.1 and 6.8 at 2500 TZS kg^{-1}. Mean value-cost ratios for Lushoto were 5.6, 1.6 and 1.3 at 1250 TZS kg^{-1} and 12.2, 5.5 and 4.8 at 2500 TZS kg^{-1}. Decreasing trends were noted in the order manure > NP > combination, which can be explained by the relative costs of manure and fertilizers. At least they were all above 1.0, indicating that there is some gain in ISFM efforts. Lyamungo division showed to be most profitable, followed by Machame and Masama. The other divisions in Lushoto did not differ significantly among themselves.

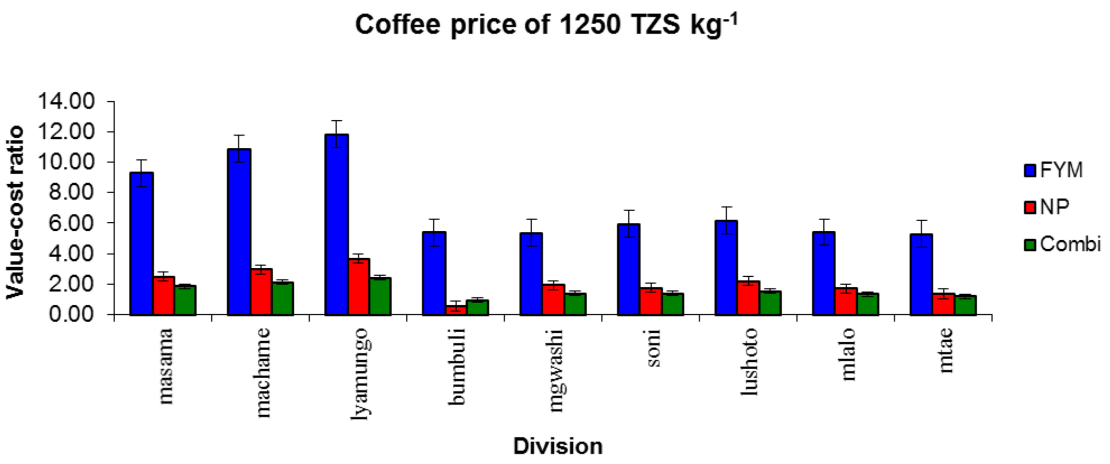


Figure 6.5(a):The value-cost ratios at coffee prices of 1250 TZS per kg

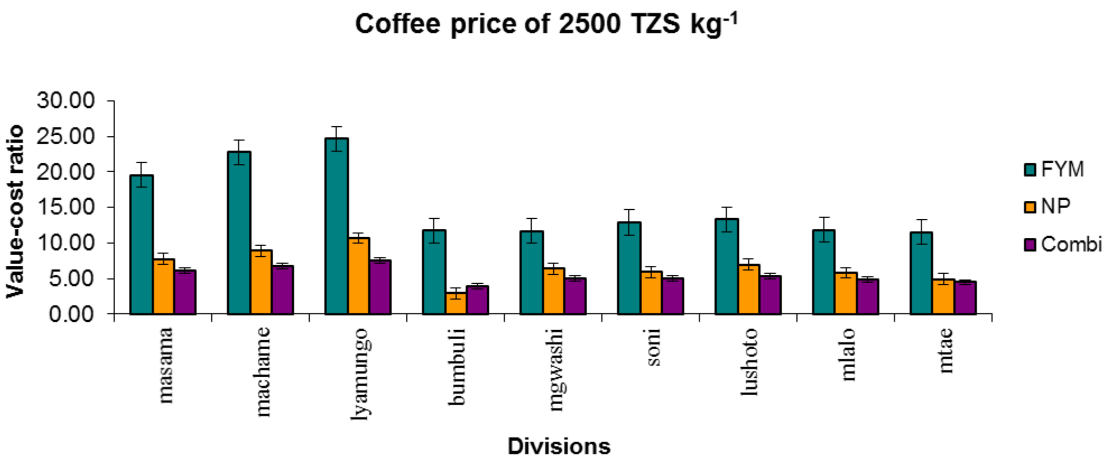


Figure 6.5(b): The value-cost ratios at coffee prices of 2500 TZS per kg

6.4.5 Discussion

The economics of agricultural production have been covered by many authors for different crops like rice (Abdullah *et al.*, 2012), plantains (Bifarin *et al.*, 2010), cowpeas (Omonona *et al.*, 2010) and groundnuts (Taru *et al.*, 2008). Most of these, however, took a more holistic approach, examining all factors of production rather than just fertilizer input as applies in this study. Their attention is therefore centred on efficiencies of resource use. Roberts (2008) made a cautious note that nutrient use efficiency should not be overemphasized at the expense of effectiveness and productivity. That is why the emphasis of the economic extension of SAFERNAC is the value of coffee yields against the value of nutrients applied for soils of low, medium and high fertility.

The theoretical calculations used in this model are simple and understandable. The model needs to be run twice; first as a baseline approach and secondly as an ISFM approach. The ISFM approach is usually followed with progressively increasing amounts of “x” until ΔY approaches zero. Then P_Y and HC_Y are used to calculate V_Y; and P_X and HC_X to calculate Ex as suggested by Moro *et al.* (2008); and the difference between (ΔY * Vy) and (X * Ex) gives the net returns to ISFM intervention, with economic optimum reached where this is maximum. In the example used in this work, HC_Y and HC_X were not considered because these differ from farmer to farmer depending on location and infrastructural capability. This, coupled with the fact that the theoretical soil was assumed to have zero nutrients, make the situation represented by the example an oversimplification of the model, serving only to clarify the concept of economically optimum nutrient application. A real-time farmer, however, must be able to estimate HC_Y and HC_X for calculating real-time profitability.

The estimation of the market price of parchment coffee was rather difficult due to fluctuating prices, and it was considered safe for modelling purposes to use the minimum (or threshold) market price, stretched over a period of 10 years. The same applies to the estimated costs of fertilizer inputs, which were based on the 2010/11 data, and these may have changed in course of time. In the calculations of economic values of FYM, many assumptions had to be made regarding prices and composition of animal manure, the latter depending on the type of animal, feed composition and level of organic matter decomposition. This means that all these parameters must be determined on location basis for the model to be realistic. It was also shown that costs of fertilizer inputs are an important factor in farmers' decisions on deviation from the optimum, and the allowable extent of such deviations, as also observed by Havlin and Benson (2006).

The calculations at the three input ranges (N alone, NP and NPK) and medium soil fertility have established the economically optimum N:P:K ratios that give highest net returns and have also indicated that net returns and value: cost ratios tend to decrease as the input ratios get further away from the optimum. The calculations also show that the highest yield increment is achieved with the maximum amount of N and P. The optimum application rate also showed to be located where the profit margin (the gap between gross returns and costs) is highest, and this corresponds with NP application. At medium soil fertility (like the one used in this example), soil-available K, which corresponds with 20 $mmol_c$ of exchangeable K per kg of soil, is likely to suffice the needs of the crop for optimum productivity where N and P are optimum. This does in no way undermine the importance of K in coffee nutrition as noted by Oberthur *et al.* (2012) and Wintgens (2012). The implication of sufficient soil K at medium soil fertility may have been over-emphasized in this work by the fact that the cost of K was indirectly estimated. The reason was that no stockist around the study areas has been dealing with straight K fertilizers (either Sulphate of Potash- K_2SO_4, or Muriate of Potash – KCl). It is interesting to note that during the soil fertility evaluation exercise (Chapter 3), the K levels in Hai were about a half of the level of 20 $mmol_c\ kg^{-1}$ used in this example, and Lushoto less than a quarter. There is a need, therefore, to fine tune the methods of fertilizer cost estimation, particularly as regards K, for better model results.

In estimating Y and ΔY for the nine divisions studied, baseline yields showed a clear difference between soils of Hai and Lushoto. Response to input use showed a generally stepwise increase in the order FYM<NP<Combination. The slight margin shown by NP over FYM is expected because the former is usually in more readily available forms than the latter, which depends on the level of decomposition of organic materials at the time of application. The combination of manure and fertilizers excelled the list because, as NP is taken up by plants, FYM slowly mineralizes and provides nutrients over a longer time in the crop cycle (Oberthur *et al.*, 2012) in addition to improvement of soil physical properties. The value-cost ratios in this study suggest Lyamungo as a division where ISFM interventions would be most profitable, followed by Machame and Masama. The other divisions in Lushoto did not differ significantly among themselves, and were less profitable than the Hai divisions.

6.5 Conclusions

An extension of SAFERNAC model has been devised for the determination of net returns to ISFM efforts and related coffee profitability. It was used to determine the economically optimum N:P:K ratios that give highest net returns and value : cost ratios for Hai and Lushoto Districts, Northern Tanzania. The model showed that, once the optimum application ratios are known, the decision to deviate from the optimum and the allowable extent of such deviation depend largely on fertilizer costs. In the medium-fertility situation which was the best fit in Hai and Lushoto districts, the highest yield increment was noted with the maximum amount of N and P. The optimum application rate was 310 kg N and 200 kg P per ha, where the profit margin (the gap between gross returns and costs) is highest. This is an indication that soil-available K is likely to suffice the needs of the crop for optimum productivity where N and P are balanced, but this is largely dependent on the K fluxes in different soil types. The optimum rates were tested with actual soil data in the two study districts, against 5 tons of farmyard manure and a combination of the two. At both the coffee prices of 1250 and 2500 TZS kg^{-1}, ISFM intervention (combination of organic and inorganic nutrient inputs) was more profitable than the other options, while coffee production was more profitable in Hai than Lushoto.

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CHAPTER SEVEN

7.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The objective of this study was to develop a model for yield prediction and integrated soil fertility management in order to enhance profitability and sustainability of coffee production in Northern Tanzania. The study was conceived in response to coffee farmers' concern on declining soil fertility as an important factor of declining coffee productivity. Its conceptual framework was based on the assumption that addressing the concerns of a community should start with the perceptions of the community followed by verification by actual field assessment. Once the concern is verified, approaches to address it are devised, tested and recommended as feedback to the community.

A series of activities were conducted in two representative districts with contrasting soil types: Hai (Haplic Nitisol) and Lushoto (Cutanic Acrisol). The perception of farmers as regards soil fertility and ISFM was assessed in order to verify the farmers' concern raised during the stakeholders' meeting of 2009. It was noted that farmers differ significantly in both problem appreciation and attitude towards ISFM; and that many demographic and farm factors play a role. Despite lower appreciation of problem in Lushoto than Hai, farmers have higher attitude towards ISFM, probably as the result of historical soil management projects. Then, the natural fertility of the soils in the two districts was evaluated through soil fertility surveys, description, soil analysis and qualitative, quantitative and spatial soil fertility assessment. All the three approaches were in agreement that the soil fertility status in the study areas was not ideal for Arabica coffee, and that the Nitisols of Hai are more fertile than the Acrisols of Lushoto. Immediate measures to address soil fertility decline have been recommended, and the need for a simpler system of soil data interpretation in quantitative terms was felt.

A review of different crop models was done and one of the Wageningen crop models called QUEFTS was selected as the best fit for use with the soil fertility and coffee yield data collected around Kilimanjaro. The model was recalibrated in line with coffee, and a new model called SAFERNAC was developed. This new model was rigorously tested in the study areas and found to be a useful tool in coffee land evaluation (baseline approach) and farm input decisions (ISFM approach). The model works on Excel spreadsheet. All that is needed is a computer with Excel Office Programme, and a spreadsheet of SAFERNAC. In the spreadsheet, one example is worked out, and should be maintained as default so as to retain the imbedded formulas. Input variables are entered in rows following the example, the formulas dragged from the example to the variables, and respective formula results displayed.

The scope of SAFERNAC was broadened by testing a variety of organic materials within reach of a smallholder coffee farmer (cattle manure, coffee leaves/prunings, pulp, husks, *Albizzia* leaves, and green manure plants – velvet bean, jackbean, lupine and sunhemp). First their nutrient release potentials were assessed through an incubation experiment in a screenhouse. The use of organic residues as either an organic farming approach or an ISFM practice was successfully imbedded into the SAFERNAC model, whereby yield estimates from different nutrient management practices were calculated. In this study, SAFERNAC demonstrated its potential in suggesting appropriate nutrient management options for both organic and conventional farmers, and also indicated that green manure plants have great potential in coffee ISFM.

To facilitate farmers' decision on ISFM interventions, which are often reached on the basis of economic considerations, the SAFERNAC model was extended to involve prices of inputs and outputs for the determination of net returns and coffee profitability. It was used to obtain yields from a soil of known properties (low, medium and high fertility) receiving different levels of inputs N, P and K from both organic and inorganic sources (ISFM). The model revealed that, for soils of medium fertility which were the best fit for the study areas, N is the most limiting nutrient followed by P and K in that order. Input application was suggested to follow the sequence N -> NP-> NPK, and an economically optimum application rate was worked out. The model was also used to compare the profitability of ISFM interventions for the nine divisions (3 in Hai and 6 in Lushoto) involved in this study.

The model developed from this study, which is a decision support tool for ISFM in coffee, will have profound effect on coffee production in the Northern zone, where most of the Tanzanian coffee estates are located. The estates have the advantage of not only having access to computers, but also access to site-specific soil data. By applying the right kind and the right dosages of nutrient inputs, coffee productivity per tree and per area will be increased, and the national total export volume will also increase. This will translate to higher income to farmers and a greater contribution of coffee to the national agricultural GDP. On the other hand, coffee estates are notorious in abusing farm inputs by making uninformed or partially informed decisions. The model will facilitate informed decisions which are not only friendly to farmers' pockets but also to the environment by preventing undue accumulation or imbalance of these inputs.

Usage of the model by smallholder coffee farmers is limited because not many of them can have access to computer, or even to the required soil analytical data. Nevertheless, they can still enjoy the services of the model through their district coffee subject matter specialists (DCSMS) who have computers and have access to “global” district-level soil fertility data from the TaCRI’s district-level soil fertility database project.

7.2 Recommendations

The following are the recommendations emanating from this work:

i. ISFM interventions should focus on young and energetic farmers with enough land for coffee production and who depend largely on coffee for their livelihood. Emphasis should now be put in encouraging youths to take coffee farming as a viable business.

ii. Factors affecting farmers’ decision on fertilizer use should be taken into consideration in devising an ISFM strategy for the coffee farmers.

iii. TaCRI and the coffee extension machinery at district level should continue promoting the right kind of nutrient management strategy and the improved coffee varieties among farmers.

iv. Farmers should be encouraged to come forward and pre-test the model. TaCRI should embark on training interested farmers on its usage, and guide them through the pre-testing process.

v. Farmers should try to work out the economically optimum N:P:K ratios that give highest net returns and value : cost ratios (or seek assistance in that regard) before embarking into serious ISFM programmes such as raising the green manure plants.

7.3 Avenues for Future Research

This study has opened up the following avenues for future research:

i. To continue research on the four green manure plants (*Mucuna, Lupine, Canavalia* and *Crotalaria*), especially as to their appropriate application methods in a farm, and notify coffee farmers as soon as the results becomes available.

ii. To include in the coffee ISFM programme other plants mentioned by farmers as having nutritive value, such as "tughutu" (*Adhatoda engleriana*), wild sunflower (*Tithonia diversifolia*) and fishbean (*Tephrosia vogelii*).

iii. To perform more research on the applicability of the model to all categories of coffee growers, with issues of shade-grown coffee, intercropped with staple food crops, etc.

iv. To search for the appropriate entry points for inclusion of secondary macronutrients and micronutrients to the model, and their consequences in improvement of the application of the model.

v. To integrate the model to more generic agro-meteorological models as climate change becomes more and more important in the coffee areas.

vi. To collaborate with computer programming specialists in developing a full-fledged software for SAFERNAC.

APPENDICES

Appendix 2.1: Sample questionnaire

SOIL FERTILITY AND ISFM BASELINE SURVEY OF ARABICA COFFEE DISTRICTS, NORTHERN TANZANIA

Enumerator: Introduce yourself and explain the purpose of this survey, which is to collect information on the soil fertility problems affecting coffee, current soil fertility management practices, enterprise characteristics, and operational constraints. Please explain that the information solicited is for research purposes only. Remember, let the farmer answer the questions .There are no right or wrong answers.

1. Basic data

Date form filled (dd/mm/yyyy) ☐☐ ☐☐ ☐☐☐☐

Name of enumerator …………………………………………………
District ……………………………………………………………….
Division……………………………………………………………….
Ward ………………………………………………………………
Village ………………………………………………………………..
Elevation: ____________ (meters above sea level, or low, medium, high zone)

2. Respondent's personal data:

a) Respondent's name …………………………………………………..

b) Sex of respondent: 1. Male…………...
2. Female ………..

c) Age of respondent ______
d) Marital status: Single _________ Married _________ Widowed ________ Divorced __________
e) Are you the head of household? Yes___ No__
f) How many people live in your household?
________ < 2 people
________ 2-4 people
________ 5-8 people
________ > 8 people.

g) Highest level of education of respondent:

___ None
___ Primary (S1-S7)
___Ordinary (F1-F4)
___Advanced (F5-F6)
___Technical College
___ University
___ Other

3. Farm management experience

a) How many years have you been growing coffee? ………………………………… (yrs)

b) Record keeping

Do you keep records of your	Yes	No
Production		
Sales		

c) What are your most important sources of information on coffee growing and management?
1. …………………………………..
2. …………………………………..
3. …………………………………..

d) How many times in the last year have you participated in a meeting or demonstration on how to grow/manage coffee?____________________

4. Land details

a) Total land owned (including all shambas) ……………………acres

b) Total land rented from others (including all shambas)……………...acres

c) Total farm area (including all shambas)…………………acres
(Owned + rented)

5. Coffee Details (use additional space to calculate total trees and acres as necessary)

a) How many coffee shambas do you have?

Garden Number	Acres	Number of Coffee Trees	Owned (O) or Rented (R)	Number	Acres	Number of Coffee Trees	Owned (O) or Rented (R)
1				2			
3				4			
5				Total			

b) If land is rented for coffee production what is the cost per growing season? _______ sh/acre

c) How many of your coffee trees (total of owned and rented are):
a. < 1 year: _______
b. 1-2 years: _______
c. 3-7 years _______
d. 8-10 years _______
e. 11-20 years _______
f. >20 years _______
g. Total trees _______

d) Do you grow other crops or trees with your coffee? Yes____No____
If yes, please list crops:____

If yes, please list trees:____

e) How many of your coffee trees are:
Shaded by trees_________
Shaded by bananas___________
Shaded by both trees and bananas_______
Not shaded_____________

f) What are the varieties of coffee trees that you grow?

Don’t know ______
KP 423 ______ (Number)
N 39 ______ (Number)
H 66 ______ (Number)
Other (specify varieties) _________________and ______________(Number)

g). Do you grow improved varieties from Lyamungu which are resistance to CBD and Coffee Leaf rust? Yes…..No….

h). **If** they do not grow any improved varieties, why? ___________________________

____

i) Are you a certified organic coffee grower? Yes____ No____
If yes, how many trees?____________

j) When you prune your coffee trees, how many stems do you leave? ___________

6. Labour

a) How much labour do you use, including hired labour to assist in the following farming activities (related to coffee production) and how much do you pay them? If only the farmer does these activities himself – write “self.”

Activity	No. of people X no. of days	Who does it (Male, Female, Both, Hired)
Mulching		
Weeding		
Pruning		
Desuckering		
Manuring		
Harvesting (picking)		

7. Inputs used
a) Do you use any commercial inputs with coffee? Yes…..No……
b) What type of inputs?

8. Output
a) A. coffee output for the last growing season:
How and where do you process coffee? i) On farm ii) Off-farm (central pulpuries) iii) both.*(Tick one or both).*

If “On farm”
Total parchment sold (Specify units (eg Kg, tonne etc.)
Average Price (Specify units) eg Tsh, US $ etc)

If "Cetral pulpuries"
Total parchment sold (Specify units) (kilogram, "debe", tonne etc)
Average Price (Specify units) (eg Tsh, US $ etc)

b) Do you prefer to process your coffee___on-farm___off-farm (centralized)___both?____

Why?____
____

c) Where do you sell your coffee?__________________________

d) Distance from "shamba" to where you sell your coffee? ______________km

e) Method and cost of transporting coffee to market (if you transport yourself how much you would pay someone to transport it for you):

i) Method: ___________________________

ii) Cost: ___________________________

f) Have you ever had your coffee rejected for sale? Yes____ No____

If yes, what reasons were given for rejection?
____
____

9. Knowledge of soil problems and ISFM:

a) Do you know anything about the soils in your farm?
____ no idea ____ sketchy idea ____ has a basic idea

Brief description of your soils ____
____
____

b) Mention any coffee problem that you know, which is related to soil conditions (*ask if there is a local name for each of the problems mentioned*)

Nutritional disorders
1.
2.
3.
Soil-borne diseases
1.
2.
3.
Soil pests
1.
2.
3.

b) Of those mentioned above, rank the three most important:

Rank	Problem
Most important:	
Second most important:	
Third most important	

10. Soil fertility management practices

a) Do you use any industrial fertilizer to your coffee? Yes__ No__If yes, name them:

Name of fertilizer	Dosage used	Number of times applied/season	When do you apply (growth stage or month)	Quantity purchased last season

If No, Why ?____

Directions: **If they are not using chemical fertilizers skip to question d.**

b) When you use any of the above fertilizers, do you record the:

	Yes	No
Application rate		
Date of application		
Fertilizer product trade name		
Operator name		

c) How do you decide when to apply the fertilizers?
We use fertilizers at regular intervals throughout the season (calendar)
We use fertilizers when we see signs of deficiency in the field (control)
We follow recommendations based on soil/leaf analytical results (standard)
Told by someone to apply (specify how told)___________________________________
Other (specify)____

d) Do you know any negative/harmful effects of using industrial fertilizers?
Yes………. No ………….

e) If yes, list the negative effects:

1. …………………………………………………………………
2. ....
3. …………………………………………………………………
4. …………………………………………………………………
5. …………………………………………………………………

11. Knowledge of other means of managing soil fertility

a) From your experience, are you aware of other methods for managing soil fertility besides chemical fertilizers? Yes……….. No …………

If yes, describe these practices:

i) _________________________

ii) _________________________

b) Do you keep livestock in your farm? _____yes _____no. If yes, what are they?

Type of livestock	Number	Primary purpose	Secondary purpose

c) Do you apply farmyard manure in your farm? _________yes _________no

If yes, how do you process farmyard manure before application?
____
____
____

If no, why?
____
____
____

d) Do you apply any of the coffee processing by-products in your farm? _____yes ______no.

If yes, how do you process the coffee by-products before application____
____
____

If no, why?____
____
____

e) Have you ever tried to make litter compost for your farm? _________yes __________no.

If yes, what is your comment on:
- i) Labour requirement ____
- ii) Time required ____
- iii) The preferred litter type in your area? ______________________________________
- iv) Relevance of the whole process in coffee? ____________________________________

f) Do you have any idea of green manure plants? ________________yes ______________no.

If yes, list the types of green manure plants available in your area.
____
____
____

(Enumerator to note down even the local names. If they can be seen around, take pictures for identification).

g) Do you apply mulch to your farm? ____________________yes ____________________no.

If yes, why? ____
If no, why? ____

12). What information do you think you need for improving your coffee production and/or marketing?

____

____

13). Have you ever received any coffee growing training (*Tick if any mentioned*):

	Yes	No	No. of times in the past yr.
Importance of soil analysis			
Integrated soil fertility management			
Identification of nutritional disorders			
Preparation of FYM and composts			
Other good agricultural practices			
Quality aspects of coffee			

14). Income

a) What is your family's?

	Major source of income (**Tick one only**)	Other sources of houshold income (**Tick as many as apply**)
Agriculture		
Salary (teaching, civil service etc)		
Trade		
Brewing		
Casual labour		
Small scale production - brick making , charcoal, house building, etc.		
Other (describe)		

b) Please estimate your total cash income from the sale of crops or livestock from your farm last year?
(**Tick one only**)

less than 100,000 TZS _____________
100,000 to 150,000 _____________
150,000 to 200,000 _____________
200,000 to 300,000 _____________
300,000 to 400,000 _____________
400,000 to 500,000 _____________
500,000 to 600,000 _____________
500,000 to 600,000 _____________
600,000 to 700,000 _____________
700,000 to 800,000 _____________
800,000 to 900,000 _____________
900,000 to 1,000,000 _____________
1,000,000 to 1,500,000 _____________
1,5000,00 to 2,000,000 _____________
2,000,000 to 2,500,000 _____________
2,500,000 to 3,000,000 _____________
3,000,000 to 3,500,000 _____________
3,500,000 to 4,000,000 _____________
4,000,000 to 4,500,000 _____________
4,500,000 to 5,000,000 _____________
Greater then 5,000.000 _____________

c) Please estimate your total cash income generated from non-farm activities by those who live on the farm (**Tick one only**)

less than 100,000 TZS ____________
100,000 to 150,000 ____________
150,000 to 200,000 ____________
200,000 to 300,000 ____________
300,000 to 400,000 ____________
400,000 to 500,000 ____________
500,000 to 600,000 ____________
500,000 to 600,000 ____________
600,000 to 700,000 ____________
700,000 to 800,000 ____________
800,000 to 900,000 ____________
900,000 to 1,000,000 ____________
1,000,000 to 1,500,000 ____________
1,500,000 to 2,000,000 ____________
1,000,000 to 1,500,000 ____________
1,5000,00 to 2,000,000 ____________
2,000,000 to 2,500,000 ____________
2,500,000 to 3,000,000 ____________
3,000,000 to 3,500,000 ____________
3,500,000 to 4,000,000 ____________
4,000,000 to 4,500,000 ____________
4,500,000 to 5,000,000 ____________
Greater then 5,000.000 ____________

15. Is there anything else you would like us to know about your coffee production?
____
____

Thank you for your time!

Appendix 3.1: Description of soil profiles Lyamungu and Yoghoi

Profile number: LY-P1

Region: KILIMANJARO
District: HAI
Map sheet no. : 56/1
Coordinates: 37°14’54. 6" E/ 03°13'58.7" S
Location: TaCRI FIELD 46

Elevation: 1336 m ASL. Parent material: Colluvial and alluvial derived from volcanic material. Landform: Plateau; gently sloping. Slope: 2 %; straight. Surface characteristics: Erosion: none or slight. Deposition: none. Natural drainage class: well drained

Ustic/Udic SMR Isohyperthermic STR

Described by G.P. Maro, B.M. Msanya, E. J. Mosi, on 07/10/2012

Soils are very deep, well drained reddish brown to dark reddish brown sandy clay to sandy clay loams, with thin brown clay loam topsoils.

Ap 0 - 9/14 cm: brown (7.5YR4/4) dry, dark reddish brown (5YR3/3) moist; clay loam; soft dry, friable moist, slightly sticky and slightly plastic wet; moderate fine and medium crumb; many fine and medium pores; many very fine, common medium and few coarse roots; clear wavy boundary to

Bt1 9/14 - 19 cm: brown (7.5YR4/4) dry, dark reddish brown (5YR3/3) moist; sandy clay loam; slightly hard to hard dry, friable moist, slightly sticky and plastic wet; strong fine and medium subangular blocky; many very fine, fine and medium pores; few fine roots; animal (mole) burrows; gradual smooth boundary to

Bt2 19 - 46 cm: yellowish red (5YR4/6) dry, dark reddish brown (5YR3/3) moist; sandy clay loam; hard dry, friable moist, sticky and plastic wet; very strong medium and coarse angular and subangular blocky; few faint clay cutans; many very fine and fine pores; few very fine and fine roots; animal (mole) burrows; gradual smooth boundary to

Bt3 46 - 80 cm: reddish brown (5YR4/4) dry, dark reddish brown (5YR3/3) moist; sandy clay loam; hard dry, friable moist, slightly sticky and plastic wet; strong medium and coarse angular blocky; common to many distinct clay cutans; many very fine and fine pores; common fine roots; gradual smooth boundary to

Bt4 80 - 102 cm: yellowish red (5YR4/6) dry, dark reddish brown (5YR3/3) moist; clay loam; slightly hard to hard dry, friable moist, sticky and plastic wet; strong medium and coarse angular and subangular blocky; many distinct clay cutans; many very fine and fine pores; very few fine roots; pottery artefact; gradual smooth boundary to

Bt5 102 - 134/142 cm: dark reddish brown (5YR3/4) dry, dark reddish brown (5YR3/3) moist; sandy clay; soft dry, friable moist, slightly sticky and plastic wet; strong fine and medium angular and subangular blocky; many distinct clay cutans; many very fine and fine pores; very few fine roots; clear wavy boundary to

Bt6 134/142 - 169/189 cm: dark reddish brown (5YR3/4) dry, dark reddish brown (5YR3/3) moist; sandy clay; slightly hard to hard dry, friable moist, sticky and plastic wet; strong fine and medium angular and subangular blocky; common faint clay cutans; many very fine and fine pores; very few very fine roots; animal (mole) burrows; clear wavy boundary to

Bt7 169/189 - 200+ cm: dark reddish brown (5YR3/4) dry, dark reddish brown (5YR3/3) moist; sandy clay; slightly hard dry, friable moist, slightly sticky and plastic wet; strong fine and medium angular and subangular blocky; many distinct clay cutans; many very fine and fine pores; very frequent medium angular slightly weathered quartz fragments; very few very fine roots.

SOIL CLASSIFICATION: WRB (IUSS, 2006): Haplic Nitisol (Humic, Dystric)

Profile number: YG-P1

Region: TANGA
District: LUSHOTO
Map sheet no. : 109/4
Coordinates: 38°16.246 E/ 04°48.166 S
Location: YOGHOI PRISONS FARM

Elevation: 1408 m ASL. Parent material: Colluvial and alluvial derived from metamorphic/gneissic material. Landform: Plateau; rolling. Slope: 6 %; straight. Surface characteristics: Erosion: slight to moderate; Deposition: none.
Natural drainage class: well drained

Ustic/Udic SMR Isohyperthermic STR

Described by G.P. Maro, B.M. Msanya, E. J. Mosi, on 09/10/2012

Soils are very deep, well drained red to dark reddish brown clay to sandy clay loams, with thick red to dark red loam topsoils.

Ap1 0 - 11 cm: very dark red (2.5YR2.5/2) dry, dark red (2.5YR3/2) moist; loam; hard dry, friable moist, slightly sticky and plastic wet; moderate fine and medium crumb; common fine and medium pores; many fine to medium and few coarse roots; charcoal artefacts; clear smooth boundary to

Ap2 11 - 23 cm: very dark red (2.5YR2.5/2) dry, dark red (2.5YR3/2) moist; loam; hard dry, friable moist, slightly sticky and plastic wet; weak coarse subangular blocky; common fine and medium pores; few very fine and few medium roots; animal (mole) burrows; clear smooth boundary to

BAt 23 - 30/35 cm: dark reddish brown (2.5YR3/3) both dry and moist; sandy clay loam; hard dry, friable moist, sticky and plastic wet; moderate medium and coarse angular and subangular blocky; few faint cutans of clay and sesquioxides; common fine and medium pores; few very fine and few medium roots; clear wavy boundary to

Bt1 30/35 - 74 cm: dark reddish brown (2.5YR2.5/4) dry, dark red (2.5YR3/6) moist; clay; hard dry, friable moist, sticky and plastic wet; strong medium and coarse angular and subangular blocky; common distinct cutans of clay and sesquioxides; many very fine and few medium pores; few very fine, few medium and few coarse roots; gradual smooth boundary to

Bt2 74 - 100/108 cm: dark red (2.5YR3/6) dry, dark reddish brown (2.5YR2.5/4) moist; clay; hard dry, friable moist, sticky and plastic wet; moderate medium and coarse angular and subangular blocky; common distinct cutans of clay and sesquioxides; many very fine and common medium pores; few very fine, few medium and few coarse roots; gradual smooth boundary to

Bt3 100/108 - 156 cm: red (2.5YR4/8) dry, red (2.5YR5/8) moist; clay; hard dry, friable moist, sticky and plastic wet; strong medium and coarse subangular blocky; common distinct cutans of clay and sesquioxides; many very fine and common medium pores; few coarse slightly weathered angular silicate fragments; few very fine and few fine roots; clear smooth boundary to

Bt4 156 - 180 cm: red (10R4/8) dry, red (2.5YR4/8) moist; clay; hard dry, friable moist, sticky and plastic wet; strong fine and medium subangular blocky; many distinct cutans of clay and sesquioxides; common very fine and common medium pores; many medium, slightly hard to hard, subspherical nodules of clay and sesquioxides and few Manganese concretions; very few very fine roots; diffuse smooth boundary to

Bt5 180 - 200+ cm: red (10R4/8) dry, red (2.5YR4/8) moist; clay; hard dry, friable moist, sticky and plastic wet; strong fine and medium angular and subangular blocky; many distinct cutans of clay and sesquioxides; common very fine and common medium pores; many medium, slightly hard to hard, subspherical nodules of clay and sesquioxides and few Manganese concretions; very few very fine roots.

SOIL CLASSIFICATION: WRB (IUSS, 2006): Cutanic Acrisol (Humic, Hyperdystric, Profondic

Analytical Data for Profile Ly-P1

Horizon	Ap	Bt1	Bt2	Bt3	Bt4	Bt5	Bt6	Bt7
Depth (cm)	0-9/14	9/14-19	19-46	46-80	80-102	102-134/142	134/142-169/189	169/189-200+
Clay %	24	28	24	26	28	24	32	20
Silt %	25	23	21	19	23	19	19	23
Sand %	50	48	54	54	48	56	48	56
Texture class	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL
Bulk density g/cc	0.903	nd	nd	0.963	0.746	nd	0.951	nd
AWC % vol	59	nd	nd	59	47	nd	55	nd
pH H_2O 1:2.5	5.11	4.92	5.27	5.68	5.73	5.15	5.35	5.61
pH KCl 1:2.5	4.70	4.53	4.64	5.11	5.14	4.74	4.66	4.80
EC 1:2.5 mS/cm	0.1311	0.0385	0.033	0.020	0.015	0.0291	0.029	0.0224
ESP	1.95	1.25	1.41	1.32	1.85	1.75	1.72	1.72
Organic C %	3.13	2.57	2.43	2.34	1.03	1.03	0.79	0.74
Total N %	0.168	0.112	0.112	0.112	0.084	0.084	0.084	0.084
C/N	18.63	22.95	21.7	20.89	12.26	12.26	9.40	8.81
Avail. P Bray-1 mg/kg	16.72	6.69	10.92	14.45	11.45	13.83	11.56	13.52
CEC NH_4OAc cmol(+)/kg	20	24	22	22	20	20	18	18
Exch. Ca cmol(+)/kg	5.58	4.25	3.78	3.68	5.76	3.77	2.82	1.56
Exch. Mg cmol(+)/g	0.81	0.62	0.57	0.70	0.71	0.64	0.63	0.50
Exch. K cmol(+)/kg	1.44	0.74	0.22	0.29	0.82	0.36	0.19	0.12
Exch. Na cmol(+)/kg	0.39	0.30	0.31	0.29	0.37	0.35	0.31	0.31
Base saturation %	41.11	24.66	22.16	22.56	38.43	25.62	21.95	13.82

Analytical Data for Profile Yg-P1

Horizon	Ap1	Ap2	BAt	Bt1	Bt2	Bt3	Bt4	Bt5
Depth (cm)	0-11	11-23	23-30/35	30/35-74	74-100/108	100/108-156	156-180	180-200+
Clay %	52	54	62	72	70	70	72	72
Silt %	11	13	11	5	7	9	7	5
Sand %	36	32	26	22	22	20	20	22
Texture class	C	C	C	C	C	C	C	C
Bulk density g/cc	0.797	nd	nd	1.194	0.96	1.178	nd	nd
AWC % vol	51	nd	nd	62	55	60	nd	nd
pH H_2O 1:2.5	5.98	5.27	5.29	5.98	4.93	5.12	5.27	5.20
pH KCl 1:2.5	5.63	5.10	5.00	5.50	4.49	5.00	5.17	5.07
EC 1:2.5 mS/cm	0.0499	0.0288	0.032	0.032	0.029	0.0134	0.016	0.0145
ESP	1.68	1.59	1.70	2.13	1.72	1.83	1.56	1.88
Organic C %	3.88	2.90	1.92	0.89	0.14	0.14	0.14	0.09
Total N %	0.168	0.168	0.168	0.112	0.084	0.056	0.056	0.056
C/N	23.10	17.26	11.43	7.95	1.67	2.50	2.50	1.61
Avail. P Bray-1 mg/kg	12.78	11.23	10.00	9.34	9.35	10.16	14.15	13.00
CEC NH_4OAc cmol(+)/kg	22	22	20	16	18	18	16	16
Exch. Ca cmol(+)/kg	4.27	3.43	2.57	2.14	1.79	1.77	0.45	1.91
Exch. Mg cmol(+)/g	0.85	0.59	0.6	0.64	0.58	0.6	0.22	0.56
Exch. K cmol(+)/kg	0.43	0.14	0.13	0.13	0.1	0.09	0.74	0.03
Exch. Na cmol(+)/kg	0.37	0.35	0.34	0.24	0.21	0.23	0.25	0.03
Base saturation %	26.91	20.50	18.20	19.69	14.89	14.94	10.38	15.81

nd= not determined

Appendix 3.2: Qualifying criteria for soil fertility scores used in this work

Characteristic	**Unit**	**0**	**1**	**2**	**3**	**4**
pH		<5.0, >7.8	5.0-5.4, 7.4-7.8	5.4-5.6, 6.6-7.4	5.6-5.8, 6.2-6.6	5.8-6.2
Total N	%	<0.05	0.05-0.08	0.08-0.10	0.10-0.12	>0.12
OC	%	<1.0	1.0-1.2	1.2-1.5	1.5-2.0	>2.0
Avail. P	mg kg^{-1}	<5	5-10	10-20	20-30	>30
CEC	cmol$_c$ kg^{-1}	<6.0	6.0-12.0	12.0-25.0	25-40	>40
Exch. Ca	cmol$_c$ kg^{-1}	<1.0	1.0-2.0	2.0-4.0	4.0-6.0	6.0 -12.0
Exch. Mg	cmol$_c$ kg^{-1}	<0.1	0.1-0.2	0.2-0.5	0.5-1.0	1.0-3.0
Exch. K	cmol$_c$ kg^{-1}	<0.05	0.05-0.1	0.1-0.2	0.2-0.5	0.5-1.0
Sulphur	mg kg^{-1}	<5	5-10	10-20	20-50	>50
Boron	mg kg^{-1}	<0.5	0.5-0.8	0.8-1.0	1.0-1.5	>1.5
Iron	mg kg^{-1}	<10	10-20	20-30	30-40	>40
Copper	mg kg^{-1}	<1.0	1.0-1.5	1.5-2.0	2.0-3.0	>3.0
Zinc	mg kg^{-1}	<2	2-4	4-6	6-8	>8
Manganese	mg kg^{-1}	<10	10-50	50-100	100-150	>150

Appendix 3.3: Description of final soil fertility scores

Total score ranges	**New score assigned**	**Description**	**Implication to coffee**
<20	0	Low	There are more than 3 limitations to coffee productivity and the coffee business is uneconomical
20-30	1	Moderately low	There are 3 limitations to coffee productivity. Intensive ISFM effort can make coffee business economical
30-40	2	Moderate	There are 2 limitations to coffee productivity. Moderate ISFM effort will make coffee business economical
40-50	3	Moderately high	There is 1 limitation to coffee productivity. Slight ISFM effort will make coffee business economical
>50	4	High	Soil is ideal for coffee productivity. Effort needed only to sustain the current soil fertility.

Appendix 3.4: Summary of soil fertility parameters involved in this study

District	**Hai**				**Lushoto**			
Parameter	**max**	**min**	**mean**	**sd**	**max**	**min**	**mean**	**sd**
pH (H_2O)	7.00	5.05	6.06	0.56	6.99	4.48	5.85	0.63
pH (KCl)	6.93	4.60	5.53	0.54	6.57	4.28	5.51	0.61
Ca^{2+}	16.40	1.30	7.95	3.06	23.70	0.60	7.46	5.12
Mg^{2+}	6.57	0.10	1.60	1.01	20.50	0.10	3.38	4.75
K^+	8.16	0.01	0.98	1.69	1.18	0.01	0.41	0.29
Na	1.62	0.02	0.42	0.32	0.53	0.01	0.14	0.10
% BS	160.82	6.66	41.68	37.61	682.97	20.00	137.33	137.97
CEC	90.00	6.00	38.45	17.85	24.00	4.00	9.88	4.20
ESP	6.75	0.00	1.51	1.57	6.58	0.04	1.70	1.34
%OC	11.34	1.37	3.96	1.80	6.72	0.22	2.02	1.44
Total N	1.04	0.01	0.17	0.17	0.18	0.04	0.08	0.03
C/N Ratio	816.75	3.07	87.47	138.62	160.04	1.54	28.93	27.01
Bray 1 P	296.00	0.52	37.90	51.54	73.50	2.70	11.52	11.65
S ppm	31.49	3.17	12.08	5.71	1.46	0.01	0.58	0.34
B ppm	10.31	0.41	1.64	2.20	56.58	1.01	16.63	12.07
Fe (ppm)	51.92	2.18	16.25	8.99	21.92	4.42	12.51	4.37
Cu (ppm)	16.82	0.93	5.11	4.64	3.89	0.00	1.03	0.80
Zn (ppm)	8.63	0.71	2.10	1.69	4.02	0.00	0.72	0.84
Mn (ppm)	41.60	2.23	12.46	7.96	69.43	10.70	44.11	17.90
ECEC	26.74	3.73	10.96	4.80	34.15	1.60	11.40	7.56
Ca:Mg	90.67	0.80	9.85	15.04	116.00	0.03	10.93	19.04
Mg:K	80.57	0.07	6.54	12.01	280.00	0.38	17.72	43.19
Ca+Mg/K	558.03	1.91	40.39	76.96	1030.00	2.68	82.62	187.10

Appendix 4.1: Summary results of calibrating QUEFTS to coffee.

Model steps	**QUEFTS**	**SAFERNAC**
1	fN= 0.25 (pH-3) fP= 1-0.5 (pH-6)^{2} fK=0.625 (3.4-0.4 pH)	ƒN = 0.25 * (pH – 3) ƒP = 1 - 0.5 * (pH - 6)^{2} ƒK = 2 - 0.2 * pH
	SN=fN * 6.8 * SOC or fN*68* SON SP=fP* 0.35 * SOC+0.5 * P-Olsen SK= (fK * 400 * exch.K)/ (2+0.9*SOC)	SAN = ƒN * 5 * SOC or ƒN * 50 * SON SAP = ƒP* 0.25* SOC + 0.5* P-Bray-I SAK = ƒK * 400 * exch.K/SOC
	Not considered	$IAN_i = MRFN * IN_i = 0.7 * IN_i$ $IAP_i = MRFP * IP_i = 0.1 * IP_i$ $IAK_i = MRFK * IK_i = 0.7 * IK_i$
	Not considered	$IAN_o = REN * MRFN * IN_o = 0.42 * IN_o$ $IAP_o = REP * MRFP * IP_o = 0.087 * IP_o$ $IAK_o = REK * MRFK * IK_o = 0.7 * IK_o$
	Not considered	ƒD = - 0.06 (D/1000)^{2} + 0.5 (D/1000) where D = number of trees per ha, and ƒD = 1 for D = 3333 ha^{-1}.
2	Refer QUEFTS papers	Adopted as in QUEFTS
3	YND = 70 * (UN-5) YNA = 30 * (UN-5) YPD = 600 * (UP-0.4) YPA = 200 * (UP-0.4) YKD = 120 * (UK-2) YKA = 30 * (UK-2)	$Y_1A = a_1 * U_1$ $Y_1D = d_1 * U_1$ (a and d referring to PhEA and PhED in kg parchment coffee per kg of nutrient taken up)
	Factor “r” subtracted from U in the equations of yields.	The “r” factor removed. Situations that U ≤ r are not applicable in coffee growing areas.
4	Refer QUEFTS papers	Adopted as in QUEFTS. Concepts of $Y_{tree}MAX$ and YMAX added: $Y_{tree}MAX = 2.2 – 0.15 X$ YMAX = 1000 * X * YtreeMAX where X is 0.001 times number of trees per ha. (YE should not exceed YND, YPD, YKD or YMAX).
5	Additional step, not in QUEFTS	AN:AP:AK = UN:UP:UK = 1/PhEMN : 1/PhEMP : 1/PhEMK = (1/14): (1/80): (1/16) or **1 : 0.175 : 0.875**
		1 kEN = 0.175*kEP =0.875*kEK Where kE = kilo nutrient equivalent per ha.
6	Additional step, not in QUEFTS	An economic loop that considers the quantities and prices of inputs and output for calculating the economic optimum nutrient application

Appendix 4.2: Physiological efficiency at maximum, medium and minimum availability of N, P and K (in kg parchment coffee)

	PhE	Symbol	N	P	K
Maximum	PhED	d	21	120	24
Medium	PhEM	m	14	80	16
Minimum	PhEA	a	7	40	8

Appendix 4.3: SAFERNAC outcomes of selected treatments in NPK reference trial Usagara C. All data in kg ha-1

		0:0:0			240:60:240		
Step	Quantity	N	P	K	N	P	K
1	SA	52	21	199	144	24	291
	I_iA	0	0	0	168	6	168
	I_oA	0	0	0	0	0	0
	A	52	21	199	312	30	459
2	$U_{1,2}$	51.7	17.5	129.2	137.4	23.1	245.1
	$U_{1,3}$	51.8	20.6	174.7	143.7	24.0	242.1
	U	52	17	129	137	23	242
3	Y.A	362	700	1033	962	925	1937
	Y.D	1086	2099	3100	2886	2774	5810
4	$Y_{1,2}$	886	1072	1084	1745	2114	2465
	$Y_{2.1}$	970	1085	1055	1716	2464	2135
	YE			**1420**			**2978**
	Y_{act}			***1143***			***2404***

Appendix 4.4: Source data from the NPK reference trial Usagara: Actual yields 1995/96

Code	N	P	K	Yield
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
0	0	0	0	1143
111	80	60	80	1514
211	160	60	80	1880
311	240	60	80	2213
112	80	60	160	1521
212	160	60	160	1912
312	240	60	160	2353
113	80	60	240	1561
213	160	60	240	1990
313	240	60	240	2404
202	160	0	160	2245
222	160	120	160	2206

Appendix 4.5: Source data from fertilizer/tree density trial: Actual yields 2000

Trees per ha	0N	90N	180N	270N	Average
1330	549	1736	1633	1763	1420
2660	1034	2612	3356	3340	2586
3200	1042	3186	3217	2721	2542
5000	814	3091	3493	3239	2659
Av4	860	2656	2925	2766	2302
Av3	963	2963	3355	3100	2595

Appendix 5.1: Parameters R9 and S in the model forsome organic materials and soil organic matter (SOM) as derived by Yang (1996); Yang and Janssen (2000)

	Green manure	Straw	Cattle manure	Compost	SOM
R_9, (y^{-1})	1.204	1.117	0.0706	0.276	0.046
S	0.6260	0.6201	0.6023	0.3125	0.3150

Appendix 5.2: Remaining fractions (Yt/Y0), calculated with Eq. 3, of some organic materials and SOM.

Time, year	Green manure	Straw	Cattle manure	Compost	SOM
0	1	1	1	1	1
0.25	0.34	0.37	0.53	0.80	0.96
0.5	***0.25***	0.27	***0.44***	***0.69***	0.94
0.75	0.20	0.22	0.38	0.62	0.92
1.0	0.16	0.18	0.34	0.56	0.91

Appendix 5.3: Substitution values for organic materials according to categories

Type of organic	Category	Yt/Y0 at 180 days	FMO	SV_N	SV_P
Cattle manure	FYM	0.44	0.56	0.6	0.87
Leaves	CP	0.69	0.31	0.33	0.48
Pulp	CP	0.69	0.31	0.33	0.48
Husks	CP	0.69	0.31	0.33	0.48
Albizzia	GM	0.25	0.75	0.8	1.16
Mucuna	GM	0.25	0.75	0.8	1.16
Lupine	GM	0.25	0.75	0.8	1.16
Canavalia	GM	0.25	0.75	0.8	1.16
Crotalaria	GM	0.25	0.75	0.8	1.16

Appendix 5.4: Calculated availability of N, P and K for the test soils and organics

		LYAMUNGU				**YOGHOI**			
		Kg/TDM	**SV**	**MRF**	**IA**	**Kg/TDM**	**SV**	**MRF**	**IA**
Nitrogen	Manure	13.00	0.60	0.7	5.46	13.00	0.6	0.7	5.46
	Leaves	24.96	0.33	0.7	5.77	15.86	0.33	0.7	3.66
	Pulp	32.63	0.33	0.7	7.54	21.06	0.33	0.7	4.86
	Husks	25.74	0.33	0.7	5.95	20.67	0.33	0.7	4.77
	Albizia	64.09	0.80	0.7	35.89	148.72	0.8	0.7	83.28
	Mucuna	185.77	0.80	0.7	104.03	145.21	0.8	0.7	81.32
	Lupine	108.29	0.80	0.7	60.64	139.49	0.8	0.7	78.11
	Canavalia	111.93	0.80	0.7	62.68	151.19	0.8	0.7	84.67
	Crotalaria	177.19	0.80	0.7	99.23	166.01	0.8	0.7	92.97
Phosphorus	Manure	6	0.87	0.1	0.52	6	0.87	0.1	0.52
	Leaves	4.14	0.48	0.1	0.20	3.12	0.48	0.1	0.15
	Pulp	4.86	0.48	0.1	0.23	3.18	0.48	0.1	0.15
	Husks	6.36	0.48	0.1	0.31	1.74	0.48	0.1	0.08
	Albizia	7.92	1.16	0.1	0.92	2.34	1.16	0.1	0.27
	Mucuna	6.42	1.16	0.1	0.74	3.84	1.16	0.1	0.45
	Lupine	16.02	1.16	0.1	1.86	3.18	1.16	0.1	0.37
	Canavalia	12.78	1.16	0.1	1.48	3.48	1.16	0.1	0.40
	Crotalaria	4.92	1.16	0.1	0.57	4.08	1.16	0.1	0.47
Potassium	Manure	14	1	0.7	9.80	14	1	0.7	9.80
	Leaves	6.16	1	0.7	4.31	7.56	1	0.7	5.29
	Pulp	1.12	1	0.7	0.78	2.38	1	0.7	1.67
	Husks	7.56	1	0.7	5.29	9.52	1	0.7	6.66
	Albizia	10.36	1	0.7	7.25	13.44	1	0.7	9.41
	Mucuna	11.9	1	0.7	8.33	15.26	1	0.7	10.68
	Lupine	12.32	1	0.7	8.62	15.4	1	0.7	10.78
	Canavalia	13.44	1	0.7	9.41	17.22	1	0.7	12.05
	Crotalaria	13.16	1	0.7	9.21	16.8	1	0.7	11.76

Appendix 6.1: Prices of chemical fertilizers urea, triple superphoshate (TSP) NPK 20:10:10, and of animal manure. Calculation of rounded prices per kg of elements N, P and K

Percentages of	Urea	TSP	NPK 20:10:10	Animal manure
N	46		20	13
P_2O_5		46	10	
K_2O			10	
P		20	4.4	6
K			8.3	14
Prices of				
Fertilizer per bag[a], TZS	23000	25000	26000	
Fertilizer, TZS/kg	460	500	520	25
N, TZS/kg	1000	2500	1000	40[c]
P, TZS/kg		2500	2500	100
K, TZS/kg			2500[b]	100

[a] A bag contains 50 kg

[b] Calculated as: 520 – 0.2 * 1000 – 0.044 * 2500

[c] It is asssumed that prices of N, P and K in animal manure are in the same proportions as in chemical fertilizers, and that possible additional value of FYM has no price.

Appendix 6.2: Optimum coffee yields (kg ha-1) and corresponding net returns (000 TZS ha-1) in relation to N and P at different K levels (in availability equivalents per ha). The bold and underlined figures refer to optimum NPK ratios

K	P	N	Yield	NR	K	P	N	Yield	NR
30	30	30	**377**	204	120	30	30	519	99
30	60	60	527	217	120	60	60	893	393
30	90	90	593	126	120	90	90	1212	617
30	120	120	619	-16	120	120	120	**1509**	**815**
30	150	150	629	-179	120	150	150	1705	885
30	180	180	630	-351	120	180	180	1866	913
60	30	30	446	196	150	30	30	534	25
60	60	60	**755**	**408**	150	60	60	942	360
60	90	90	933	456	150	90	90	1280	609
60	120	120	1054	434	150	120	120	1591	823
60	150	150	1135	361	150	150	150	**1887**	**1019**
60	180	180	1187	251	150	180	180	2086	1094
90	30	30	491	158	180	30	30	537	-65
90	60	60	832	410	180	60	60	981	316
90	90	90	**1132**	**611**	180	90	90	1339	589
90	120	120	1321	674	180	120	120	1663	820
90	150	150	1468	683	180	150	150	1969	1028
90	180	180	1582	651	180	180	180	**2264**	**1223**

Appendix 6.3: Comparison of fertilizer costs, coffee yields, net returns and value-cost ratios obtained with a number of N, P and K combinations

Deviation	N	P	K	Fertilizer costs '000 TZS ha^{-1}	Yield Kg ha^{-1}	Net return '000 TZS ha^{-1}	Value/ cost
	Availability equivalents ha^{-1}						
0	120	120	120	1071	1509	815	1.76
30	150	120	90	1021	1386	712	1.70
	90	150	120	1160	1386	573	1.49
	120	90	150	1034	1386	699	1.68
60	180	120	60	876	1122	432	1.45
	60	180	120	1248	1122	154	1.54
	120	60	180	996	1122	406	1.41

Appendix 6.4: Average soil data per division (Hai and Lushoto); adapted from soil fertility survey (Objective 2) and used in this work

District	Division	OC g kg-1	N g kg-1	P Bray, mg kg-1	K exch mmol kg-1	pH water
Hai	Masama	37.60	1.40	30.60	10.20	6.09
	Machame	40.40	1.80	43.70	12.00	5.91
	Lyamungo	41.10	1.80	39.40	17.20	6.28
Lushoto	Lushoto	24.21	0.85	9.73	6.22	5.98
	Soni	16.57	0.80	17.68	3.33	5.85
	Bumbuli	15.24	0.89	13.10	1.56	5.73
	Mgwashi	26.93	0.60	4.67	7.30	6.52
	Mlalo	22.12	0.74	11.84	4.19	5.64
	Mtae	14.69	0.80	8.60	2.50	5.88

Appendix 6.5: Average value-cost ratios per division (Hai and Lushoto); calculated by SAFERNAC from soil fertility data (Appendix 6.4), using various soil fertility management options and the coffee prices of 1250 and 2500 TZS per kg.

District	**Division**	**Organic**		**Fertilizer**		**Combination**	
		1250	**2500**	**1250**	**2500**	**1250**	**2500**
Hai	Masama	9.3	19.5	2.5	7.7	1.9	6.2
	Machame	10.9	22.7	3	8.9	2.1	6.8
	Lyamungo	11.8	24.6	3.7	10.7	2.4	7.5
Lushoto	Bumbuli	5.4	11.8	0.6	2.9	1	3.9
	Mgwashi	5.4	11.7	1.9	6.4	1.4	5
	Soni	5.9	12.9	1.8	5.9	1.4	5
	Lushoto	6.2	13.3	2.2	7	1.5	5.3
	Mlalo	5.4	11.8	1.7	5.8	1.4	4.9
	Mtae	5.3	11.5	1.4	4.9	1.2	4.5