Adapting to change in banana-based farming systems of northwest Tanzania:

The potential role of herbaceous legumes

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To

My father and to the memory of my mother and mother in law

Abstract

The banana-based farming system in Bukoba District, Tanzania, has been in existence for over 300 years. At present, banana productivity in home gardens is declining largely due to the decline in soil fertility, which in many years was counteracted by the availability of manure. The grazing land is being converted to crop fields and other uses. Crop fields have in part, assumed the role of grazing land of providing for fodder to the few cattle kept today, which is not sustainable in many years. This thesis firstly, describes the changes in the system that occurred. Secondly it explores opportunities for integrating herbaceous legumes in the farming system, to act as an engine to maintain the farming system by providing fodder to the cattle (hence manure for use in the home gardens) and ameliorating the fertility of soils of annual crop fields as improved fallows.

The area of grasslands was shown to have decreased over 50 years by 40% whereas the area of annual crop fields increased by 225%. Encroach on grassland reduced the ability of farmers to restore the fertility of their soils as possibilities to keep livestock, thus the supply of manure diminished. This had a consequence on nutrient balances where by the home gardens receiving manure, had positive balances of N, P and K whereas the home gardens receiving no manure had negative nutrient balances. Nutrient balances of annual crops were negative particularly with maize, indicating that they are vulnerable to impoverishment.

Field experiments showed that the biomass, N accumulation and N_2-fixation varied among the legume species. The performance of legumes was regulated by the soil N and the soil pH. The non-forage species *Tephrosia candida*, *Crotalaria grahamiana* and the forage species *Mucuna pruriens* and *Macrotyloma axillare* performed better among the tested legumes, and were selected by farmers on the basis of biomass yield, weed suppression and tolerance to pest and diseases.

Laboratory experiments showed that the rate of N release from decomposing legume residues depended on the quality [(polyphenols + lignin)-to-N ratio, lignin-to-N ratio and lignin content] of residues, whereby residues with low (polyphenols + lignin)-to-N ratio, lignin-to-N ratio or lignin contents decomposed faster.

Maize yield doubled or tripled when legume residues were applied though the yield response to legume residues was limited when compared with the application of the recommended rate of mineral N fertilisers (50 kg N ha^{-1}). It was further observed that, in short term, application of large quantities of legume residue (above 2 Mg ha^{-1}) does not add to significant higher maize production. In the degraded soils, the biomass yield and N accumulation of legume species increased by 100% when established with farmyard manure and had higher residual effect (80%) on the yield of the subsequent maize. Mulching with legume residues was the best option to apply legume residues as it suppressed weeds in the maize crop and had higher labour productivity. Field experiments with farmers showed that the growing legumes as improved fallows increase maize production and maintained a positive N balance. However, growing legumes for fodder was in conflict with maize production and N balance of annual crop fields.

The model experiments with a multiple goal liner programming (MGLP) model showed that legumes can act as an engine to maintain the farming system by providing fodder to the cattle, hence manure to the home gardens and ameliorating the fertility of soils of annual crop fields as improved fallows. Farmers have different preferences on legumes and choice of legumes to be introduced in the farming system should be based on farmer production objectives. The main policy implication of the findings is that promotion of legumes is best approached by taking the socio-economic systems into account. These include securing other farm inputs and marketing of farm produce by reliable and attractive markets.

Key words: *Land use changes; Herbaceous legumes; Adoptability;* N_2*-fixation; Residual effect; Legume management; Exploration of options, Nutrient depleted soils.*

Contents

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Frederick Baijukya,
Wageningen, 8 November, 2004.

Chapter 1

General introduction

Chapter 1

General introduction

1.1 The problem of poor soil fertility in sub-Saharan Africa

Throughout the world, agricultural systems have met increasing food needs by intensification, and technology has always played an important role in this process (Rabbinge, 1997). However, much of the crop and livestock production in Africa is extensive. Globally, per capita food production has increased by 30% over the past decade, but it has decreased by 7% in sub-Saharan Africa (FEWS-NET, 2003). Poor soil fertility is widely accepted to be the factor which most severely limits agricultural production in sub-Saharan Africa (Stoorvogel and Smaling, 1990; Smaling et al., 1977; Hilhorst et al., 2000). Shifting cultivation and recycling of manure and crop residues, the traditional options of managing soil fertility, are not sustainable. As population gradually increases, fallow periods become too short to be effective in restorting soil fertility or land is continuously cultivated (TSBF, 2002). Moreover, quantities of traditional organic inputs, such as crop residues continue to decline as a result of reduced yields and other uses such as animal feed (Palm et al., 2001). Amounts of manure are also limited as the number of cattle per unit of cultivated land has often decreased.

Measures to improve agricultural production in sub-Saharan Africa are undermined by low world market prices for Africa's key agricultural exports and the removal of subsidies on agricultural inputs, as a result of the implementation of structural adjustment policies (Reijntjes et al., 1992). Optimistic expectations that economic liberalization will facilitate investments in land by smallholder farmers (Pretty, 1995), seem questionable. Overall, the use of mineral fertilisers in Africa is below 9 kg ha^{-1} and continues to decline (Bumb and Baanante, 1996). Where fertilisers are used they are commonly targeted to cash crops such as tea, coffee, cotton etc. and rarely used on food crops. The real situation in sub-Saharan Africa remains that farmers cannot or will not pay for external inputs like fertilisers as along as the increased production has no immediate outlet. As most agricultural soils in Africa are inherently poor in nutrients (Stoorvogel and Smaling, 1990), increased land and labour productivity has to come from use of external inputs to the farms, whether in the form of mineral fertilisers or organic inputs (Snapp et al., 1998; Giller, 2001; Ridder et al., 2004).

1.2 The farming system in northwest Tanzania

While intensive agriculture is a comparative rare phenomenon in sub-Saharan Africa, the farming systems in northwest Tanzania has long been considered an example of a sustainable intensive agricultural system (Milne, 1938; McMaster, 1961). In its original form, agricultural land is situated on man-made ‘islands’ of fertile soil, the home gardens, amidst large expanses of infertile grassland. Soil fertility was locally improved by the concentration of nutrients from the grassland in the form of mulch and manure (Milne, 1938; Rald and Rald, 1975; FSRP, 1990). Nutrient were preserved in the system by constant application of manure, recycling of crop residues, protection of the soils against erosion by maintaining a layered soil cover consisting of shade trees, the canopy of perennial crops (bananas and coffee), annual crops (common beans) and a thick layer of mulch consisting of grass from the grassland and the banana refuse (Friedrich, 1965).

Currently, the farming system is dealing with a decline in productivity of its major components; the home gardens and cattle. The extensive grassland is perpetually degraded because of continuously grazing on a shrinking area and it cannot support even the few cattle herds that are kept today (FSRP, 1990; Kop, 1995). The majority of farmers have restricted access to manure, but nutrients continue to be exported from the system in larger quantities than imported (Baijukya and Steenhuijsen Piters, 1998). The farmers’ response to the decline in homegarden productivity has been a shift to cultivation of annual crops including cassava, sweet potatoes and maize, which has replaced banana as the main food crop. At present, pockets of productive home gardens are more surrounded by annual crop fields, which are cultivated in increasing areas, extending into the degraded grasslands.

With the continued shrinkage of grasslands, farmers have now shifted from extensive to more intensive cattle management by keeping zero-grazed dairy cattle. This shift has substantially increased the rate of nutrients mining from the annual cropping field as more than 80% of fodder fed to dairy cattle is collected from annual cropping fields, in the form of weeds and or crop residues. The manure collected from dairy cattle is applied in the home gardens (Kop, 1995; Omolo et al., 1999). This indicates that future production of cattle and homegardens will depend much on the productivity level of annual cropping fields. From production and economic consideration it appears that herbaceous legumes can have a role both in improving fodder availability and building-up the fertility of soils of annual cropping fields.

1.3 Legume cover crops as an option for sustaining soil fertility

Studies conducted in southern and eastern Africa have reported on the potentials of herbaceous legumes for maintaining and building-up soil fertility, and for supplying fodder (Raquet, 1990; Mureithi et al., 1998; Roothaert et al., 2003). Some of the best bets herbaceous legumes identified suitable for different ecological zones of East Africa include; *Mucuna pruriens*, *Tephrosia vogelii*, *Tephrosia candida*, *Crotalaria grahamiana*, *Macroptilium atropurpureum* and *Desmodium intortum* (Gachene et al., 1999). The advantage of short fallow legumes over other types of legumes is that they grow fast and allow for rotation with annual crops in areas with high land pressure (Gachene et al., 1999). Other advantages include higher rates of N_2-fixation and N-accumulation in short periods, ability to maintain internal nutrient cycling in the system and production of relatively high ‘quality’ residues (Palm et al., 1997).

Legume residues and other organic resources can contribute to soil fertility by either releasing nutrients when the material is decomposing, or by contributing to soil organic matter for long term sustainability (Vanlauwe et al., 1997). Soil organic matter is essential to provision of many soil-based ecosystem services e.g. indigenous nutrient supply, improving efficiency of water capture and use by crops and ameliorating otherwise soil hostile chemical conditions e.g. pH and Al toxicities (Ridder and Keulen, 1990)

The ability of plant residues to contribute nutrients for crop growth largely depends on the nutrient contents and residue ‘quality’ (Palm et al., 2001). Research has demonstrated that in legume residues the most important parameters influencing nutrient release are carbon to nitrogen ratio, and also the complex molecules of lignins and polyphenols which retard decomposition (Cadisch, et al., 1997; Handayanto et al., 1997; Mafongoya et al., 1998). This information has been useful in the development of a decision guide to manage organic matter decomposition to optimise short and long term release of nutrients and maintenance of soil organic matter (Palm et al., 2001).

1.4 Rationale of the study

Research on the use of soil improving legumes in the farming systems of the tropics has gained popularity and examples are available to indicate that legumes are effective methods of sustaining soil fertility (Giller, 2001; Sanchez, 2002). However, much of the reported information was collected on agronomic trials which were conducted on research stations with optimum supplies of water, nutrients (apart from N) and with inoculation (Giller, 2001). These technical solutions have been promoted with blanket recommendations to farmers as if they are undifferentiated mass. Unfortunately, conditions at research stations may bear little relation to the situation on-farm where the technology is intended. The farming population is ecologically and socio-economically highly differentiated, thus agricultural technologies have to be specified for these different situations. In some cases, soil fertility technologies that have performed well in some regions have been recommended blindly for harsh conditions where they have failed completely, and this may be one of the reasons for restricted adoption of legumes.

The soils in northwest Tanzania, notably Bukoba District, are inherently infertile as they were formed from poor parent materials (Sandstones, shale and quartizete) and are highly weathered and leached. Studies by Lorkeers and Sentozi (1995) have indicated that N is the most limiting nutrient in northwest Tanzania closely followed by K, Ca and Mg. Where soil amendments of these nutrients are available, efficient use will be of paramount importance to make production of crops economically viable and sustainable. Farmers are poor and there appears to be little scope for system improvement with expensive approaches. The challenge, therefore, is to identify technologies that can act as alternative sources of N and minimise N losses while also being economically feasible for smallholder farmers.

This study was carried out with the focus to assess the effect of land use changes on nutrient balances, and to reveal opportunities for utilisation of fodder and non-fodder legume cover crops for improving manure availability (for use in the home garden) and maize production as a part of innovation of soil fertility management of home garden and annual cropping fields. The trade-offs between attaining the economic objectives of maize yields and manure production and sustainability through less negative N balance were revealed. The study was largely conducted on-farm, involving farmers with the aim to familiarize them with the technology and to allow for easy future scaling out of promising results. The study was conducted in Bukoba District at sites that are representative of the whole banana-based farming system of northwest Tanzania.

1.5 Objectives of the study

The main objective of the study was to assess the potential contribution of various fodder and non-fodder legume cover crops to the management of N and improvement on soil productivity in smallholder farms in northwest Tanzania. The specific objectives, which together allow us to answer the main objective were:

i) to evaluate the type and extent of changes in land use, cropping patterns and cattle keeping for the period 1961-1999 and the causal factors of change;

ii) to assess the impact of changes on soil fertility management practices by farmers and the sustainability of the farming system in terms of nutrient balances;

iii) to assess the adaptability and N_2-fixation by forage and non-forage herbaceous legumes under on-station and on-farm conditions;

iv) to understand factors that may hinder the adoption of legumes by farmers and identify the types of herbaceous legume species that are most desired by farmers;

v) to understand the nitrogen release behaviour of farmer selected herbaceous legumes and the effect of application of their residues on maize yield under on-station and on-farm conditions;

vi) to determine the N fertiliser equivalency of the above ground parts of legume cover crops and the efficiency of use of legume residue N by the subsequent maize crop;

vii) to determine the best way to manage legume cover crops and their residues and the associated labour cost and labour productivity under farmer conditions;

viii) to identify opportunities for soil fertility improvement through use of legumes cover crops by farm household with different resource endowment through higher production of maize and manure and

ix) to assess the trade-offs among the economic goals (crop and manure production) and a sustainability goal (N-balance) of alternative crop activities in the annual cropping fields.

1.6 Structure of the thesis

Following this general introduction, Chapter 2 gives a detailed account of changes in land use, cropping pattern and cattle keeping, and the impact of changes on the sustainability of the farming system (Objectives i and ii). The difficulties in anticipating expensive interventions to improve agriculture production receive a special attention, and use of N_2-fixing legumes is seen as cheap source of N for both crops and livestock. The following chapters report the results of experiments dealing with specific questions: the performance and N_2-fixation of legume cover crops under on-station and on-farm and adoptability of legumes by farmers (Chapter 3), the nitrogen release patterns of decomposing legume residues and the residual effect of soil incorporated legume residues on maize yield the fertiliser equivalency values of legume residues, and legume-N uptake and the use efficiency by maize (Chapter 4), the effect of application of small quantities of cattle manure on legume performance, effect of combined use of legume residues, farmyard manure and mineral N fertilisers on maize yield, the optimum application rates of legume residues and the effect of different methods of legume residue management on weeds, maize yield and labour requirements (Chapter 5). In these consecutive chapters the answers to objectives iii-vii are given. In Chapter 6 the results from previous chapters are synthesized to explore the windows of opportunity for soil fertility improvement using the herbaceous legumes by households with different resource endowment (Objectives viii and xi). The study's overall conclusions and recommendations are made in Chapter 7.

A: The banana-based farming system in Bukoba District, showing collective banana grooves (*kibanja*) on fertile soils, and grassland (*rweya*) on poor soils. The *rweya* with some trees is extensively used for cultivation of annual crops (*omusiri*) in a shifting cultivation.

Insets:

B: *Kibanja* with bananas and under cover of beans and maize;

C: The *kikamba* cultivated with maize with (left) and without (right) incorporating legume residues

Chapter 2

Dynamics of banana-based farming systems in Bukoba District, Tanzania: changes in land use, cropping and cattle keeping

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Chapter 2

Dynamics of banana-based farming systems in Bukoba District, Tanzania: changes in land use, cropping and cattle keeping

Abstract

The spatial and temporal change of land use, cropping patterns and cattle keeping were assessed for the period 1961-1999 in Kyamtwara division, Bukoba District, Tanzania. The assessment was based on interpreting aerial photographs, surveys and a review of historical statistical data. The area of grassland declined by 40% with a concomitant increase in annual crop fields and forest of 225% and 36%, respectively. The cropping pattern changed from a predominance of banana/coffee/beans to a complex mixed cropping of banana/coffee/beans/maize and root crops in the homegarden, and increased cultivation of maize and root crops in pure stands. Farmers stopped cultivating sorghum and finger millet. The population of indigenous cattle decreased by 50% and an equal percentage of dairy cattle was introduced, but cattle-owning households decreased by 85%. Nutrient balances of homegardens ranged between -27 and 17 kg N ha^{-1} yr^{-1}, -1 and 7 kg P ha^{-1} yr^{-1} and -5 and 12 kg K ha^{-1} yr^{-1}, with the positive balances achieved by resource-rich households. Nutrient balances of crops in pure stand ranged between -15 and -2 kg N.ha^{-1} yr^{-1}, -2 and -1 kg P.ha^{-1} yr^{-1} and -14 and -1 kg K ha^{-1} yr^{-1}, with more negative balances observed with maize, implying that soil nutrient stocks are decreasing. Increasing population density, coupled with an unequal distribution of resources among households, land tenure, economic policies and poor crop markets were identified as major causal factors of the above changes. Reversing soil fertility decline requires external inputs of nutrients. Within the current poor economic situation of the farming community, different potential soil fertility improvement strategies, including exploitation of N_2-fixing legumes are discussed.

Key words: *Land use changes*; *Cropping pattern; Livestock systems; Nutrient balances; Sustainability*

2.1 Introduction

The farming system in Bukoba District, Tanzania is typical of the highlands of Uganda, Rwanda and Burundi. This production system has been relatively stable and has sustained large human populations for many decades (Kendall, 1968; Schmidt, 1978). Many studies have attributed the sustained productivity of the system to highly efficient traditional farming methods, which allowed maximum interactions of the system's major components; the crops, woody species and cattle (Milne, 1938; Möberg, 1972).

At present, the productivity of the farming system is declining. Rugalema *et al*. (1994) and NEI (1994) reported a decline of more that 50% in production of bananas (the staple food) and coffee (the major cash crop) between the late 1970s and early 1990s. This yield drop is partly attributed to inadequate return of nutrients to compensate for losses when crops are harvested and increasing pressure of crop pests and diseases (Baijukya and Steenhuijsen Piters, 1998; Bosch et al., 1996, Rugalema *et al*., 1994). As banana production continues to decline, the population is forced to depend more on maize and root crops, extending the cultivation of these crops into marginal areas (FSR Project, 1990; Steenhuijsen Piters, 1999).

Although many studies conducted in the district raised concerns on the negative impact of changes in land use, cropping patterns and livestock keeping, the extent of these changes, the underlying causal factors and their consequences on soil fertility management by farmers are still poorly understood. This paper reports results of a study with the objectives to: *i*) evaluate the type and extent of changes in land use, cropping patterns and cattle keeping for the period from 1961 to 1999; *ii*) identify causal factors behind the changes; *iii*) identify the impact of changes on soil fertility management practices by farmers; and *iv*) assess the sustainability of the farming system.

2.2 Materials and methods

2.2.1 Description of study area

Bukoba District is located on the west shore of Lake Victoria (1^o-$1^o30'$ S and 31^o-32^o E) at 1,200 m above sea level and is comprised of two major agro-ecological zones; the high and low rainfall zones, using criteria of rainfall, parent material and soils (Lorkeers, 1995). The present study focused on part of the high rainfall zone (Kyamtwara division; at $31^o46'$ - $31^o52'$ E and $1^o17'$-$1^o26'$ S), covering about 81 km^2.

Mean annual rainfall is 2000 mm (average of 1961-2001) in a bimodal pattern. Soils are Alumihumic Ferralsols developed from sandstone and shale materials (Touber and Kanani, 1994). Human population in 2002 was 22,720 at a population density of 347 persons km^{-2} (Bureau of Statistics, 2002). The economy in the area depends largely on agriculture, which employs over 87% of the population. Other activities include tree production, small-scale fishing and dairying and waged labour in Bukoba town and surrounding institutions. Farm households are of diverse nature in terms of resource base and economic activities (Table 2.1).

The farming system is comprised of three distinct but closely linked land use types; the homegardens (*kibanja*); the area for annual crop cultivation (*kikamba*) and grasslands (*rweya*) which serve as communal grazing land, source of mulch and thatch grass and area for shifting cultivation. (Rald and Rald, 1975; FSR Project, 1990). Common crops in the *kibanja* are bananas (*Musa* spp.), coffee (*Coffea canephora*), beans (*Phaseolus vulgaris*), maize (*Zea mays*), taro (*Colocasia esculenta*), cassava (*Manihot esculenta*) and various fruit trees (Rugalema *et al*., 1994). Crops in *kikamba* include maize, cassava, sweet potatoes (*Ipomea batatas*), yams (*Dioscorea* spp.) and occasionally taro (FSR Project, 1990). Bambara nuts (*Vigna subterranea*), cassava and yams are also cultivated on *rweya* under shifting cultivation (*omusiri*). Cultivation of trees (*Eucalyptus* spp. and *Pinus* spp.) and tea (*Camelia sinensis*) is increasingly extended on *rweya*. The three land use types vary in soil nutrient status particularly P and exchangeable cations (Table 2.2).

2.2.2 Development of land use database

Land use maps were derived from black and white aerial photographs from the Survey Department of the Ministry of Land and Human Settlement Development, Dar es Salaam, Tanzania, flown in April 1961 (scale 1:30,000), June 1985 (scale 1:60,000) and March 1999 (scale 1:12,500). The photographs were interpreted using a mirror stereoscope and the resulting maps were scaled to 1:25,000 using a pantograph, then geo-referenced using a topographic map of the area. Land use was broadly classified as *kibanja*, annual cropping (*kikamba* and *omusiri*), *rweya*, forest (natural and planted) and others (towns, institutions, swamps, beaches and rock outcrops). Small scattered smallholder tea plots were included in the *rweya* category, but large tea plots were classified as tea estate. The map data was digitised and processed using a Arcinfo and Arc View Geographical Information System software (Arcinfo, version 3.4 and Arc View, version 3.2, ESRI, Redland, USA).

Table 2.1 Quantitative household profile by household category in the high rainfall zone of Bukoba District based on a survey of 120 households (From Nkuba, 1997).

Household Category	Resource base						Source of income (%)			
	Family[1] size (persons)	Family[1] labour force (persons)	*Kibanja*[2] size (ha)	*Kikamba*[2] size (ha)	No. Cattle	Available manure (Mg yr^{-1})	Crops	Livestock	Wage labour	Others[3]
Resource- rich	8.5	6.1	1.0	0.4	3	3.4	45	5	0	50
Medium-resource	5.8	4.1	0.6	0.1	1	0.8	64	1	20	15
Resource-poor	5.8	4.1	0.4	0.1	0	0.0	20	0	80	0

[1] Include children aged between 9 and 15 years who are considered to be equal to 0.5 labourers; [2] See glossary, [3] Includes trade and formal employment.

Table 2.2 Average chemical and physical characteristics of topsoil (0-30 cm) from kibanja, kikamba and rweya[1] land use types in the high rainfall zone of Bukoba District (From Touber and Kanani, 1994).

Land use type	*n*	pH (H_2O)	OC (g kg^{-1})	Total N (g kg^{-1})	P- Total (g kg^{-1})	P -Bray (mg kg^{-1})	Exch. Ca (mmol kg^{-1})	Exch. K (mmol kg^{-1})	Sand (%)	Silt (%)	Clay (%)
Kibanja	24	5.7 (4.8-6.8)	26 (16-48)	2.2 (2.2- 4.2)	2.3 (0.6-4.1)	123 (10-515)	49 (10-103)	4 (1.0-6.0)	67 (64-68)	7 (5-10)	19 (11-21)
Kikamba	22	5.5 * (4.5-6.6)	22 ns (8-46)	1.7 ns (0.8-3.7)	2.0 * (0.4-3.2)	21* (5-480)	13 * (8-44)	2* (0.8-4.0)	59 ns (59-68)	14 * (8-16)	20 ns (10-26)
Rweya	18	5.2 * (4.2-5.8)	26 ns (5-56)	1.3 * (0.4 -2.1)	1.0 * (0.3-1.3)	13 * (5-250)	9* (2-18)	1 * (0.4-2.0)	70 ns (66-74)	8 ns (5-16)	23 ns (25-35)

n = number of observations; Data in parenthesis are ranges; * Indicate significance for differences (P = 0.05) by t test between means for the *kibanja* and other land use types: ns = not significant; [1] See glossary.

2.2.3 Survey and review of literature

To understand farmers' perspectives of changes in cropping patterns, livestock keeping and to gather data required to estimate nutrient balances of *kikamba*, a survey was conducted in Ibaraizibu and Buhembe villages between January and March 2002. The villages had been studied earlier and were judged to represent the area (Touber and Kanani, 1994). Data on time trends in cropping patterns, and cattle holdings were obtained through discussions with 50 well-informed farmers in each village.

The degree of soil mining was assessed by calculating the partial nutrient balances at field and crop levels (for *kikamba*) for elements N, P and K. The information on nutrient balances of *kibanja* and *omusiri* were available from past studies (Wijnalda, 1996; Baijukya and Steenhuijsen Piters, 1998). Nutrient balances of crops in the *kikamba* (primary production units, PPUs) were estimated from 18 fields for each crop per village, cultivated by an equal number of farmers from the resource-rich, medium and resource-poor households. The farmers were randomly selected from the village household list by the key informants, using criteria given in Table 2.1. Vlaming *et al*. (2001) defined a PPU as "a crop activity consisting of one or various crops grown deliberately in one field for a variety of possible reasons". In the study area, three PPUs, namely maize, sweet potato and cassava were common in *kikamba*.

A structured questionnaire was used to collect the information on type and proportion of different PPUs in *kikamba*, input used, yields and utilisation of crop residues. Individual PPUs were visited to measure their size, to assess the types of fertility management used, and to collect samples of crops and crop residues, weeds and soils for the determination of nutrient contents. A review of published and archival sources provided information on historical statistics, production problems and policy development.

2.2.4 Analysis of field data

Data were analysed for descriptive statistics and analysis of variance using SPSS version 8.0; SPSS Inc. (1997). The QUEFTS model (Janssen *et al*., 1990) was used to interpret the *kikamba* soil test results using the default values for all parameters. It is acknowledged that the QUEFTS model has not been validated for the Bukoba soils but it has been widely used elsewhere. Due to lack of data and uncertainty associated with nutrient inputs and outputs by natural processes, the calculations of nutrient balances were based on inputs by mineral fertilisers (IN 1), organic materials (IN 2) and outputs by harvested crops (OUT 1) and crop residues (OUT 2) (see Smaling, 1993). Nutrient balances of PPUs on *kikamba* were calculated using the Farm-NUTMON model (Vlaming *et al*., 2001).

2.3 Results

2.3.1 Changes in land use

The land use in Kyamtwara division has undergone dramatic modifications (Table 2.3). In 1961, the cultivated land accounted for 26% of the total land area and *rwey*a 43%. The *kibanja* occupied 90% of the cultivated land, 1% for *kikamba* and 9% for *rweya*. About 13% of land was under forest with 1% occupied by planted forest, surrounding institutions such as missions and schools. The other land use category occupied 17% of the land, with half of it covered by Bukoba town.

In 1985, transitions in different types of land use became more apparent. The area under *kibanja* increased by 7% but *kikamba* and *omusiri* decreased. It must be remarked here that the *kikamba* area for the year 1985 may be underestimated due to the small scale of aerial photographs, which made it difficult to delineate all *kikamba* plots that occurred between banana groves. Between 1961 and 1985, 143 ha of natural forest were cleared, apparently followed by establishment of 304 ha of forest on *rweya*.

Between 1985 and 1999 the area under *kibanja* slightly decreased, following abandonment of some of the *kibanja* previously established on *rweya*. By the end of this period the cultivated land was 36% of the total land area, where *kibanja* accounted for 67% of the cultivated land, *kikamba* 25% and *omusiri* 8%. The area under *rweya* decreased by 35% but the area under forest increased by 6% following extension of tree cultivation on *rweya* and rejuvenation of previously cleared natural forests. More institutions were established and Bukoba town further extended into areas of beaches and on *rweya*.

3.3.2 Changes in crops and cropping patterns

Farmer estimated trends of changes in cropping patterns in the *kibanja*, *kikamba* and *omusiri* are summarised in Figure 2.1. In 1961, banana, coffee and beans were dominant in *kibanja.* Between 1961 and 1985, 15% of banana was replaced by coffee and maize. By 1999, banana production had declined by 20% leading to planting of more roots/tuber crops. Overall, the production of beans remained unchanged. In *kikamba*, sweet potato, sorghum (*Sorghum bicolor*), maize and cassava were dominant around 1961. Between 1961 and 1985, cultivation of sorghum declined by 35% but cultivation of sweet potato and maize increased by 10% and 23%, respectively. Between 1985 and 1999, maize occupied about 50% of the cultivated *kikamba* area, partly replacing sweet potatoes and sorghum which vanished completely.

Table 2.3 Change in the proportions of broad and specific category of land use types in Kyamtwara Division from 1961 to 1999; estimated from the digitized land use maps.

Land use Category		Year							
Broad category	Specific category	1961		1985			1999		
		Area		Area		Changes[2]	Area		Changes[2]
		(ha)	(%)	(ha)	(%)	(ha)	(ha)	(%)	(ha)
Kibanja	*Kibanja*[1]	1914	24	2044	25	130	1965	24	51
Annual cropping	*Kikamba*[1]	27	-	14	1	-13	748	9	421
	Omusiri[1]	181	2	177	1	-4	229	3	48
Rweya	*Rweya*[1]	3444	43	3130	39	-314	2032	25	-1412
Tea estate	Tea estate	0		62	1	62	59	1	
Forest	Planted forest	117	1	421	5	304	661	8	544
	Natural forest	1002	12	859	11	-143	862	11	-140
Other land use	Swamp and beach	339	4	249	3	-90	120	1	-219
	Rock outcrop	300	4	333	4	33	313	4	13
	Institutions	89	1	116	1	27	134	2	45
	Bukoba township	615	8	689	9	74	958	12	343
Total		8028	100	8094	100		8081	100	

[1] See glossary; [2] Calculated using 1961 as a base year.

Around 1961, Bambara nuts, finger millet (*Eleusine coracana*), and yams were the major crops in *omusiri*. By 1985, cassava occupied about 40% of *omusiri*, replacing Bambara nuts, yams and finger millet. Between 1985 and 1999, *omusiri* was dominated by cassava and farmers stopped cultivating finger millet. The area under Bambara nuts and yams continued to decline.

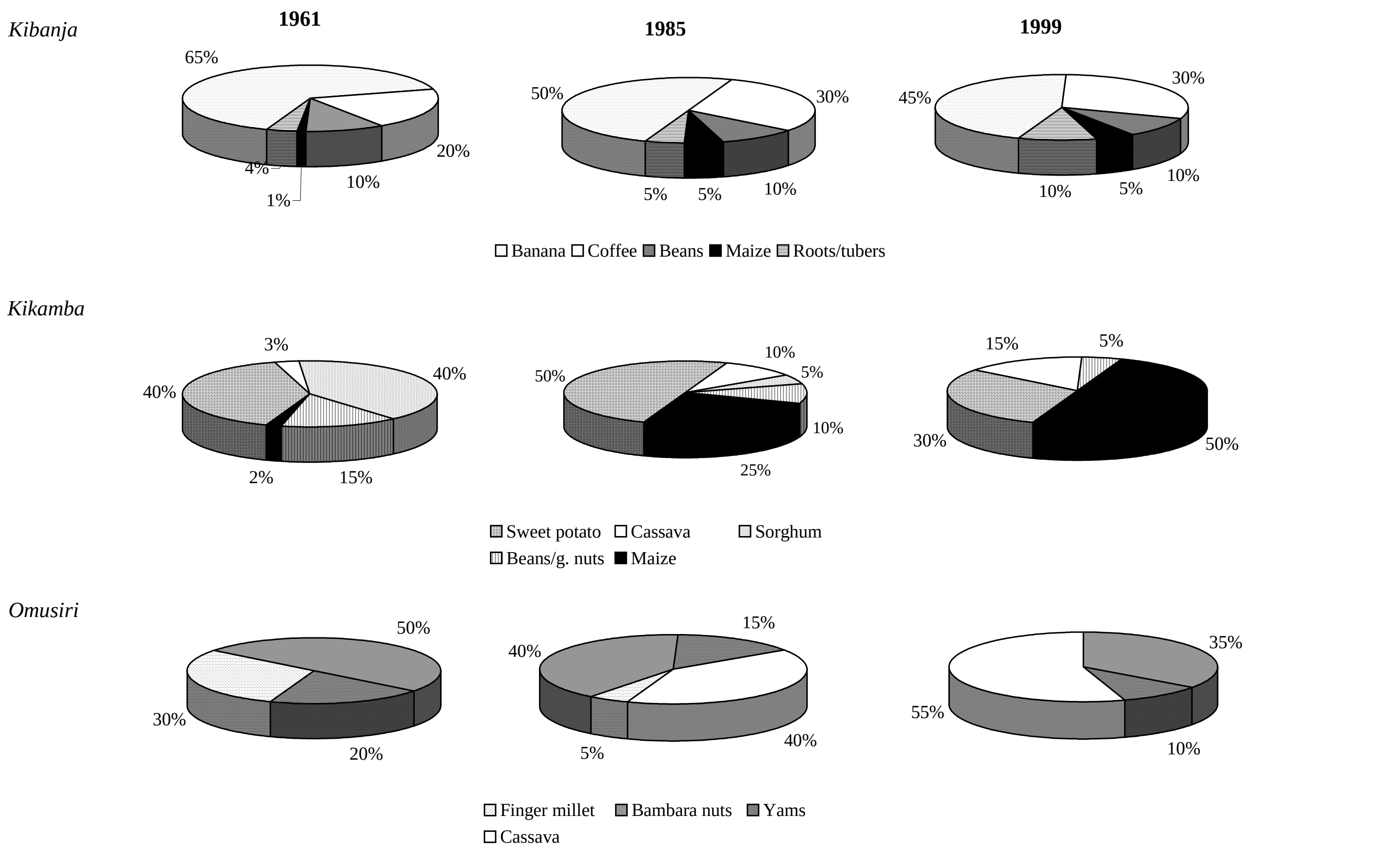

Figure 2.1 Changes in relative importance of major crops grown in different land use systems in Kyamtwara division over the period 1961-1999 based on the farmer interviews. See glossary for explanation of kibanja, kikamba and omusiri.

3.3.3 Changes in population and cattle keeping

In 1999, the population in Kyamtwara was more than double that in 1961(Table 2.4). Translated into density, the data suggests a change from 156 to 347 persons km^{-2} between 1961 and 1999. In this traditional system where the *kibanja* forms the household unit, and where *kibanja* is usually acquired through inheritance, an increased number of households mean a decrease in the size of individual *kibanja* holdings. The number of indigenous cattle and the number of cattle-owning households decreased by 50% and 85%, respectively. In 1989, Kagera Livestock Development Project introduced exotic breeds as dairy cattle, which contributed to maintaining the total cattle population in the area.

Table 2.4 Changes in human population, cattle holding and availability of grazing land for cattle in Kyamtwara Division for the period from 1961 to 1999.

Characteristic	Year		Change (%)
	1961	1999	
Total population [1]	9802	20861	213
Number of households	2680	3882	145
Average household size	4	5	113
Cattle holders	998	315	32
Cattle holding households (%)	51	8	-
Number of cattle	2301 [2]	1192 + (990)[3]	55
Rweya [4] area (ha)	3444	2032	59
Grazing area per cattle (ha /No. of cattle) [5]	1.5	0.9	62

[1] Population for 1961 by Anonymous, 1962; for 1999 from Bureau of Statistics, 1998; [2] Estimates by elderly farmers then extrapolated for the division based on numbers of households in the year 1961; [3] From Bukoba District Council, 2001; data in parenthesis are for dairy cattle; [4] See glossary; [5] Calculated on the basis of numbers of local cattle and available *rweya* area in Table 3.

2.3.4 Socio-economic and institutional development

Historical records show that before independence (1961), land in Bukoba District was a property of clans under the jurisdiction of chiefs (Rald and Rald, 1975). After independence, all land in Tanzania was declared government property to enhance adoption of socialism (*Ujamaa*), and to give protection against socially disruptive tendencies such as land speculation and excessive aggregation by the rich minority (Nyerere, 1967). This policy was gradually abandoned in 1985 after the government had signed an agreement with the International Monetary Fund (IMF) to liberalise the economy. Consequently, a clandestine land market emerged with rich people buying more *kibanja* from the poor or claiming the *rweya* by planting of trees (Steenhuijsen Piters, 1999).

Until mid 1980s, farmers in Kyamtwara obtained cash from sale of coffee and tea (Smith, 1984). A fall in price of these crops in the world market since 1986 and continued decline in banana production led to crops like maize, cassava and sweet potato attaining local marketable values and these became alternative sources of income for farmers. Moreover, the increased demand for wood as a source of fuel energy and construction material also encouraged the establishment of more trees on *rweya*.

Food crises as a result of recurrent droughts have also contributed to changes in land use in Kyamtwara division. Severe food shortages due to droughts prompted the government to launch several campaigns such as “agriculture for survival” (*kilimo cha kufa na kupona*) in 1974, and the village development fund (MFUMAKI) in 1984 (Maliyamkono and Bagachwa, 1990). Such campaigns are imposed when drought is forecast where each household is obliged to cultivate 0.2 ha of cassava and most fields are opened in *rweya*.

2.3.5 Kikamba size, allocation of crops and yields

The mean *kikamba* size was 0.4 ha for resource-rich and medium-resource households and 0.3 ha for resource-poor households (Table 2.5). All households allocated 50% of *kikamba* to the cultivation of maize. Medium and resource-poor households allocated more *kikamba* to cultivation of sweet potato and cassava. Yields of all crops were below experimental yields obtained in the area being 5, 6 and 10 Mg DM ha^{-1} for maize grain, sweet potato tubers and cassava roots, respectively (Kapinga et al., unpublished). Resource-rich households realised 0.6 and 0.9 Mg ha^{-1} yr^{-1} more maize grain than medium and resource-poor households respectively. Yields of sweet potato and cassava were comparable for all household categories. Using the QUEFTS model, less than 5% of the *kikamba* soils (data not reported) were observed to have N, P and K concentrations sufficient for a very low maize productivity (Table 2.6). In most cases N and K or their combinations were most limiting.

2.3.6 Nutrient inputs, outputs and balances of kibanja, kikamba and omusiri

Distinguishing nutrient balances of *kibanja* and *kikamba* of farmers with different resource endowment (see Table 7) allowed making comparisons between farm nutrient management and concluding whether the balances offered by one crop are more favourable than those of others. *Kibanja* of resource-rich households had positive nutrient balances, whereas nutrient balances of *kibanja* of medium-resource and resource-poor households were negative. Differences between nutrient balances of resource-rich households and medium and resource-poor households were on average

Table 2.5 Size, allocation and yield of crops from primary production units (PPUs) in *kikamba*[1] by household category and nutrient concentrations of various composite parts of crops collected during the survey. Data were collected from 12 farmer's fields of each household category.

Name of PPU	Household category	Size of PPU (ha)[2]	Allocation (%)	Grain or tuber yield (Mg ha^{-1})	Mean nutrient concentration (%)					
					In grain or tubers			In stover		
					N	P	K	N	P	K
Maize	Rich	0.25 (0.10 – 0.40)	50	1.8	1.2	0.1	0.7	0.5	0.1	0.3
	Medium	0.26 (0.10 – 1.51)	50	1.2						
	Poor	0.17 (0.09 – 0.13)	50	0.9						
	SED[3]	0.04	-	0.2						
Sweet potato	Rich	0.09 (0.05 – 0.16)	20	2.7	0.6	0.2	0.9	1.0	0.2	0.6
	Medium	0.12 (0.04 – 0.24)	33	2.3						
	Poor	0.08 (0.05 – 0.13)	25	2.3						
	SED	0.02	-	0.2						
Cassava	Rich	0.07 (0 – 0.12)	10	1.2	0.3	0.1	0.7			
	Medium	0.04 (0.01 – 0.01)	17	1.3						
	Poor	0.06 (0.01 – 0.13)	25	1.3						
	SED	0.03	-	0.4						
Weedy fallow	Rich	0.08 (0.09 - 0.14)	20							
	Medium	-	-							
	Poor	-	-		Weeds			1.6	0.2	0.8

[1] See glossary.
[2] Figures in parentheses are ranges indicating the maximum and minimum sizes of individual PPUs.
[3] SED = Standard error of the differences between means at *P*< 0.05.

25, 7 and 17 and 44, 8 and 17 kg ha^{-1} $yr^{-1}$of N, P and K, respectively. As resource-rich households account for only 10% of the total households in the area (Nkuba, 1997), it means therefore that a large proportion of *kibanja* is nutrient depleted. Mineral fertilisers are not used in *kibanja* but farmers apply ash from the kitchen, which accounts for higher K and P inputs via IN 1.

Table 2.6 Frequency of N, P and K deficiency or their combinations, occurring as major limiting nutrient(s) based on analysis of the surveyed *kikamba*[1] soils in the high rainfall zone of Bukoba District, estimated using QUEFTS.

Survey village	Productivity level	N	P	K	NP	NK	PK	NPK
Ibaraizibu village (*n = 10*) [2]	Moderate yield [3]	0	0	0	0	0	0	0
	Low yield	0	0	0	3	2	1	1
	Very low yield	1	0	0	0	3	0	0
Buhembe village (*n =12*)	Moderate yield	0	0	1	0	0	0	0
	Low yield	0	0	0	2	3	0	1
	Very low yield	0	0	0	2	2	2	3

[1] See glossary; [2] *n* = number of observations; [3] Moderate, low and very low productivity correspond with QUEFTS maize yield estimates of 3.5 - 5.0, 2.5 - 3.5 and < 2.5 Mg ha^{-1}, respectively, assuming that the productivity is mostly constrained by N, P or K availability. In both villages no field was estimated to have sufficient levels of N and K to give maize yield greater than 4 Mg ha^{-1}.

Nutrient balances of crops in *kikamba* range between -2 and -15 kg N ha^{-1} yr^{-1}, -1 and -2 kg P ha^{-1} yr^{-1} and -1 and -14 kg K ha^{-1} yr^{-1}. More negative balances were observed with maize of resource-rich households. Nutrient balances for cassava and sweet potatoes were comparable for all households due to similar management. Nutrient balances of *omusiri* (not shown) were less negative compared to *kikamba* as a result of poor yields of crops in *omusiri*.

2.3.7 Causal-effect relationships

Figure 2.2 summarises the causal-effect of changes in the Bukoba farming system. Change in *rweya* tenure and economic policy stimulated planting of trees and tea on *rweya*, as it could be privately owned (Bukoba District Council, 2001). Population growth induced demand for food and increased fragmentation of *kibanja* leading to expansion of *omusiri* and *kikamba* at the expense of *rweya*. A decrease of *rweya* caused a decline of indigenous cattle population, consequently, a shortage of manure and mulch grass for use in *kibanja*. Lower farmer income due to falling prices of cash crops (coffee and tea) in the world market reduced input use in *kibanja* as farmers lacked incentives to do so.

The shortage of manure and other fertiliser inputs caused a decline in soil fertility, which in turn increased vulnerability of banana to attack by pests and disease, finally resulting in a decline in banana production. To cope with shortage of bananas, farmers increase densities of maize and root crops in less productive *kibanja* and extend *kikamba* into the *rweya*. As no inputs are used in *kikamba*, soil fertility continues to decline keeping farmers trapped in a vicious cycle of soil degradation from which they lack resources to break out.

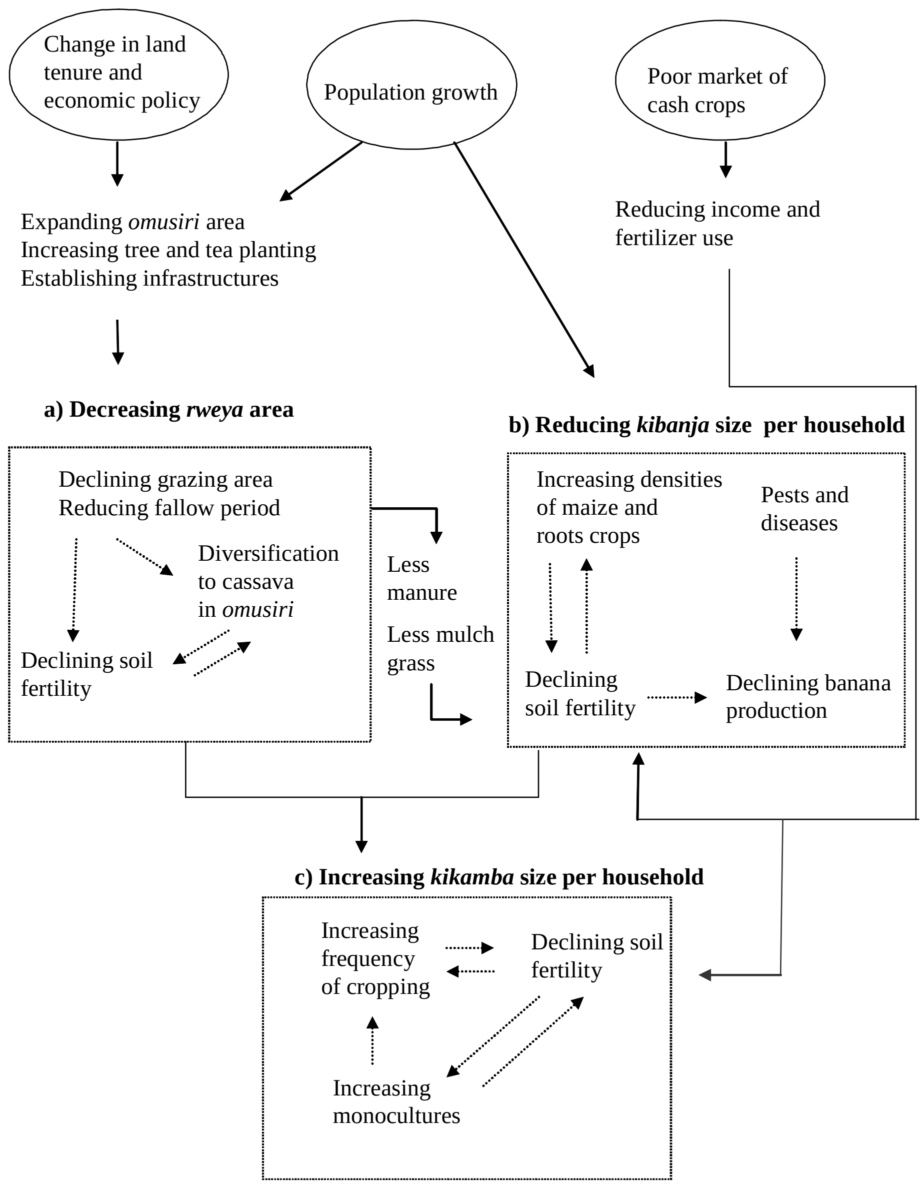

Figure 2.2 Contemporary causes of changes in land use and cropping patterns in Kyamtwara division, Bukoba District, Tanzania; hard arrows indicate forces exerted by leading driving factors (in oval shape) and events from individual land use types (in rectangular shape); broken arrows indicate causal effect chains within the land use types; a) *rweya*, b) *kibanja* and c) *kikamba* (see glossary).

2.4. Discussion and conclusions

2.4.1 Changes in land use and cropping patterns

Compared with 1961, the *rweya* in 1999 decreased while the cultivated land and forest cover increased. The decrease in the proportion of *kibanja* in the cultivated land and the increase of the *kikamba* is remarkable, whereas the total area of *kibanja* and *omusiri* only slightly changed. Aerial photos of 1999 indicated that part of *rweya* in 1961 and 1985 was occupied by the *kibanja* whereas part of *kibanja* and *omusiri* in 1961 and 1985 were occupied by *kikamba*. This indicated that new *kibanja* and *omusiri* were established and parts of old *kibanja* were converted to *kikamba*. The declining proportion of *kibanja* implies less dependence of the population on bananas as staple food, which is in conformity with trends of crops and cropping patterns estimated by the farmers (see Figure 2.1).

The observed increase in forest cover is in contrast to the general notion of increased deforestation in sub-Saharan Africa. A similar increase in forest cover was reported in Western Kenya (Holmgren *et al*., 1994). Although aforestation in Bukoba has reduced over-exploitation of indigenous forests, it has marginalised other activities i.e. cattle keeping, grass collection and shifting cultivation. Moreover, it has accelerated the conversion of common land into a resource for richer members of the society. Our experience in the area indicates however, that there is lack of awareness among the poor of being exploited, partly due to immediate benefits they obtain by working as labourers for the rich.

Population density in Bukoba District has historically been high and land scarce (Milne, 1938). According to Milne, firm traditional laws restricted extensive cultivation of *rweya* and natural forests. Out-migration was a way to relieve population pressure (McMaster, 1960). Therefore, the observed changes can partly be explained by the population growth but in combination with changes in *rweya* tenure, fall of prices of cash crops in the world market, the launching of food security campaigns and increased social differentiation of farm households.

2.4.2 Impact of changes on soil fertility management

The old management of soil fertility has generally deteriorated with the reduction of fallow periods, shortage of grass mulch and manure due to reduced portion of cattle grazing on *rweya* and bringing nutrients to *kibanja*. As such, farmers in Bukoba regard the presence of cattle in the system as the fundamental factor determining productivity of *kibanja*. However, the number of dairy cattle is increasing and optimists perceive them as the potential strategy for the sustainable intensification of smallholdings. Nevertheless, due to unavailability of feed and poor markets for milk, keeping of dairy cattle is limited to few resource rich households. Dairy cattle feed largely on weeds and crop residues collected from *kikamba*. As manure obtained is used in *kibanja* (Kop, 1995), the dairy cattle accelerate the depletion of nutrients from the *kikamba* soil. This new delicate balance between the closely linked system components illustrates the threat to Bukoban agriculture in terms of soil fertility decline as has been reported elsewhere in Africa (Hilhorst *et al*., 2000). The evidence so far leads to the conclusion that in Bukoba, the theory of induced innovation in agriculture (Boserup, 1981), which has been reported to work elsewhere in Africa (e.g. Northern Nigeria, Mortimore, 1993), applies only to the *kibanja* of resource rich farmers.

2.4.3 Nutrient supply in the farming system

Using a generalised example of *kibanja*, the net nutrient balance (Table 2.7) indicates that 48 kg of N is lost from 1 ha per year through crop harvest. If we have to redress the situation using manure, 3.2 Mg ha^{-1} (N =1.5%) is needed. If all *kibanja* has to receive manure, 6.3 x 10^4 Mg would be required. However, given the presence of about 1463 livestock unit (TLU) in the area, with average production of 650 kg manure yr^{-1} TLU^{-1} and collection of 50% in stables (Kop, 1995), the potential manure production in the area is 4.7 x 10^3 Mg, which is 8% of the requirement. With the current technology, increasing number of cattle will not lead to more manure as the carrying capacity of *rweya* is low and cannot support more livestock than is kept today. This means that part of nutrients which are not supplied by manure will have to come from other sources outside the system.

In this paper, nutrient dynamics in Bukoba farming system was assessed using GIS in combination with NUTMON and QUEFTS to allow assessment at different hierarchical levels of the farming system. GIS was used to quantify and understand the spatial relations of the interacting land use types, NUTMON was used to quantify nutrient flows in and out of fields and QUEFTS to evaluate productivity of soils and potential limiting nutrients. The negative nutrient balances and progressive soil mining, which are indicators of non-sustainability in the medium or long term (Smaling, 1993; Smaling, 1998), are obvious at field and crop scales. Although no attempt was made to relate nutrient depletion with available stocks (because of wide variations among fields, see Table 2.2), predictions by QUEFTS arrived at similar conclusions as the nutrient balances estimated with NUTMON, i.e. N, P and K are limiting rendering the system unsustainable. Soils in Bukoba have inherently low fertility, nutrient stocks are inevitably limited and the risk is high of soils becoming further degraded.

2.4.4 Directions for future research and development

Farmers in Bukoba district have an ethnic preference for *kibanja* not only because of they like eating bananas but also because the *kibanja* system to some degree enhances the fertility of land through prevention of excessive leaching, soil erosion and recycling of soil nutrient when dead leaves and the pseudo-stems are used as mulch. However, at present only a minority of households are capable of managing *kibanja* to achieve a desirable production. While research to improving *kibanja* productivity should continue, focus should also be on sustainable production of annual crops in *kikamba,* which has become an important production unit and is at risk, in terms of nutrient mining. Attention also should be given to reserve and improve the *rweya*, which is essential for sustainable crop and production of indigenous cattle in the future.

Given limited sources of organic inputs in Bukoba, soil productivity can be best improved by use of mineral fertilisers. However, mineral fertilisers are unaffordable to the majority of farmers and not profitable (Wiig *et al*., 2001), as is often the case in smallholder African farming. Alternatives are supplementary feeding of dairy cattle with feeds from outside the system and growing of N_2-fixing legumes. The latter has proved to work in areas of East Africa with climatic conditions similar to that of Bukoba (Fischler and Wortmann, 1999). However, as N_2-fixation addresses only N, other nutrients still have to come from external sources. The Government should therefore deliberately formulate comprehensive policies that will make farming profitable. Such policies should (among other things) focus to improve farmers accessibility to inputs, better access to markets and reduce farming risk through provision of safety nets although this is in conflict with structural adjustment policies.

Acknowledgement

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Glossary

Kibanja: Homegardens with a mixture of crops but banana as a main crop.
Kikamba: Area cultivated with annual crops, i.e. maize and root and tuber crops.

Rweya: Grasslands in common use for grazing and collection of fuel and construction wood, mulch, and thatch grass.
Omusiri: Parts of the *rweya* cultivated with Bambara nuts, cassava and yams in a shifting cultivation system.

A

B

A shift from keeping of indigenous free-grazed cattle to exotic zero-grazed dairy cows is among the changes taking place in Bukoba District. The reason for keeping cattle remains largely to obtain manure for use in the *kibanja*.

A: Indigenous cattle in the shed;

B: Improved dairy cow in the shed.

Chapter 3

Partnerships with farmers to assess the adoptability, productivity and biological N_2-fixation of herbaceous legumes in Bukoba District, Tanzania

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Chapter 3

Partnerships with farmers to assess the adoptability, productivity and biological N_2-fixation of herbaceous legumes in Bukoba District, Tanzania

Abstract

On-station and on-farm trials were undertaken to assess the productivity, N_2-fixation and adoptability of herbaceous legumes by farmers in two major agro-ecological zones of Bukoba District, northwest Tanzania. The legumes studied were non-forage species; *Tephrosia candida, Tephrosia vogelii, Crotalaria grahamiana, Crotalaria paulina* and *Crotalaria juncea* and forage species; *Lablab purpureus, Mucuna pruriens, Macrotyloma axillare, Macroptilium atropurpureum* and *Desmodium intortum*. N_2-fixation was estimated using the ^{15}N natural abundance and N difference methods. A participatory assessment of adoptability of legumes by farmers was done using a Gender Analysis Matrix (GAM) and a matrix ranking method. Shoot biomass, nitrogen (N) yield and the amount of N_2-fixed varied between legume species and sites. The mean shoot biomass yields and N yield (in parentheses) ranged between 0.3 and 5.5 Mg ha^{-1} (8 to 143 kg N ha^{-1}) and 0.8 and 5.6 Mg ha^{-1} (8 and 186 kg N ha^{-1}) for the non-forage and forage legumes, respectively. Estimates of N_2-fixation by the ^{15}N natural abundance method were uniformly high (52-81%) for most legumes except *M. atropurpureum* which derived less than 44% of its N from N_2-fixation. The average amounts of N_2-fixed ranged from 11 to 106 kg N ha^{-1} for non-forage legumes and from 14 to109 kg N ha^{-1} for forage legumes. N accumulation was primarily related to biomass production which in turn was regulated by soil N and pH in most sites. Most of non-forage and forage legumes species fixed between 15 and 20 kg shoot N for every Mg of shoot dry matter. The species *T. vogelii, C. paulina*, *C. juncea, C. paulina* and *L. purpureus* were susceptible to attack by pests and diseases hence performed poorly. On the other hand *T. candida, C. grahamiana, M. pruriens and M.axillare* showed better performance at most sites. Hence farmers selected these legume species on the basis of their higher biomass yields, tolerance to pest and diseases, weed suppression, drought tolerance and fodder value. Availability of land, labour, cash and farmer production objectives were identified as possible socio-economic factors that would dictate the adoption of herbaceous legumes. The possible actions to take in order to improve productivity of legumes and to achieve wide adoption by farmers are discussed.

Key words: *Legume performance; Farmer participation; Adoption of technology*

3.1 Introduction

Soils in the Bukoba District of northwest Tanzania are acidic, highly weathered and leached (Möberg, 1972; Touber and Kanani, 1994). In this farming system cattle manure and crop residues, which have been the principal means of managing soil fertility, are increasingly becoming scarce causing a decline in crop production (Kop, 1995; Baijukya and Steenhuijsen Piters, 1998). Low soil nitrogen (N) content has been a major factor causing this declining yield trend (Kop, 1995). In addition, low protein contents in the forages of Bukoba rangelands cause poor productivity and infertility in cattle (Evans and Mitchell, 1961; Roeleveld et al., 1994).

While crop production might be improved with fertiliser applications and cattle production by supplementary feeding with protein rich feeds, most farmers cannot afford to purchase such inputs. Earlier participatory work in Bukoba District identified legumes as an option for soil fertility improvement (Baijukya et al., 2001). Diversification of the cropping system and improved supply of N through N_2-fixing legumes is proposed elsewhere among the strategies to increase crop and livestock productivity and recharging soil N reserves (Giller, 2001; Sanchez, 2002). There is scope to increase the area of legumes by replacing weedy fallows with short duration fallow legumes, by developing more effective annual crop-legume rotations, and by establishing legume fodder banks. However, research is needed to assess the likely impact such changes can have on individual farmers and the farming community as a whole.

Although comprehensive scientific knowledge exists on symbiotic N_2-fixation and its benefits for agricultural systems (e.g. Unkovich and Pate, 2000; Giller, 2001; Stewart, 2001), hardly any studies have been undertaken in Bukoba District. This is despite favourable climatic conditions for legume growth and a long history in growing common beans (*Phaseolus vulgaris* L.) in this district. More importantly scarce data are available on the performance of legume cover crops that have been identified as ‘best bet’ technologies for soil improvement elsewhere in the tropics.

To address this fundamental knowledge gap, we conducted on-station and on-farm trials in partnership with farmers with the objectives to (*i*) assess the performance and N_2-fixation of forage and non-forage herbaceous legumes (*ii*) identify the environmental factors that may affect the N_2-fixation by legumes (*iii*) understand factors that may hinder the adoption of legumes by farmers and *(iv)* identify legumes species that are most desired by farmers for wider dissemination.

3.2 Materials and methods

3.2.1 Site description

The trial was conducted on station and in farmer fields in the high and low rainfall zones of Bukoba District ($1^o13'$ -1^o 30' S and 31^o 19' -31^o 52' E), in the period between February and September 2001. During this time frame most annual cropping fields (*kikamba*) are left under weed fallow. In the high rainfall zone, trial sites were located at Maruku Agricultural Research Institute (ARI-Maruku) and in the villages Butairuka and Kiilima. In the low rainfall zone, the trial sites were located in the villages Kabirizi and Kyaitoke. The villages were judged to represent the zones (Touber and Kanani, 1994) and are used for on-farm trials by ARI-Maruku. The important characteristics of the zones and of the soils at the trial sites are summarised in Table 3.1. The average and actual monthly precipitation during the growing season collected from weather stations situated in the two zones are presented in Figure 3.1.

Table 3.1 Main characteristics of the study zones and of the topsoil (0-30 cm) [a] at the trial sites; data in parenthesis are ranges.

Agro-ecological zone	Parent material (soil type)	Av. annual rainfall (mm)[b]	pH (H_2O)	OC ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	P -Bray ($mg\ kg^{-1}$)	Exch. K ($mmol\ kg^{-1}$)	Sand (%)	Silt (%)	Clay (%)
High rainfall	Sandstone and shale (Alumi-humic ferralsols)	2100	5 (4-6)	24 (13-43)	1.1 (0.6-3.1)	19.0 (5.1-25)	1.6 (1.2-3.6)	58 (54-62)	26 (22-28)	16 (14-24)
Low rainfall	Quartzite and shale (Humic-Acrisols and Ferralsols)	800	6 (4-7)	18 (12-31	1.2 (0.8-2.7)	14.4 (5.6-26)	1.8 (1.0-4.2)	30 (10-36)	28 (24-30)	42 (34-48)

[a] Soils from *kikamba* fields.
[b] Mean of 40 years (1961-2001).

3.2.2 Trial design and treatments

The trial design at ARI-Maruku site was a completely randomised block in four replicates, with a plot size of 21 m^2. Treatments comprised of 5 legume fodder species: *Macrotyloma axillare, Macroptilium atropurpureum, Lablab purpureus, Desmodium intortum* and *Mucuna pruriens* (white seed colour) (obtained form Zimbabwe at Marondera Grassland Research Institute). Another 5 non-forage legumes were selected

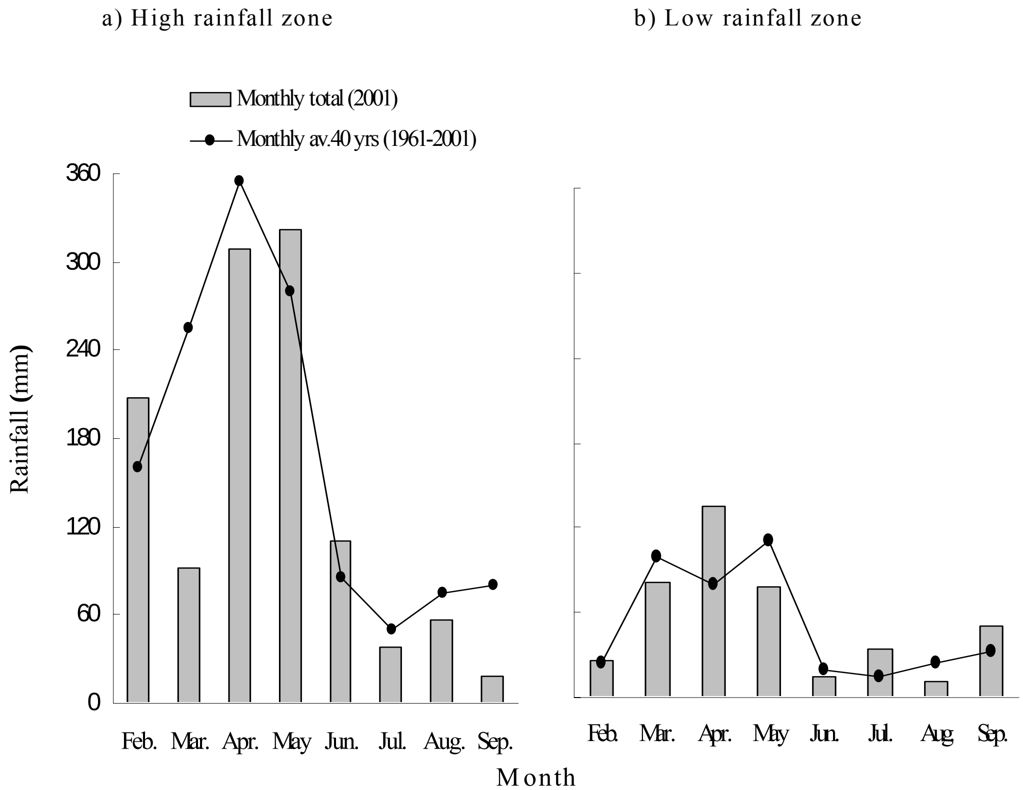

Figure 3.1 Average and actual monthly precipitation during the trial period in the a) high rainfall and b) low rainfall zones of Bukoba District.

which are widely used as green manures or 'improved fallows': *Tephrosia vogelii, Tephrosia candida*, *Crotalaria grahamiana*, *Crotalaria paulina and Crotalaria juncea* (Obtained from ICRAF Maseno, Kenya). Maize and weed fallow (the farmer practices) were included as control to compare the N contribution by legumes to the system. The weed fallows were the re-growth of the natural vegetation in plots, which were cultivated at the start of the study. The choice of legumes was based on the availability of seed, their uses and performance history in areas with soils and climatic conditions similar to those in Bukoba.

On-farm trials were located in farmer fields at 16 sites in each zone. Treatments at each site comprised of 7 legume species (a subset of those at the on-station site), maize and weed fallow in a single replicate, each with a plot size of 34 m^2. Each legume species (except *M. axillare*, *M. atropurpureum* and *D. intortum*) was replicated 14 times in each zone. The species *M. axillare*, *M. atropurpureum* and *D. intortum* were established at 4 sites in each zone due to shortage of seeds.

3.2.3 Trial establishment and management

At all sites, the trials were established on fields previously planted with maize, with the purpose to reduce the within site variations in nutrient availability. The trials were established by the farmers, with assistance from researchers, in the fourth week of February 2001 at the onset of long rain season. At all sites, *M. axillare* and *M. atropurpureum* were sown at a spacing of 0.45 x 0.25 m at a seeding rate of 4 kg seeds ha^{-1} (Skerman et al., 1988). *C. juncea* and *D. intortum* were drilled in furrows spaced at 0.30 m apart at seeding rates of 4 and 1 kg seeds ha^{-1}, respectively. Other legumes were established at a spacing of 0.6 x 0.3 m by putting 3 seeds per planting hole. Maize was planted at a spacing of 0.75 x 0.45 m. Three weeks after sowing *M. pruriens*, *Tephrosia* spp. *C. grahamiana*, *C. paulina* and maize, were thinned to leave 2 plants per planting hole. The on-farm trials were left under farmer management but researchers made frequent visits for data collection. Data collected included: emergence date, population density at emergence, pests and disease incidence. In addition, farmers were asked to record the desired and undesired characteristics of legumes throughout the trial period.

3.2.4 Soils sampling and analysis

At sowing, a composite topsoil (0-0.3 m) sample was taken from each site, air dried and ground to pass a 2 mm sieve. Samples were analysed for texture (hydrometer method), pH- H_2O (1:2.5w/v); Organic C (OC; Walkley and Black); total N (macro-Kjeldahl); available P (Bray and Kurtz) and exchangeable K (1 M NH_4Oc at pH 7.0). These methods of analysis are described in detail by Page et al. (1982). The parameters analysed have been reported to influence N_2-fixation in the tropics (Hungria and Vargas, 2000; Giller, 2001; Graham and Vance, 2003).

Soils were generally sandy clay in the high rainfall and clay loam in the low rainfall zone (Table 3.1). Based on the classification by Landon (1991), soils in the high rainfall zone were strongly acid, had medium organic carbon and available P and were poor in total N and available K. Soils in the low rainfall zone were slightly acidic, had medium contents of organic carbon and available P and had poor total N and available K. Average soil chemical characteristics did not differ between zones, but varied widely between sites mainly due to differences in past management (fertilisation, past crops grown and fallowing).

3.2.5 Plant harvesting, sampling and analysis

Harvesting of the trials was done at 20 weeks after sowing, by quadrat cutting (2 x 1 m^2) at ground level on three locations in each plot. At harvest, only *M. pruriens, C.*

juncea, *L. purpureus* and maize had attained the maximum growth. All other species had just flowered except *T. candida* and *T. vogelii* which were still in the vegetative stage. From each site an additional sample of *Hyparrhenia* grass spp. was collected, for use together with maize as non-N_2-fixing reference plants to estimate the N_2-fixation by legumes. The harvested plant shoot samples were oven dried at 70^0C to constant weights and weighed. From the large samples of 2-4 kg, sub-samples of 1 kg (the whole shoot parts) were taken and ground to < 1 mm in a cyclotech mill in preparation for N and ^{15}N analysis. The %N and ^{15}N in plant shoot materials were determined at the Imperial College at Wye, by combustion in an automatic N and Carbon Analyser (ANCA-SL) interfaced to a 20-20 stable isotope mass spectrometer (formerly Europa Scientific, Crewe, UK). The ^{15}N sample enrichment was expressed as δ^{15}N values [parts per thousand (‰)] relative to atmospheric N_2 (Shearer and Kohl, 1986), using the equation;

$$\delta\,^{15}\text{N}\,(‰) = 1000 \times \left[(R_{\text{sample}}/R_{\text{standard}}) - 1\right] \qquad (3.1)$$

Where R is the ratio of ^{15}N/^{14}N atoms in the sample and atmospheric N_2 was used as the standard ($R_{standard}$). By definition the δ^{15}N of atmospheric N_2 is zero. The precision of analysis including all procedures was ±0.02‰.

3.2.6 Calculations

Shoot biomass yields of the treatments were calculated using the mean weights of samples taken at three locations in each plot. The measured values of shoot biomass and %N were used to estimate the total N yields of each treatment, which were expressed in kg N ha^{-1}. The % of legume N derived from N_2-fixation was estimated using two methods:

a) ^{15}N natural abundance method (Shearer and Kohl, 1986; Peoples et al., 1997):

$$\%\text{ N from N}_2\text{-fixation} = 100\left(\frac{\delta\,^{15}\text{N}_{\text{ref}} - \delta\,^{15}\text{N}_{\text{legume}}}{\delta\,^{15}\text{N}_{\text{ref}} - B}\right) \qquad (3.2)$$

Where $\delta^{15}N_{ref}$ is the ^{15}N natural abundance of shoots of a non-N_2-fixing reference plant deriving its entire N from the soil; $\delta^{15}N_{legume}$ is the ^{15}N natural abundance in the legume shoots and B is the δ^{15}N of shoots of the target legume depending solely on N from N_2-fixation. In the current study, the B values were mainly derived from literature and where this information was lacking a lower value of N_{legume} recorded in the farmer fields was used as suggested by Shah et al. (1997).

b) N difference method:

$$\%\text{N from N}_2\text{-fixation} = 100 \times \left(\frac{\text{Ntfp} - \text{Ntnp}}{\text{Ntfp}} \right) \quad (3.3)$$

Where Ntfp is the total N in the N_2-fixing legume and Ntnp is total N in the non-N_2-fixing reference plant. In our case, the Ntnp was the mean N yields of maize, recorded on-station and on-farm in the two agro-ecological zones. Quantities of N_2-fixed by the legume species were calculated using the %N from N_2-fixation as:

$$\text{N fixed (kg ha}^{-1}) = \left(\frac{\%\text{N from N}_2\text{- fixation}}{100} \right) \times \text{N in legume biomass} \quad (3.4)$$

Recent studies have indicated that nodulated roots of legume plants contain substantial amount of fixed N and that the proportion varies with species (Rochester et al., 1998; Unkovich and Pate, 2000). In the present study, no attempt was made to estimate the fixed N in roots of the studied legumes.

3.2.7 Farmer assessment

Farmer assessment was done during the planning (*ex-ante*) and just before harvesting of the trials (*post-ante*). *Ex-ante* evaluation was done during farmer workshops, which were organised by a multidisciplinary team of researchers, in Kiilima in the high rainfall zone and Kabirizi in the low rainfall zone. A total number of 53 farmers; 25 in Kiilima and 28 in Kabirizi, men and women attended the workshops. The age of farmers ranged between 24 and 67 with a mean of 42 years in both villages.

The evaluation was done using a simplified Gender Analysis Matrix (GAM) (Joldesma, 1998). During the workshops, the potentials of legumes for soil fertility improvement and as source of livestock feed were presented. Farmers were then separated into 4 groups: men and women; keeping and not keeping diary cows. The farmers in these groups gave their views on possible (positive and negative) effects of adopting legumes to men, women, households and to the community. Results of analysis were presented in the GAM. The GAMs developed by the individual groups were discussed by all farmers to identify similarities and differences and a consensus GAM was developed.

The *post-ante* assessment involved 28 farmers in the high rainfall zone and 32 farmers in the low rainfall zone both trial and non-trial farmers. The assessment was conducted through discussions and ranking after a short tour to the on-station and to the respective sites in each zone. During discussions, farmers listed the criteria they thought were important to assess the performance of legumes. The given criteria were ranked in the order of importance. Using a matrix ranking method (Rowley, 2001) and scores were assigned to each legume according to the criteria mentioned. Scores were summed and the legume species with high scores per criterion were identified.

For this study the primary focus of researchers was on soil fertility improvement and increased production of quality fodder. Thus, the desired characteristics for legume ranking were biomass production, N accumulation and %N from N_2-fixation. To relate researcher preferences with those of farmers, the data were normalised by giving the higher value an index of 1 (100%). The indices for each attribute were summed per legume species and ranked.

3.2.8 Statistical analysis

On-station data were subject to analysis of variance and on-farm data were subject to the mixed model (RELM) of GENSTAT release version 6.1 (Lawes Agricultural trust, Rothamsted Experimental Station). Comparisons of treatment means were made by standard errors of differences (SED) when there were significant effects. The effect of soil characteristics on legume growth and N_2-fixation was analysed using stepwise linear regression.

3.3 Results

3.3.1 Farmer participation

On-farm, the final data were collected at 24 out of 32 established sites. Three sites in the high rainfall zone and 5 sites in the low rainfall zone were excluded after farmers had failed to weed their trials. Farmers mentioned shortage of labour (7 cases) and poor performance of the trial (one case) as reasons for not weeding their trials. At one site in the high rainfall zone, maize, *M. axillare, M. atropurpureum* and *D. intortum* were grazed by cattle before taking measurements. Farmer dropout and damage to treatments led to an unequal number of observations and subsequently to an unbalanced design for the on-farm trial.

3.3.2 Performance of legumes

Establishment, pests and disease incidences

At all sites, seed germination was good (>90%) for all legumes species and maize. Pests and diseases (data not shown) were observed on *C. juncea* (apple mosaic virus *Ilarvirus*), *C. paulina* (cowpea rugose mosaic *Potyvirus*) and on *L. purpureus* (bean fly

Ophyiyomyia phaseoli). No data for *C. juncea* is available for on-station site as it was completely wiped out by the virus. *Fusarium* wilts and root knot nematodes were observed on *T. vogelii* in most sites although only a few plants were affected. *C. grahamiana* was attacked by caterpillars of the orange butterfly (*Catochrysops* sp.) though later, at the flowering stage.

Nitrogen contents, shoot biomass, and shoot N yield

The % N in shoots of legumes varied among the species (1.7 to 3.6%) with lower values being recorded on *M. pruriens* both on-station and on-farm (Tables 3.2 and 3.3). Also, shoot biomass and N yields at all locations varied among legume species. The highest shoot biomass and N yield for non-forage legumes was recorded with *T. candida* both on-station and on-farm. For forage legumes the highest shoot biomass and N yield was recorded on *M. axillare* on-station and on-farm in the high rainfall zone but on *M. pruriens* in the low rainfall zone. *M. axillare*, *M. atropurpureum* and *D. intortum* yielded high shoot biomass (5 to 6 Mg ha^{-1}) and N (160-186 kg N ha^{-1}) on-farm in the high rainfall zone.

Table 3.2 Shoot nitrogen content, dry matter and nitrogen yields of maize, weedy and legume fallow species recorded at ARDI, Maruku, 5 months after planting.

Fallow type	Shoot N (%)	Shoot biomass (Mg ha^{-1})	Shoot N (kg ha^{-1})
Maize	0.7	2.9 [a]	21
Weedy fallow	0.8	1.1	8
Non-forage legumes			
Tephrosia candida	2.3	5.5	127
Tephrosia vogelii	2.4	1.7	41
Crotalaria grahamiana	2.7	2.1	57
Crotalaria paulina	2.2	0.8	18
Crotalaria juncea	-	-	-
Forage legumes			
Lablab purpureus	2.2	0.8	18
Mucuna pruriens	1.7	4.1	70
Macrotyloma axillare	2.4	3.7	89
Macroptilium atropurpureum	2.4	2.7	65
Desmodium intortum	2.4	2.8	67
SED	0.1***	0.7***	17***

[a] This value is for the total above ground biomass (grain and stover) four months after planting.
SED = Standard error of differences between legume species means

Table 3.3 Shoot nitrogen, dry matter and nitrogen yields of maize, weedy and legume fallow species observed in farmer fields in the high and low rainfall zones of Bukoba District, 5 months after planting.

Fallow type	High rainfall zone				Low rainfall zone				Y_{hrz} - Y_{lrz}	
	No of obs.	Shoot N (%)	Shoot biomass (Mg ha^{-1})	Shoot N (kg ha^{-1})	*No of obs.*	Shoot N (%)	Shoot biomass (Mg ha^{-1})	Shoot N (kg ha^{-1})	Shoot biomass (Mg ha^{-1})	Shoot N (kg ha^{-1})
Maize	12 [a]	1.2	1.8	22	11 [a]	1.2	1.4	17	0.4	5
Weedy fallow	13 [a]	1.0	2.0	20	11 [a]	1.1	1.6	17	0.4	3
Non-forage legumes										
Tephrosia candida	12 [a]	2.9	4.3	125	10 [a]	2.7	5.3	143	-1	-18
Tephrosia vogelii	11 [a]	2.6	1.0	26	9 [a]	2.4	1.1	26	-0.1	0
Crotalaria grahamiana	12 [a]	2.8	1.7	48	10 [a]	3.6	2.7	97	-1	-49
Crotalaria paulina	11 [a]	3.0	0.7	21	9 [a]	2.2	0.6	13	0.1	7
Crotalaria juncea	11 [a]	2.5	0.3	8	9 [a]	2.7	1.9	51	-1.6	-43
Forage legume										
Lablab purpureus	12 [a]	2.6	0.9	23	9 [a]	2.5	1.0	25	-0.1	-2
Mucuna pruriens	11 [a]	2.1	3.7	78	10 [a]	2.0	5.1	102	-1.4	-24
Macrotyloma axillare	3 [b]	3.2	5.8	186	2 [b]	2.8	3.3	92	2.5	94
Macroptilium atropurpureum	3 [b]	3.2	5.1	163	2 [b]	2.7	3.2	86	1.9	77
Desmodium intortum	3 [b]	3.2	5.0	160	1 [b]	2.6	1.9	49	3.1	111
SED Average		0.2***	0.6***	19.3***		0.5***	0.1***	24.8***		
Maximum		0.4	0.9	29.3		0.7	1.5	38.9		
Minimum		0.2	0.4	14.1		0.3	0.6	16.6		

SED = Standard error of differences between legume species means (****P*< 0.001).

[a] Number of replications out of the original 14 on which data were collected after farmer dropout or cattle grazing on treatments.

[b] Number of replications out of the original 4 on which data were collected after farmer dropout, cattle grazing on treatments or plant death due to drought.

Y_{hrz} = Yield in the high rainfall zone; Y_{lrz} = Yield in the low rainfall zone.

3.3.3 N_2-fixation

Natural ^{15}N abundance values for legumes and reference plants

The estimated $\delta^{15}N$ values of individual legumes and non-N fixing reference plants varied between species and were influenced by site (Tables 3.4, 3.5 and 3.6). The $\delta^{15}N$ values of non-N fixing reference plants ranged between +1.12 and +5.35‰ in the high rainfall zone, and between +1.56 and +5.51‰ in the low rainfall zone. The $\delta^{15}N$ of legumes were in the range of –0.48 and +1.64‰ and of –1.81 and 1.98‰ in the high and low rainfall zones, respectively. In all cases, the mean $\delta^{15}N$ values of non-N_2-fixing reference plants were above those of legumes with higher enrichments recorded on maize, indicating a general contribution from N_2-fixation to legume growth.

Soil pH was found to influence $\delta^{15}N$ in the non-N_2-fixing reference plants. For example, in more acidic soils (pH about 5.5 or less), the $\delta^{15}N$ values of maize and *Hyparrhenia* were above those of legumes (e.g. Figure 3.2 a, b and c). However, on slightly acidic soil (pH about 5.5 or more), there were occasions where the $\delta^{15}N$ values of *Hyparrhenia* were below those of *T. candida*, *T. vogelii* and *C. grahamiana* (e,g Figure 3.2 d and e). This indicates that N_2-fixation by these legumes was underestimated when *Hyparrhenia* was used as a non N_2-fixing reference plant using the ^{15}N natural abundance method.

N_2-fixation by legumes in different agro-ecological zones

Due to uncertainty on which reference crop was most appropriate, the $\delta^{15}N$ and %N values of the two reference crops were used to estimate the %N from N_2-fixation using the ^{15}N natural abundance method and ranges of estimates are reported (Tables 3.4, 3.5 and 3.6). The amount of N_2-fixation varied with legume species but the majority fixed a large proportion (>50%) of their N requirements. Despite being attacked by pests and diseases, *T. vogelii, C. juncea* and *L. purpureus* acquired more than 50% of their N requirements from N_2-fixation (as estimated by the ^{15}N natural abundance method). The poor N_2-fixation was closely linked with small biomass production (Figure 3.3) or in the case of *M. atropurpureum*, with a very low %N from N_2-fixation. In some occasions, using the N different method, negative values of N_2-fixation were obtained particularly with *T. vogelii*, *C. paulina*, *C. juncea* and *L. purpureus*. In this case these values were recorded as zero (Tables 3.4 and 3.5).

Table 3.4 Shoot δ ^{15}N of reference crops and legume species, estimated %N derived from N_2-fixation and amount of nitrogen fixed by legumes species, at ARDI, Maruku, 5 months after planting.

Species	*B*-value (‰)	Shoot $\delta^{15}N$ (‰)	%N from N_2 fixation estimated by			N_2-fixed (kg ha^{-1}) estimated by		
			^{15}N-Natural abundance method		N- difference method	^{15}N-Natural abundance method		N-difference method
			Range[a]	Mean [b]	Mean	Range[a]	Mean [b]	Mean
Non-forage legumes								
Tephrosia candida	-0.39 [c]	0.93	55-93	77	79	55-93	106	108
Tephrosia vogelii	-0.66 [d]	0.40	65-72	70	48	65-74	28	21
Crotalaria grahamiana	-0.13 [d]	1.24	38-66	53	57	38-75	32	36
Crotalaria paulina	-	-	nd	nd	0	nd	nd	0
Crotalaria juncea	-1.57	-		-	-	-	-	-
Forage legumes								
Lablab purpureus	-0.82 [c]	-	nd	nd	0	nd	nd	0
Mucuna pruriens	-0.91 [d]	1.47	22-47	36	62	21-61	24	48
Macrotyloma axillare	-1.83 [e]	0.03	59-62	61	75	59-73	54	68
Macroptilium atropurpureum	-2.34 [d]	0.76	39-42	41	66	39-74	26	44
Desmodium intortum	-1.00 [f]	0.02	67-83	74	66	67-83	49	46
SED		0.14***		1.1***	7.2**		17**	18.5**
Non N_2-fixing plants:								
Maize		4.08						
Hyparrhenia spp.		2.13						

SED = Standard error of differences between fallow species means (***P* < 0.01, ****P* < 0.001); nd = not determined.
[a] Range indicating the highest and lowest estimates of N_2-fixation of each species as derived from the two reference crops.
[b] Mean values of N_2-fixation of each species as estimated using the two reference crops.
[c] Lowest value measured in farmer fields; [d] values adopted Gathumbi et al. (2002);[e] From Cadisch (2002, personal communication).
[f] Value from Snoeck *et al*. (2000).

Table 3.5 Shoot $\delta^{15}N$ of reference crops and legume species (with their standard errors), estimated %N derived from N_2-fixation and amount of nitrogen fixed by legumes species, observed in farmer fields in the high rainfall zone of Bukoba District, 5 months after planting.

Species	*B* -values	Shoot $\delta^{15}N$ (‰) (range)	%N from N_2-fixation estimated by: ^{15}N-Natural abundance method		%N from N_2-fixation estimated by: N-difference method	N_2-fixed (kg ha^{-1}) estimated by: ^{15}N-Natural abundance method		N_2-fixed (kg ha^{-1}) estimated by: N- difference method
			Range[a]	Mean[b]	Mean	Range[a]	Mean[b]	Mean
Non-forage legumes								
Tephrosia candida	-0.39[c]	0.49 (-0.39 to +1.40)	45-100	70	72	8-201	97	113
Tephrosia vogelii	-0.66[d]	0.60 (+0.22 to +1.64)	27-78	58	0	5-39	13	0
Crotalaria grahamiana	-0.13[d]	0.84 (+0.38 to +1.53)	35-83	63	24	2-74	32	30
Crotalaria paulina	-	-	-	-	0	-	-	0
Crotalaria juncea	-1.57	-	-	-	0	-	-	0
Forage legumes								
Lablab purpureus	-0.82[c]	0.49 (+0.13 to +1.38)	40-79	62	0	5-67	16	0
Mucuna pruriens	-0.91[d]	-0.18 (-0.48 to +0.21)	64-89	78	62	21-135	62	64
Macrotyloma axillare	-1.83[e]	0.07 (-0.22 to +0.31)	38-62	52	94	48-150	102	169
Macroptilium atropurpureum	-2.34[d]	0.51 (-0.09 to+0.81)	33-43	38	94	52-75	61	146
Desmodium intortum	-1.00[f]	-0.01(-0.12 to +0.19)	55-77	68	93	81-140	109	142
SED Average				7.9***	48.4***		22.6***	24.1***
Maximum				10.9	70.0		31.0	34.9
Maximum				5.5	34.4		15.6	17.2
Non N_2-fixing plants								
Maize		2.76 (+1.38 to +5.35)						
Hyparrhenia spp.		2.51 (+1.12 to +3.70)						

SED = standard error of the difference between legume species means (*** $P < 0.001$).

[a] Range indicating the highest and lowest estimates of N_2-fixation of each species as derived from the two reference crops.

[b] Mean values of N_2-fixation of each species as estimated using the two reference crops.

[c] Lowest value measured in farmer fields; [d] values from Gathumbi et al. (2002); [e] From Cadisch (2002, personal communication);

[f] Value from Snoeck *et al.*(2000).

Table 3.6 Shoot δ ^{15}N of reference crops and legume species (with their standard errors), estimated %N from N_2-fixation and amount of nitrogen fixed by legume species, observed in farmer fields in the low rainfall zone of Bukoba District, 5 months after planting.

Species	*B*-values	Shoot $\delta^{15}N$ (‰) (range)	% N from N_2 fixation estimated by			N_2-fixed (kg ha^{-1}) estimated by		
			^{15}N-Natural abundance method		N-difference method	^{15}N-Natural abundance method		N-difference method
			Range[a]	Mean[b]	Mean	Range[a]	Mean[b]	Mean
Non-forage legumes								
Tephrosia candida	-0.39[c]	0.85 (-0.24 to +1.68)	38-76	57	85	27-145	78	109
Tephrosia vogelii	-0.66[d]	0.76 (-0.02 to +1.98)	24-79	55	20	9-32	11	8
Crotalaria grahamiana	-0.13[d]	0.76 (+0.14 to +1.71)	54-84	67	80	17-147	66	83
Crotalaria paulina	-	-	-	-	0	-	-	0
Crotalaria juncea	-1.57	0.78 (+0.19 to +1.71)	42-74	58	40	7-80	38	33
Forage legumes								
Lablab purpureus	-0.82[c]	0.26 (-0.82 to +1.91)	58-81	68	24	6-35	14	11
Mucuna pruriens	-0.91[d]	-0.26 (-0.82 to +0.11)	69-98	81	78	22-135	85	91
Macrotyloma axillare	-1.83[e]	-0.81 (-1.81 to -0.44)	57-87	72	62	16-102	80	82
Macroptilium atropurpureum	-2.34[d]	0.60 (+0.55 to -0.65)	20-46	33	69	8-42	46	75
Desmodium intortum	-1.00[f]	-0.13	-	71	48	-	42	37
SED Average				8.8***	35.9*		20.8***	31.5***
Maximum				12.9	53.1		29.1	46.7
Minimum				6.1	24.8		14.0	21.7
Non N_2-fixing plants								
Maize		2.41 (+1.56 to +5.51)						
Hyparrhenia spp.		2.09 (+1.89 to +2.61)						

SED = standard error of the difference between legume species means. (*** $P < 0.001$); [a] Range indicating the highest and lowest estimates of N_2-fixation of each species as derived from the two reference crops. [b] Mean values of N_2-fixation of a each species as estimated using the two reference crops; [c] Lowest value measured in farmers fields; [d] values from Gathumbi et al. (2002); [e] From Cadisch (2002, personal communication);
[f] Value from Snoeck *et al*. (2000)

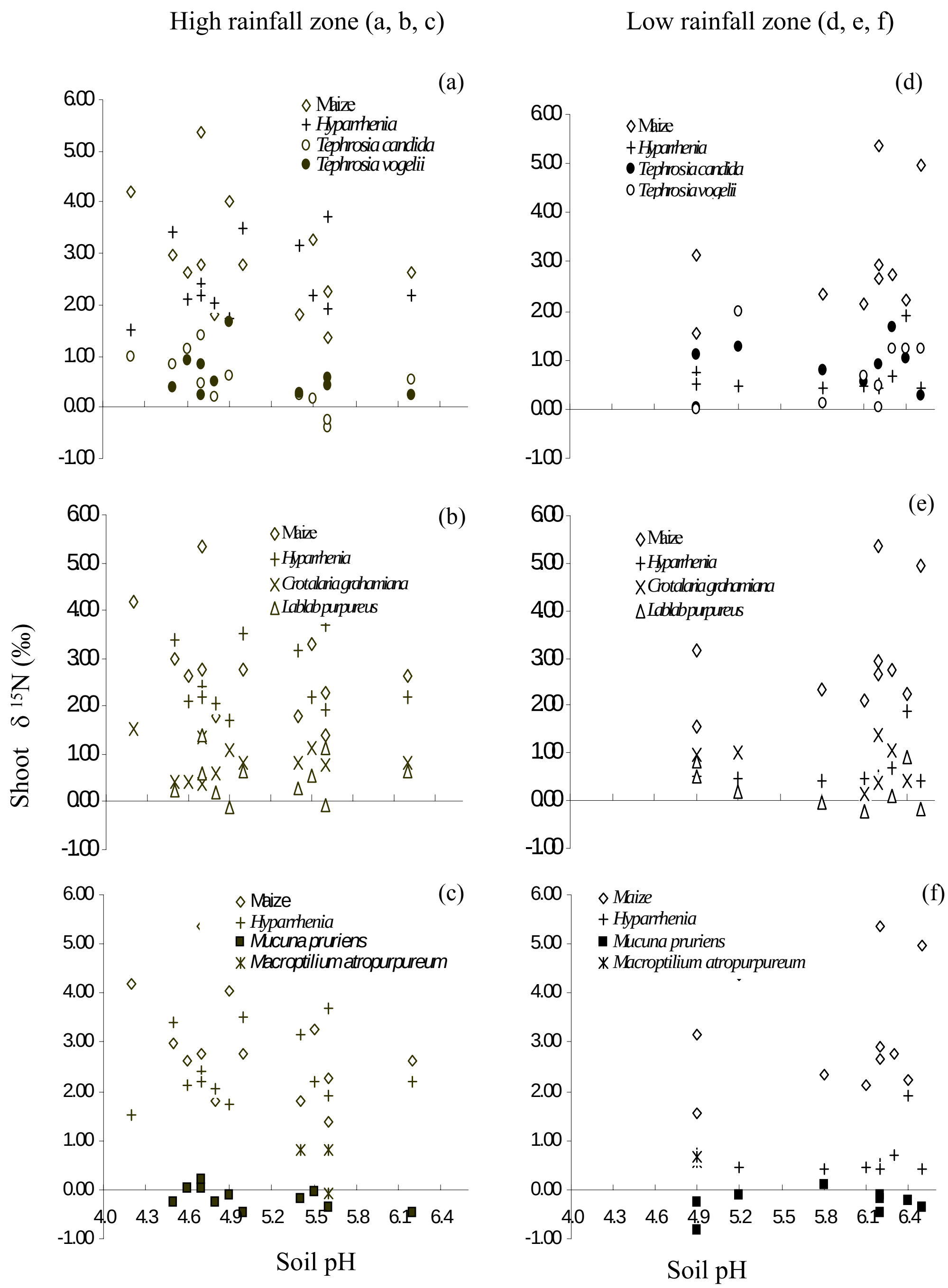

Figure 3.2 $\delta^{15}N$ in shoots of non-N_2-fixing reference plants and legume species growing on soils with different pH at 13 experimental sites in the high rainfall zone and 11 experimental sites in the low rainfall zone of Bukoba District.

Amounts of N fixed per Mg dry matter production

To derive benchmark values for comparing the symbiotic performance between legumes and across locations, we calculated the amount of shoot N fixed for every Mg of legume shoot biomass produced (Table 3.7). The calculation made use of N_2-fixation estimated by the ^{15}N natural abundance method. Despite large variations in values of % N from N_2-fixation and shoot N recorded on different legume species (Tables 3.5 and 3.6), the calculated values of N fixed per Mg shoot biomass indicated some uniformity. In the high rainfall zone, the mean N fixed by the non-forage legumes ranged between 15 and 21 kg Mg shoot biomass^{-1} and between 13 and 24 kg Mg shoot biomass^{-1} in the low rainfall zone. For forage legumes, the values obtained in the high rainfall fall zone were closer to those in the low rainfall zone. In general 21 kg N were fixed per Mg shoot biomass produced in the high rainfall zone. In the low rainfall zone this value was 17 kg (Figure 3.3).

Table 3.7 Estimated amount of shoot N_2-fixed per Mg of legume herbage dry matter (DM) produced for legumes grown in farmers fields in the high and low rainfall zones of Bukoba District, 5 months after planting.

Species	High rainfall zone		Low rainfall zone	
	Range	Mean	Range	Mean
Non-forage legumes				
Tephrosia candida	9-32	21	12-20	15
Tephrosia vogelii	7-21	15	8-18	13
Crotalaria grahamiana	9-21	18	12-54	24
Crotalaria paulina	-	-	-	-
Crotalaria juncea	-	-	11-20	16
Forage legumes				
Lablab purpureus	9-23	16	11-22	17
Mucuna pruriens	11-24	16	11-27	16
Macrotyloma axillare	12-20	17	14-28	21
Macroptilium atropurpureum	11-14	12	4-15	10
Desmodium intortum	18-25	22	-	19
SED Average				6.2
Minimum		ns		4.3*
Maximum				2.9

SED = Standard error of differences between fallow species means (*P < 0.05); ns = not significant.

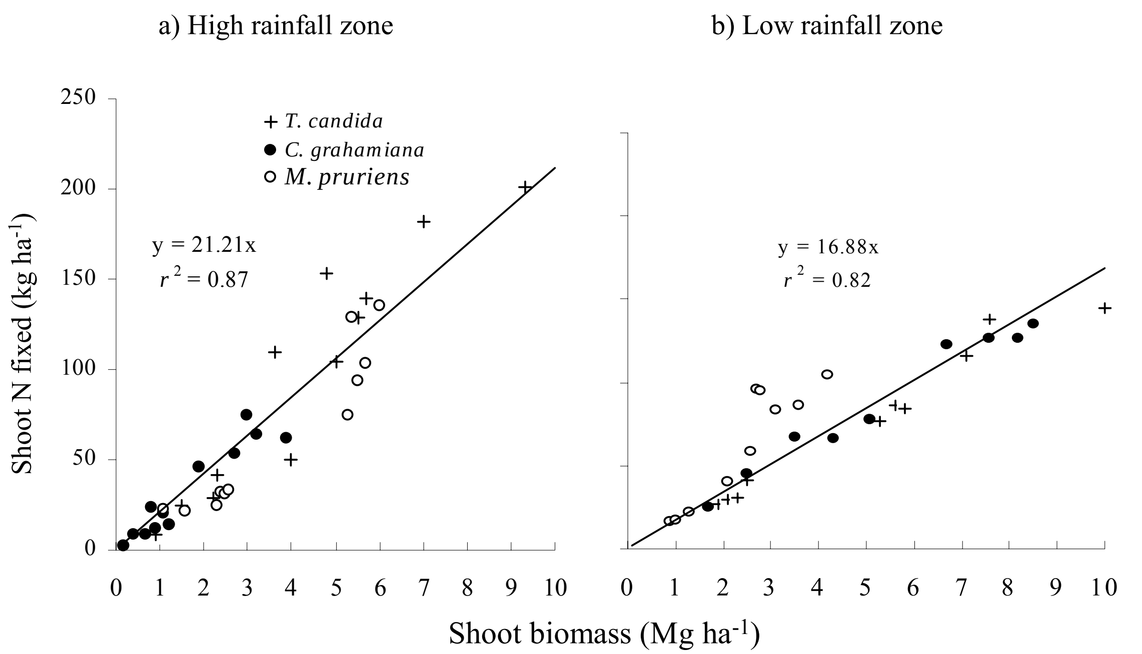

Figure 3.3 Relationship between shoot N fixed and shoot DM production by legume species in the a) high rainfall and b) low rainfall zones of Bukoba District.

Relationship between N_2-fixation and soil chemical characteristics

Soil pH and total soil N showed a strong relationship with measured N_2-fixation (Figure 3.4). For the sake of brevity we show only the relationships of these soil parameters with shoot biomass though the trend was the same for shoot N and N fixed. In the high rainfall zone, shoot biomass was positively correlated with soil pH, with *T. candida, M. pruriens* and *C. grahamiana* being more sensitive to the low pH values. In the low rainfall zone, shoot biomass was positively correlated with total soil N for all legumes. The percentage of variance encountered for these soil parameters was above 50% except for *C. grahamiana*, which was 34%.

3.3.4 Farmer assessment

Ex-ante assessment

Changes that farmers expect from the legumes and the way they are appreciated are summarised in Table 3.8. Men and women expected legumes to increase soil fertility, leading to improved crop yields, improved accessibility to cash from sales of extra yields and improved food security for households and the community. Men and women keeping dairy cows expected legumes to yield more biomass reducing shortage of fodder, increasing milk production and, in turn, adding cash. Men keeping dairy cows also expected legumes to increase manure production.

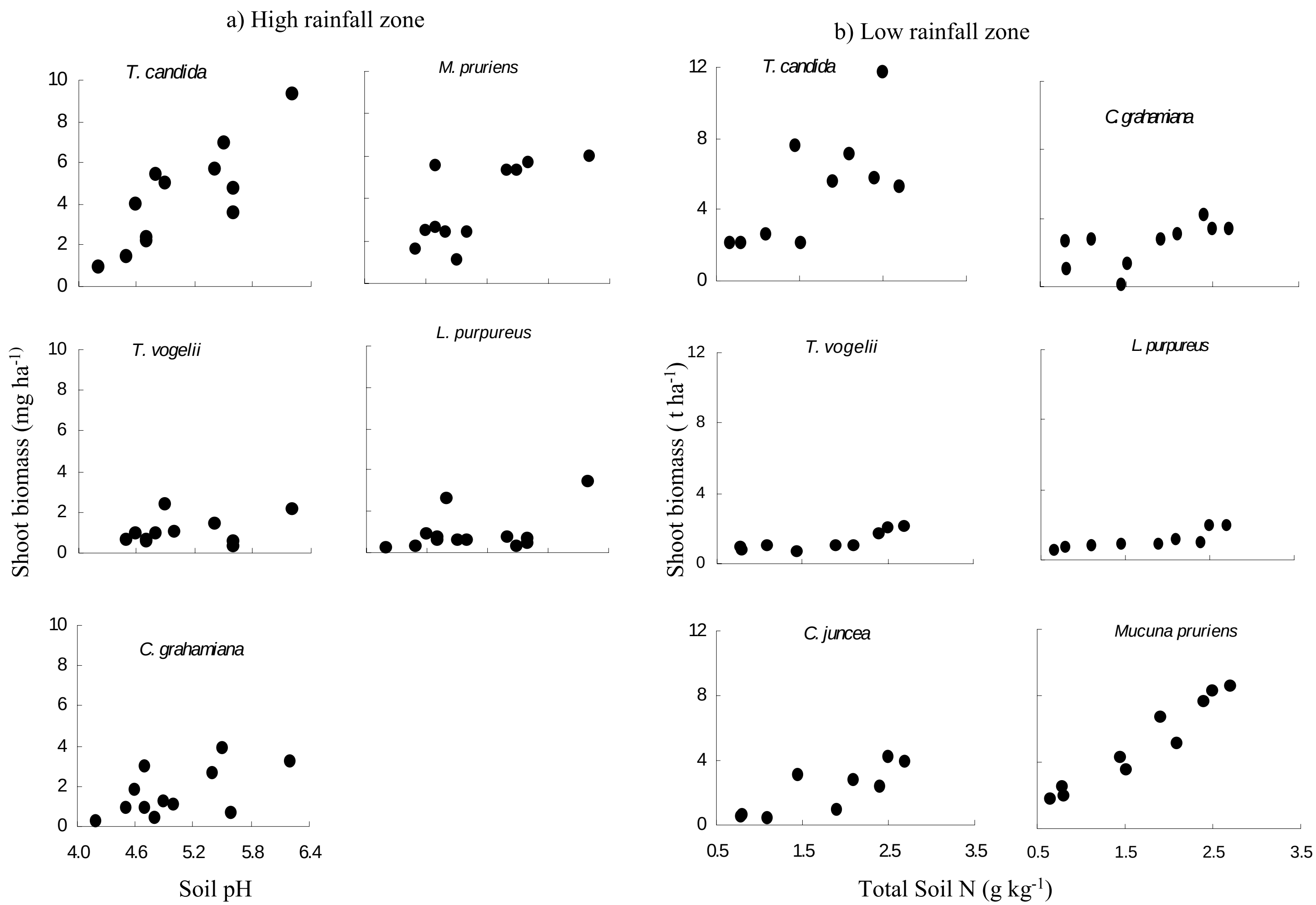

Figure 3.4 Relationships between shoot biomass yield of legume species and soil pH and shoot biomass yield and soil N in two agro-ecological ones of Bukoba District.

Both men and women feared that the introduction of legumes will increase demand for labour and time needed for farm activities and suggested relay cropping of legumes with annual crops as a solution. Men keeping dairy cows proposed integration of fodder legumes with fodder grass and indicated that they would hire labour if the technology becomes available. Women not keeping cattle feared to lose control over the annual cropping land because their husbands would decide to use it once it becomes fertile. All households feared that legumes would compete for land with other crops.

The solutions to the problem depended on whether the household kept dairy cows or not. Households not keeping dairy cows proposed to plant fast growing legumes in rotations with food crops, or grow legumes with food value. Households keeping dairy cows proposed to integrate fodder legumes with fodder grass (which were already established) and to grow fodder legumes on the edges of their homegardens. At the community level, it was feared that households with inadequate land would lose accessibility to borrowed land in anticipation that farmers with excess land will not be ready to lend out their fertile land. Strengthening of cultural arrangements for land sharing was proposed as the solution if this problem emerges.

Post-ante assessment

Except drought tolerance, which was only mentioned in the low rainfall zone, other criteria applied in both zones. Abilities of legumes to grow in different soils and to produce sufficient biomass were among the most important criteria (Table 3.9). In the high rainfall zone where weeds are a problem (see also Table 3.3), weed suppression was also ranked high. In the low rainfall zone, fodder legumes were highly valued despite their poor performance at most sites. In the high rainfall zone where pests and disease pressure is high, the tolerant legumes were thought important but the opposite was true in the low rainfall zone where pest and disease pressure is low.

In both zones, *T. candida* and *C. grahamina* were highly preferred among the non-forage legumes as they met most of the selection criteria (Table 3.10). For forage legumes, *M. pruriens* and *M. axiilare* were the first two choices in both zones on similar criteria as for the non-forage legumes. Farmers and researchers had different choices. While farmers ranked *M. pruriens* first, it was ranked fourth by researchers (Table 3.11). In the low rainfall zone, the differences in ranking were observed on *L. purpureus*, *M. atropurpureum* and *D. intortum*. The reasons for the differences between rankings of farmers and researchers are two-fold. First, farmers' selections were based on qualitative assessment whereas researchers used quantitative data.

Secondly researchers did not consider other farmer priorities e.g. weed suppression and food value.

Table 3.8 Modified simplified Gender Analysis Matrix for the introduction of forage and non-forage legumes in Bukoba District [25 men (6 dairy cattle keepers and 19 non-cattle keepers) and 25 women (4 cattle keepers and 21 non-cattle keepers)].

Category	Positive possible effects	Negative possible effects	Possible actions to reduce negative effects
Women -not keeping dairy cattle	• Increased soil fertility • Increased crop yields • Increased accessibility to cash	• Increased labour demand • Increased time for farm activities • Decreased control of annual cropping land	• Relay crop legumes with annual crops
Women -keeping dairy cattle	• Increased soil fertility • Increased crop yields • Increased accessibility to cash	• Increased time for farm activities	• Relay crop legumes with annual crops
Men –not keeping dairy cattle	• Increased soil fertility • Increased crop yields • Increased accessibility to cash	• Increased labour demand • More time required to learn the technology	• Relay crop legumes with annual crops
Men keeping dairy cattle	• Increased soil fertility/ crop yields • Increased crop yields • Increased accessibility to cash • Decreased expenditures cattle feeds	• Increased labour demand • Increased expenditures on hired labour • Declined milk prices	• Hire labour • Relay crop legumes with annual crops • Integrate legumes with fodder grass

Table 3.8 continued…..

Households not keeping dairy cattle	• Improved food security • Improved household income • Improved access to productive land • Increased household's prestige	• Competition for labour from other activities • Decreased land for other crops	• Plant fast growing legumes • Use legumes with food value • Relay crop legumes with annual crops
Households keeping dairy cattle	• Increased food security • Improved household income	• Increased expenditure on hired labour • Decreased land for other crops	• Integrate fodder legumes with fodder grass • Plant fodder legumes on farm borders
Community	• Improved food security • Increased investment in agriculture • Decreased crime incidences	• Decreased accessibility to land for households with inadequate land	• Strengthen cultural arrangements of land borrowing

Table 3.9 Farmer selection criteria in the high and low rainfall zone (28 and 32 farmers in the high and low rainfall zone respectively).

Criterion	High rainfall zone	Low rainfall zone
Drought tolerance	Nr.	1
Adaptability to different soils	1	2
Biomass accumulation	2	3
Weed suppression	3	5
Tolerance to pests and diseases	4	7
Fodder value	5	4
Multiple uses	6	6

Key: 1 is the highest score and 7 the lowest possible score.

Nr = Not relevant.

Table 3.10 Matrix ranking of legume species by farmers according to their selection criteria (26 farmers in the high rainfall zone, 10 men and16 females; 34 farmers in the low rainfall zone 15 men and 19 women).

Legume species	Drought tolerance	Adaptability to diff. soils	Biomass accumulation	Weed suppression	Tolerance to pests /diseases	Fodder value	Multiple uses	Total	Rank
a) High rainfall zone									
Non-forage legumes									
Tephrosia candida	-	5	5	4	5	-	5	24	A
Tephrosia vogelii	-	2	3	2	3	-	4	14	C
Crotalaria grahamiana	-	4	4	4	3	-	2	17	B
Crotalaria paulina	-	2	2	2	2	-	1	9	D
Crotalaria juncea	-	1	1	1	1	-	3	7	E
Forage legumes									
Lablab purpureus	-	2	2	1	2	4	4	15	E
Mucuna pruriens	-	4	5	5	5	3	5	27	A
Macrotyloma axillare	-	4	4	5	5	5	3	26	B
Macroptilium atropurpureum	-	3	4	3	3	5	3	21	D
Desmodium intortum	-	3	4	4	3	5	3	22	C
b) Low rainfall zone									
Non-forage legumes									
Tephrosia candida	4	5	5	5	5	-	5	29	A
Tephrosia vogelii	3	2	2	2	2	-	3	14	D
Crotalaria grahamiana	4	4	3	4	3	-	2	20	B
Crotalaria paulina	3	2	2	2	1	-	1	11	E
Crotalaria juncea	3	3	3	3	3	-	3	18	C
Forage legumes									
Lablab purpureus	2	4	3	3	2	4	4	23	C
Mucuna pruriens	5	5	5	5	5	3	4	32	A
Macrotyloma axillare	3	3	3	4	4	4	3	24	B
Macroptilium atropurpureum	3	2	2	3	3	4	3	20	D
Desmodium intortum	1	2	2	2	3	4	3	17	E

Scores: 5 = Excellent; 4 = Good; 3 = Average; 2 = Bad and 1 = Very bad; Rank: A = most desired and E least desired.

Table 3.11 Ranking of legume species by researchers based on shoot biomass, N accumulation and %N derived from N_2-fixation attained in different agro-ecological zones (figures are normalised results of shoot biomass and N in Table 3.3 and %N from N_2-fixation in Tables 5 and 6).

Legume species	Shoot biomass	Shoot N	% N from N_2-fixation	Total	Rank
a) High rainfall zone					
Non-forage legumes					
Tephrosia candida	1.00	1.00	0.85	2.85	A
Tephrosia vogelii	0.23	0.21	0.82	1.26	C
Crotalaria grahamiana	0.40	0.38	1.00	1.78	B
Crotalaria paulina	0.16	0.17	0.00	0.38	E
Crotalaria juncea	0.07	0.06	0.87	1.00	D
Forage legumes					
Lablab purpureus	0.16	0.12	0.84	1.12	E
Mucuna pruriens	0.64	0.42	1.00	2.06	D
Macrotyloma axillare	1.00	1.00	0.89	2.89	A
Macroptilium atropurpureum	0.88	0.88	0.41	2.16	C
Desmodium intortum	0.86	0.86	0.88	2.60	B
b) Low rainfall zone					
Non-forage legumes					
Tephrosia candida	1.00	1.00	1.00	3.00	A
Tephrosia vogelii	0.21	0.18	0.14	0.53	D
Crotalaria grahamiana	0.51	0.68	0.85	2.03	B
Crotalaria paulina	0.11	0.09	0.00	0.20	E
Crotalaria juncea	0.36	0.36	0.49	1.20	C
Forage legumes					
Lablab purpureus	0.20	0.25	0.17	0.61	E
Mucuna pruriens	1.00	1.00	1.00	3.00	A
Macrotyloma axillare	0.65	0.90	0.94	2.49	B
Macroptilium atropurpureum	0.63	0.84	0.54	2.01	C
Desmodium intortum	0.37	0.48	0.49	1.25	D

Rank: A = Best performance and E least performance.

3.4 Discussion and conclusions

3.4.1 Legumes performance under different soil and environmental conditions

The legumes yielded between 0.8 and 5.8 Mg of shoot biomass ha^{-1} and between 8 and 186 kg N ha^{-1}. The observed large variations indicate that legumes do not perform equally well in all locations due to differential abilities to tolerate environmental stresses like low soil N, low soil pH and tolerance to damage by pests and diseases (Hungria and Vargas, 2000; Giller, 2001). The observed pests and diseases on *T. vogelii* (nematodes) *L. purpureus* (Bean fly) and *C. paulina* (Mosaic virus) have also been reported in Kenya (Gachene et al., 1999; Qureshi, 2002, personal communication). To avoid becoming a secondary host for pests of beans (an important crop in the area) we recommend that farmers should not grow *L. purpureus*. Moreover, the root knot nematodes (*Meloidogyne* spp.) harboured by *T. vogelii* would be damaging on other legumes or other crops like tomatoes found in the farming systems.

Although the shoot biomass and N yield recorded on *T. candida, C. grahamiana* and *M. pruriens* were similar to those reported in the humid tropics of West Africa (Houngnandan et al., 2000; Ibewiro et al., 2000) and in the highland of Western Kenya (Gathumbi et al., 2002; Niang et al., 2002), the values of *M. axillare, M. atropurpureum* and *D. intortum* in the high rainfall zone, were higher than measured elsewhere e.g. 1.9-2.3 Mg ha^{-1} in Ghana (Barnes and Addo-Kwafo, 1993), but were comparable to those reported in Western Kenya 4-8 Mg ha^{-1}(Niang et al., 2002). We attribute the good performance of these legumes species (in Kenya and in Bukoba) to the combinations of good management and good moisture availability throughout the trial period.

3.4.2 N_2-fixation by legumes in different agroecological zones

Comparison of N fixation estimates by N difference and ^{15}N natural abundance methods

It is not our intention to discuss the suitability of the methods used to estimate N_2-fixation but rather the reliability of data so obtained. The negative estimates of N_2-fixed by *T. vogelii, C. paulina, C. juncea* and *L. purpureus* obtained using the N difference method (values reported as zero in Tables 3.4 and 3.5) are rather misleading and would discourage use of maize as reference for assessing N_2-fixation and soil N uptake by legumes. In this case, the legumes failed to grow well and accumulated less N than maize. Thus, reliability of estimates of N_2-fixation by the N difference method for these species is questionable. Nevertheless, the estimates made for other legumes fell within the ranges of values estimated by the ^{15}N natural abundance method.

One of the important potential problems with the use of ^{15}N natural abundance method is the required '*B'* value. This value has been found to vary with microsymbiont (Unkovich and Pate, 1998) and growing conditions (Ledgard, 1989). The *B* values used in the present study were obtained from the literature or taken as the lower values of specific legume species detected in the farmers' fields (Shah et al., 1997). Nevertheless, the mean values of %N from N_2-fixation estimated by the ^{15}N natural abundance method were in all cases below 85% indicating small errors associated with the use of inaccurate *B* values (Unkovich et al., 1994). We believe that the correct estimates of N fixed for each of the legumes species fall within the respective ranges.

N_2-fixation and influencing factors

The majority of legumes attained high values of %N from N_2-fixation (>60%) with large variations between sites. These variations were partly caused by site differences in soil pH and total N. The soil pH influenced the uptake of $\delta^{15}N$ by the reference plants (Figure 3.2), which in turn affected the estimates of N_2-fixation. There was evidence to suggest that soil pH and soil N were related to growth demand for N in the respective zones. In the high rainfall zone, soils with pH below 5.2 have Al saturation between 60 and 80% (Touber and Kanani, 1994), which can negatively affect rhizobia population and the effectiveness of the symbiosis (Hungria and Vargas, 2000; Giller 2001). On the other hand, low soil N might have reduced the growth of legumes in the first month when N_2-fixation ability had not fully established. Similar results have been reported on fast growing legumes (Amstrong et al., 1994, 1997). However, further work is warranted to substantiate these suggestions.

Despite the wide range of %N from N_2-fixation, the mean values for *T. candida*, *C. grahamiana*, *T. vogelii*, and *M. pruriens* were comparable to those by Houngnandan et al. (2000) and Niang et al. (2002). At many locations, the values of %N from N_2-fixation of *T. candida* and *M. pruriens*, *M. atropurpureum* and *D. intortum* were high. To the contrary, *M. atropurpureum* consistently fixed lower % of its N (>41%) at all sites, exhibiting high reliance on soil N for growth. Similar results were reported by Gathumbi et al. (2002). We conclude from the regression analyses that total amount of N-fixed by the legumes was influenced primarily by legume growth, i.e. shoot biomass (see Figure 3.3). Differences in legume growth and N_2-fixation may be partly explained by considerable damage caused by pests and diseases. Field observations indicated only small variability in plant populations and there were no significant differences in timing of weeding.

Despite the inherent differences in N concentration and site conditions, there seemed to be remarkable uniformity in values of kg N_2-fixed Mg biomass^{-1} between the legumes (Table 3.7). In the high rainfall zone for example, *M. axillare* derived a lower %N from N_2-fixation than *M. pruriens* but the herbage of *M. axillare* had higher N content so that similar amount of N were calculated to be fixed per unit biomass in both legumes. The majority of legumes fixed on average 17-21 kg shoot N biomass^{-1} per Mg in both zones. The data indicated little difference between forage and non-forage legumes. However, *M. atropurpureum* fixed lower N Mg biomass^{-1} in both zones. Overall, the amount of N fixed was 60 kg N ha^{-1} in 5-months on average, the value which is above the recommended fertiliser application rate for maize in the study area of 50 kg N ha^{-1} (Mowo et al., 1993). It is likely that total amounts of N fixed were much larger as our estimates do not account for N_2-fixation in the roots, which for some legumes has been estimated to be as high as 40% (Jørgensen and Ledgard, 1997; McNeill et al., 1997). It would be desirable to include such measurements in future studies.

3.4.3 Socio-economic factors determining legume adoption

Availability of land, labour, and cash were the major factors considered to influence the adoption of legumes (Table 3.8). The analysis also indicated that individual farmers would adopt different types of legumes depending on their production objectives and opportunities. For example, while the non-dairy cattle keepers showed more interest on the non-forage legumes to increase food production, cattle keepers also showed interest on forage legumes to increase cash income through producing marketable surplus milk and manure. Thus, it would be desirable to assess the net effect of legumes on yields, labour requirements, economic benefits and comparisons of trade-offs under different farmer conditions. This also includes agronomic evaluation of legume performance, and the functioning of the spatial temporal niches proposed by farmers.

3.4.4 Potential legumes for inclusion in the farming system

Although farmers in two zones used similar criteria to select the legumes, the importance attached to each criterion varied according to the zones reflecting the production constraints that were experienced. For example, weed suppression and tolerance to pests and diseases were ranked high in the high rainfall zone probably because of high weed infestations and the observed damage on some of the legumes (see Section 3.3). Likewise, moisture, and fodder availability are problems in the low rainfall zone, thus were ranked higher. Soil fertility is a problem in both zones, so farmers preferred legumes that did better across many soils. Overall, *T. candida* and *C. grahamiana* were most preferred among the non-forage legumes and *M. pruriens* and *M. axillare* among the forage legumes.

From this study we were able to understand better farmers' desires and the best legumes that could suit their conditions. What remains unknown is whether these legumes can make substantial differences to crop and livestock production and meet farmers objectives, and if these benefits will be sustainable. With the observed poor performance of legumes on poor soils, little should be expected from them unless strategies to substantially increase their biomass yields and N from N_2-fixation are found. Liming to increase soil pH and application of starter N would be an option, but in the context of the present constraints to farmers', other alternatives should be considered. One possible option which could be tried is boosting of legume growth through application of small quantities of manure where available.

Acknowledgement

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A

B

Participatory technology development with farmers ensures early adoption.

A: Farmers are evaluating legumes species in the field;

B: Farmers are doing the ranking exercise to identify legume species with most desired characteristics.

Chapter 4

Nitrogen release from decomposing residues of herbaceous legumes and their effect on maize yield on nutrient depleted soils of Bukoba District, Tanzania

This chapter is in press as:

Baijukya, F.P., Ridder, N. de and Giller K.E. Nitrogen release from decomposing residues of herbaceous legumes and their effect on maize yield on depleted soils of Bukoba District Tanzania. Plant and Soil.

Chapter 4

Nitrogen release from decomposing residues of herbaceous legumes and their effect on maize yield on nutrient depleted soils of Bukoba District, Tanzania

Abstract

Nitrogen release patterns from decomposing shoot residues of *Tephrosia candida, Crotalaria grahamiana, Mucuna pruriens, Macrotyloma axillare, Macroptillium atropurpureum* and *Desmodium intortum* were studied in the laboratory for a period of 22 weeks in a sandy clay soil and 10 weeks in a clay soil using a leaching tube technique. The residual effect of soil incorporated shoot residues of *T. candida*, *T. vogelii*, *C. grahamiana*, *M. pruriens* and *C. juncea* on maize yield was evaluated at 4 sites each in the high rainfall zone (mean precipitation 2100 mm year^{-1}) and low rainfall zone (mean precipitation 800 mm yr^{-1}) of Bukoba District, Tanzania. N mineralised from the legume residues ranged from 24 to 61% of the initial N after 22 weeks in a sandy clay soil and –1 to 34% after 10 weeks in a clay soil. The N mineralisation rates of the residues decreased in both soils in the order *M. atropurpureum* > *M. axillare* > *C. grahamiana* > *D. intortum* > *T. candida* > *M. pruriens* and were mostly strongly related to (polyphenols + lignin)-to-N ratio, lignin-to-N ratio and lignin. Relative to the control, legume residues resulted in two and three-fold increase in maize grain yield i.e. from 1.1 to 3.2 Mg ha^{-1} and from 1.4 to 3.8 Mg ha^{-1} in the high and low rainfall zone, respectively. However, maize yield response to legume residues was limited when compared with application of 50 kg N ha^{-1}of mineral fertiliser. The % fertiliser equivalency of legumes ranged between 25 to 59% with higher values recorded with *C. grahamiana*. At harvest, apparent N recoveries in maize ranged between 23 and 73 % of the N applied in the legume residues. Highest recovery was found with application of *C. grahamiana* and least recovery from *T. candida* residues. These results suggested that application of legume residues alone might not be sufficient to meet N requirements and to achieve the yield potential of the maize crop in Bukoban soils unless supplemented with small doses of mineral fertilisers.

Key words: *Legume cover crops; Residue quality; N-minerlaisation; N-uptake; Maize yield; N-use efficiency*

4.1 Introduction

One of the main advantages of N_2-fixing legumes in cropping systems is that they supply substantial amounts of N to the soils when their residues decompose (Kang et al., 1999; Giller, 2001). However, the effectiveness of released N to growing crops can be poor compared with that of mineral fertilisers (Mulongoy and Meersch, 1988; Giller et al., 1997). The restricted uptake of organic N by the crops is attributed to the lack of synchrony between the N release and N demand by the crop (Palm et al., 1997; Mafongoya et al., 1998). This can arise under two situations; firstly, when mineral N supply comes too late for the crop demand, in the case of slowly decomposing residue materials and, secondly, when N supply comes too early for the crop demand and is lost to the environment, in the case of fast decomposing organic materials (Giller and Cadisch, 1995; Akinnifesi et al., 1997; Myers et al., 1994, 1997). Understanding the N release patterns of decomposing legume residues may therefore help in optimising N-use efficiency in the legume-crop rotation systems.

The rates at which the decomposing legume residues release N has been linked to their structural and chemical characteristics or "residue quality", to the soil physical-chemical and biological activities and to environmental factors such as temperature and moisture (Veen and Kuikman, 1990; Giller and Cadisch, 1995; Palm et al., 2001). Various indicators such as carbon (C)-to-N ratio, lignin-to-N ratio, polyphenols-to-N ratio and polyphenols plus lignin-to-N ratio for predicting N release from organic materials have been developed (e.g. Palm and Sanchez, 1991; Vanlauwe et al., 1997; Mafongoya et al., 1998; Palm et al., 1997, 2001). Other quality parameters of organic resources such as condensed tannins, soluble carbon and fibre-bound N have also been reported to modify N release patterns (Handayanto et al., 1997).

In Bukoba District, northwest Tanzania, as in most parts of sub-Saharan Africa, organic resources continue to be a major source of plant nutrients in smallholder farming (Baijukya and Steenhuijsen Piters, 1998). However, quantities of the traditional major organic input, cattle manure, are declining as only a few households can afford to keep livestock (Kop, 1995; Baijukya et al., submitted (a)). The types of organic resources available are maize stover and weeds, poor in nitrogen (N), which cause N immobilisation initially when added to the soils (Giller et al., 1997; Sakala et al., 2000). Attention is now focusing on generating sufficient quantities of organic residues, high in N contents, by introducing N_2-fixing short fallow legumes for rotation with annual crops (Baijukya et al., submitted (a). As a first step, farmers have selected some herbaceous legumes for soil fertility improvement and for fodder based on biomass yields, tolerance to pests and diseases and adaptability to infertile soils. The ability of these legumes to contribute N and their impacts on the performance of subsequent crops in Bukoba is not yet known.

This study was conducted with the following objectives; *i*) to understand the nitrogen release behaviour of farmer selected herbaceous legumes under laboratory conditions (*ii*) to determine the effect of application of legume cover crop residues on maize yield in farmers fields in Bukoba District with different soils and climatic conditions and *iii*) to determine the N fertiliser equivalency of the above ground parts of legume cover crops and the efficiency of use by maize crop.

4.2 Materials and methods

4.2.1 Nitrogen release from decomposing legume residues

A nitrogen mineralisation study was conducted using a modified leaching tube technique (Stanford and Smith, 1972). The materials studied were 5 month old residues (dry leaves and stems) of *Tephrosia candida*, *Crotalaria grahamiana*, *Mucuna pruriens*, *Macrotyloma axillare*, *Macroptilium atropurpureum* and *Desmodium intortum*, grown at Maruku Agricultural Research Institute (ARI Maruku). N release by the decomposing residues were compared in a sandy clay soil (Alumi-humic Ferralsol) and a clay soil (Humic Acrisol). The soils were collected from the high and low rainfall zones of Bukoba District, where they widely occur in annual cropping systems in the respective zones (*see 4.2.2* for explanations of zones). An unamended soil treatment was included in each case as a control. The characteristics of the soils and legume residues studied are given in Table 4.1.

The soils were ground to pass a 2 mm sieve and the legume residues ground to <1 mm in a cyclotech mill. Forty-five grams of soil was mixed thoroughly with 45 g of acid-washed sand (w/w). The soil-sand mixture was mixed with plant material at a rate of 100 mg N kg^{-1} soil and added to the leaching tubes. De-ionised water was added to bring the moisture content in the tube to about 70% of the water holding capacity. After setting up of the experiment, the tubes were immediately leached with a leaching solution (containing 1 mM $CaCl_2$; 1 mM $MgSO_4$ and 0.1 mM KH_2PO_4 and 0.9 mM KCl_2) (Cassman and Munns, 1980). The initial leachates (day 0) were analysed for mineral N (NH_4^+ and NO_3^-) and for organic N after Kjeldahl digestion**.**

The tubes were loosely covered with aluminium foil and transferred to an incubator with controlled temperature (27^{o}C) and humidity (70%). The experiment was set in a completely randomised design with each treatment replicated 4 times. Leaching was done after 1, 2, 4, 6, 8, 10, 14, 18 and 22 weeks for the sandy clay whereas for clay soil leaching was stopped at 10 weeks. This was because the clay particles had blocked drainage. The leaching was done using 100 ml of a leaching solution in 50 ml aliquots. After each leaching, the moisture content in the tubes was brought back at 70% by removing the excess water with mild suction. The leachates were analysed for mineral N (NH_4^+ and NO_3^-).

Nitrogen mineralization/ immobilisation (expressed in percent) was calculated from the difference in cumulative amounts of mineral nitrogen between soil treated with legume residues and a control at each sampling time divided by the initial nitrogen of the plant residues.

$$N_{min} = \frac{\text{Min N (treat) - Min N (control)}}{\text{Total residue N added}} \qquad (4.1)$$

The rate constants of nitrogen mineralisation (*k*) for the residues were estimated assuming a single exponential decay equation (Wieder and Lang, 1982) as:

$$Y = Y_o \exp(-kt) \qquad (4.2)$$

where *Y* is the percentage of N remaining of the soil plant mixtures at time *t*. The *k* value was obtained as a slope of the linear regressions of ln *Y* versus *t*; immobilisation values were omitted. The obtained data on % cumulative N mineralisation/ immobilisation and *k* were correlated with all legume quality data except P and K content (Table 4.1).

4.2.2 Assessment of maize response to the application of legume residues

Experimental sites and their characteristics

The experiment was carried out on station and in farmers fields in the high (mean precipitation 2100 mm yr^{-1}) and low rainfall zone (mean precipitation 800 mm yr^{-1}) of Bukoba District ($1^o13'$ - $1^o30'$ S and $31^o19'$ - 31^o 52' E), in two seasons (September 2001- January 2002 and March - June 2002). The high rainfall zone occurs on the ridges (appr.1400 m. a s l) with N-S orientation stretching into Lake Victoria, and the low rainfall zone occurs on the leeward side of the ridges 50 - 60 km from the shores of Lake Victoria.

The geological material is predominantly Bukoban Sedimentary System in the high rainfall zone, and Karawe-Ankolean Metamorphic and Alluvial System in the low rainfall zone (Touber and Kanani, 1994). The daily rainfall during the experimental period is summarised in Figure 4.1. In the high rainfall zone, the experiment was conducted at ARI Maruku hereafter called on-station and in the villages Butairuka and Kiilima (4 sites in each village). In the low rainfall zone, the experiment was located in the villages Kabirizi (4 sites) and Kyaitoke (3 sites). The soil types at the trial sites in the respective zones are Alumi-humic Ferralsols and Humic Acrisols and their characteristics are summarised in Table 4.2.

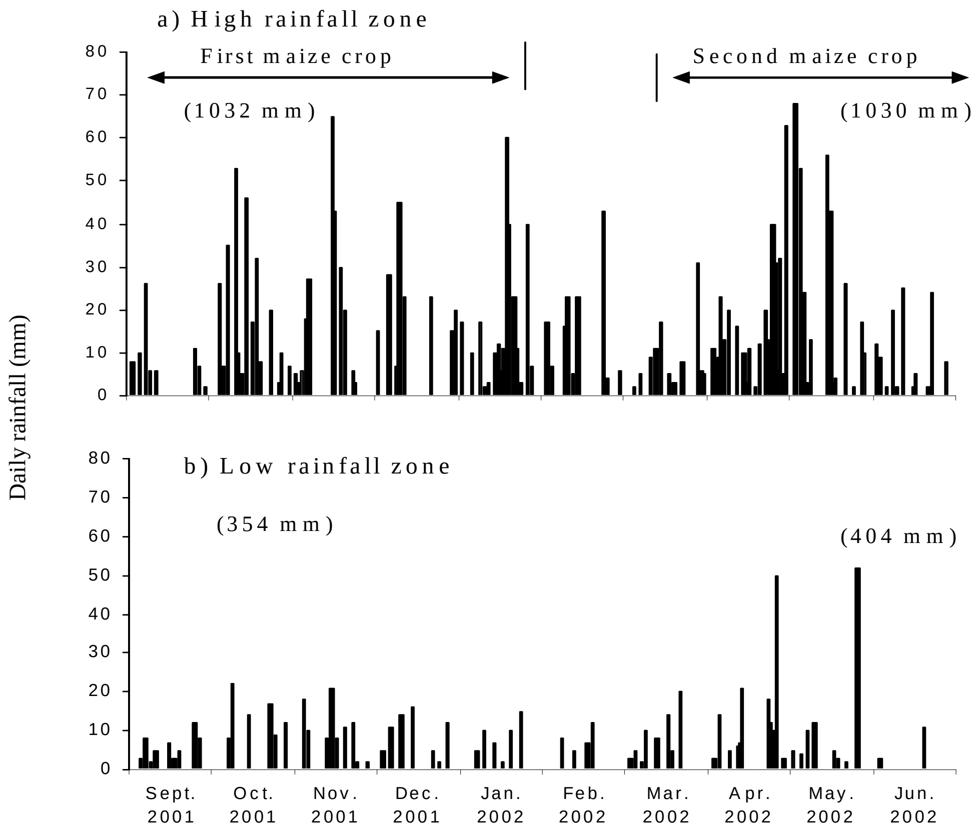

Figure 4.1 Daily precipitation during the maize growing seasons in the high (a) and low (b) rainfall zone of Bukoba District. Data in parenthesis are means over two seasons.

First maize crop (September 2001 – January 2002)

This experiment was in the plots where previously the adaptability, productivity and N_2-fixation of legume cover crops had been studied between March and August 2001 (Chapter 3; Baijukya et al., submitted). In the previous experiment, treatments comprised 10 legume species, weedy fallow and sole maize crop. Four legume species, namely *Tephrosia candida*, *Crotalaria grahamiana*, *Crotalaria juncea* and *Mucuna pruriens*, were selected by farmers for use as short fallow crops and were part of the current treatments. The treatments were i) *T. candida* ii) *C. grahamiana* iii) *M. pruriens* residues incorporated into the soil, respectively, iv) N mineral fertiliser at a rate of 50 kg N ha^{-1} (current recommended rate for maize) in plots previously under maize and v) a control (without any amendments) in plots previously under weedy fallow. *T. vogelii* residues incorporated into the soil was an additional treatment at the on-station site and incorporated *C. juncea* residues was an additional treatment in the low rainfall zone. The mineral fertiliser and weedy fallow treatments replicate current farmer practices and act as reference plots for comparison.

Prior to the maize crop, soil samples were taken from each of the previous treatments to measure the N, P and K stocks. Although below-ground parts of legumes residues can provide a significant amount of N in the form of dead tissue and nodules (McNeill et al., 1997; Peoples et al., 2001; Cadisch et al., 2002), measurements in this study were restricted to above-ground legume residues, as root sampling was not possible given the on-farm nature of the experiment.

The above-ground parts of the specific legume species were harvested, weighed, chopped into pieces < 10 cm and incorporated into the soils (about 15 cm) using a hand hoe, in the period of 3 to 5 days after harvest. The amounts of legume residues applied per site depended on biomass yield of the particular legume species, which was in the range of 1 to 9 Mg ha^{-1}. Weeds and maize stover in plots previously under weedy fallow and maize were removed from the plots. On-station, the experiment was arranged in a completely randomised block design in four replicates, with a plot size of 21 m^2. On-farm, the experiment was arranged in a randomised design with a plot size of 34 m^2, each site being a replicate.

The maize variety *Kilima* was sown in the third week of September 2001, one week after legume residues were incorporated into the soil, at a spacing of 0.75 x 0.45 m by placing 3 seeds per planting hole. Prior to planting of maize, all plots received basal fertiliser of 15 kg ha^{-1} P and 20 kg ha^{-1} K as triple super phosphate (46% P_2O_5) and muriate of potash (60% K_2O), respectively. The maize pockets without germination were replanted two weeks after first sowing. Mineral N fertiliser in the form of calcium ammonium nitrate ($Ca(NO_3)_2\ NH_4NO_3$) was applied to + N-fertiliser plots in two splits of 25 kg N ha^{-1}, at 4 and 7 weeks after maize emergence. Maize was weeded manually at regular intervals and weeds were left in the plots.

The maize was harvested between the second and fourth week of February 2002, from the inner 16 m^2 of the plot on-station, and 18 m^2 on-farm. Maize stover from the

Table 4.1 Characteristics of a) soils and b) legume residue materials used in the decomposition study. Legume residues were 5 month old and collected at ARI Maruku.

a) Soils [a]	pH		OC [b] (g kg^{-1})	Total N (g kg^{-1})	C:N	P –Olsen (mg kg^{-1})	Exchangeable cations (cmol c kg^{-1})			Exch. acidity (cmol c kg^{-1})
	(H_2O)	1N KCl					Ca	K	Mg	
Sandy clay soil	5.2	4.6	38.1	2.5	15.0	7.3	0.5	0.18	0.1.	1.3
Clay soil	6.1	4.1	20.9	1.4	15.0	7.1	2.4	0.20	0.7	0.6

b) Legume residues [a]	%N	% P	% K	% lignin	% soluble polyphenols	Lignin:N ratio	Polyphenols: N ratio	(Lignin + Polyphenols): N ratio
Tephrosia candida	2.0	0.1	0.5	15.6	3.4	7.9	1.7	9.6
Crotalaria grahamiana	2.3	0.2	0.8	4.6	1.8	2.0	0.8	2.7
Mucuna pruriens	1.7	0.1	0.5	16.6	2.0	9.6	1.1	10.7
Macrotyloma axillare	2.3	0.3	1.3	8.2	2.1	3.5	0.9	4.4
Macroptillium atropurpureum	2.4	0.2	1.3	9.3	1.7	3.9	0.7	4.6
Desmodium intortum	2.5	0.2	1.0	12.8	4.8	5.2	2.0	7.2

[a] analyses by TSBF/ ICRAF laboratories, Nairobi, Kenya; [b] Organic Carbon.

Table 4.2 Soil chemical and physical properties of topsoil (0-30 cm) of the trial sites at maize plant time. Data are means and ranges (in parentheses) for 8 sites in the high rainfall zone and 7 sites in the low rainfall zone.

Zone	pH (H_2O)	Organic C (g kg^{-1})	Total N (g kg^{-1})	Exchangeable cations (cmol c kg^{-1})			Particle size (%)		
				Ca	K	Mg	Sand	Silt	Clay
High rainfall (Sandy clay soil)	5.3 (4.1-6.3)	21.2 (13.0-42.0)	1.1 (0.6-3.1)	0.7 (0.4-2.1)	0.2 (0.2-3.6)	0.2 (0.1-0.3)	58 (54-62)	26 (22-28)	16 (14-24)
Low rainfall (Clay soil)	6.0 (4.9-6.5)	18.3 (11.7-30.6)	1.2 (0.8-2.7)	0.7 (0.4-2.1)	0.2 (0.2-3.6)	0.2 (0.1-0.3)	30 (10-36)	28 (24-30)	42 (34-48)

harvest area was weighed and sub-samples taken for dry matter determination and analysis for the N contents. Maize cobs were weighed and after shelling, the maize grains were weighed, oven dried at 72° C for 48 hrs and re-weighed to determine their dry matter contents. Maize grain yields were expressed at 14% moisture content. Samples of maize grain and stover were taken for the analysis of N contents. The plots were pegged so that data collection was done within the same area during the second maize crop. The effect of mineral N fertiliser and legume residue was calculated as the difference between maize yield after fertiliser or residue amendment and maize yield with no amendment.

Second maize crop (March 2002 - July 2002)

The residual fertility of mineral N fertiliser and legume residues was re-assessed on the second maize crop that was planted one month after harvesting of the first maize crop (six months after legume residues were incorporated into the soils). Maize stover was removed from the plots and the plots were weeded, leaving the weeds in the plots. Planting of maize was done in the second week of March. The maize crop received the same management as in the first season except that no additional fertilisers and organic amendments were applied. Harvest of maize was done in the second week of June 2002, and measurements were taken on maize cobs, grain and stover as in the first season.

4.2.3 Fertiliser N equivalence and use efficiency

The fertiliser N equivalence (FE) of the legume residues in the respective zones was determined by comparing the changes in maize grain yield following application of mineral N fertiliser assuming a linear response. In earlier studies (Baijukya and Folmer, 2002) the N response curve for maize at ARI Maruku ceased to be linear with application of 80 kg N ha^{-1} or more. The first season maize grain yields attained after legume residue incorporation were horizontally projected onto the fertiliser N response curves of the respective zone to determine the fertiliser equivalence (FE) see Figure 4.6. To compare the FE of legume residues in different zones and where the amounts of residue N applied were different, the percent fertiliser equivalency values (%FE) were calculated as:

$$\%FE = \frac{FE \times 100}{N_{applied}} \qquad (4.3)$$

Where $N_{applied}$ = actual amount of N applied in legume residues.

Nitrogen uptake (kg ha^{-1}) was calculated for grain and total above ground biomass as the N contents (%) multiplied with the yield (Mg ha^{-1}). The efficiency of use of N fertiliser (mineral fertilisers and residue N), its recovery and utilisation efficiency by the maize crop and was calculated using the following equations:

$$\text{N use efficiency} = \frac{kg\ yield}{kg\ N\ applied} \qquad (4.4)$$

$$\text{N recovery efficiency} = \frac{kg\ N\ uptake}{kg\ N\ applied} \qquad (4.5)$$

$$\text{N utilisation efficiency} = \frac{kg\ yield}{kg\ N\ uptake} \qquad (4.6)$$

Where *Yield* (Y) = ($Y_{fertiliser} - Y_{control}$); *N uptake* ($U$) = ($U_{fertiliser} - U_{control}$)

4.2.4 Soil, plant material and leachate analyses

Soil samples were analysed using the following procedure: pH H_2O (1:5 w/v) and in 0.01 M KCl, organic carbon by Walkley-Black wet oxidation method, total N by the micro-Kjeldahl digestion method. Available P was determined by Bray I acid-fluoride method and P in solution determined by ascorbic acid blue colour method of Murphy and Riley (1962), exchangeable cations by ammonium acetate extraction, with Ca and Mg estimated by the atomic absorption spectrometry (AAS) and K by flame photometer. Exchangeable acidity was determined using the KCl method. Particle size distribution was analysed by standard hydrometer method (Page et al., 1982). The plant materials (legume residues, grain and stover) were analysed for total N by the micro-Kjeldahl digestion method followed by distillation and titration. Using the same digestion solution, P was measured colorimetrically by a spectrophotometer and K by flame photometry (Okalebo et al., 1993). Extractable polyphenols were determined by the Folin-Denis method (Anderson and Ingram, 1996). Lignin was determined by the acid detergent fibre method (Goering and Soest, 1970). Mineral N (NH_4^+ and NO_3^-) in the leachates were determined using a colorimetric method (Temminghoff et al., 2000). All analyses were done with two replicates, from which the mean was calculated.

4.2.5 Statistical analysis

Analysis of variance was conducted on maize grain, total aboveground biomass yield and for N use efficiencies using GENSTAT (Genstat release 6.1, Lawes Agricultural Trust). Standard errors of the difference between means were calculated. The correlation coefficients were calculated between the soil chemical parameters, the legume biomass and N applied and maize yield (grain and total above ground biomass).

4.3. Results

4.3.1 Chemical composition of soils and legume residues

The sandy clay soils from the high rainfall zone were strongly acidic, with high organic C and exchangeable acidity compared to the clay soils from the low rainfall zone (Tables 4.1 and 4.2). In both zones, prior to maize establishment, no significant differences in soil N, P and K (data not presented) were apparent between plots previously under weedy fallow, maize and legume fallows. The legume species *T. candida* and *M. pruriens* had lower N contents, intermediate soluble polyphenol contents but high lignin contents. *D. intortum* had high N content, intermediate lignin content and high soluble polyphenols contents whereas *C. grahamiana*, *M. atropurpureum* and *M. axillare* had high N contents and low lignin and soluble polyphenol contents (Table 4.1). Except for *T. candida* and *M. pruriens*, which had low percentages of P and K, contents of these nutrients in other legume residues were comparable.

4.3.1 N released from decomposing legume residues

The proportion of N released from the residues as mineral N ranged from 25 to 61% for the sandy clay soil and from –1 to 26% in the clay soil after 22 and 10 weeks of incubation, respectively (Figure 4.2). In the sandy clay soil, *T. candida, M. pruriens, M. axillare* and *D. intortum* showed net immobilisation in the first two weeks of incubation (Figure 4a). A similar trend was observed in the clay soil except for *M. axillare*, which exhibited net immobilisation from the first week (Figure 4.2 b). After 4 weeks, re-mineralisation of N was observed on these residues, but relative to unamended soil, *M. pruriens* continued to immobilise N up to 10 weeks. Residues of *C. grahamiana*, *M. axillare* and *M atropupureum* showed net mineralisation from the first week of incubation in the two soils.

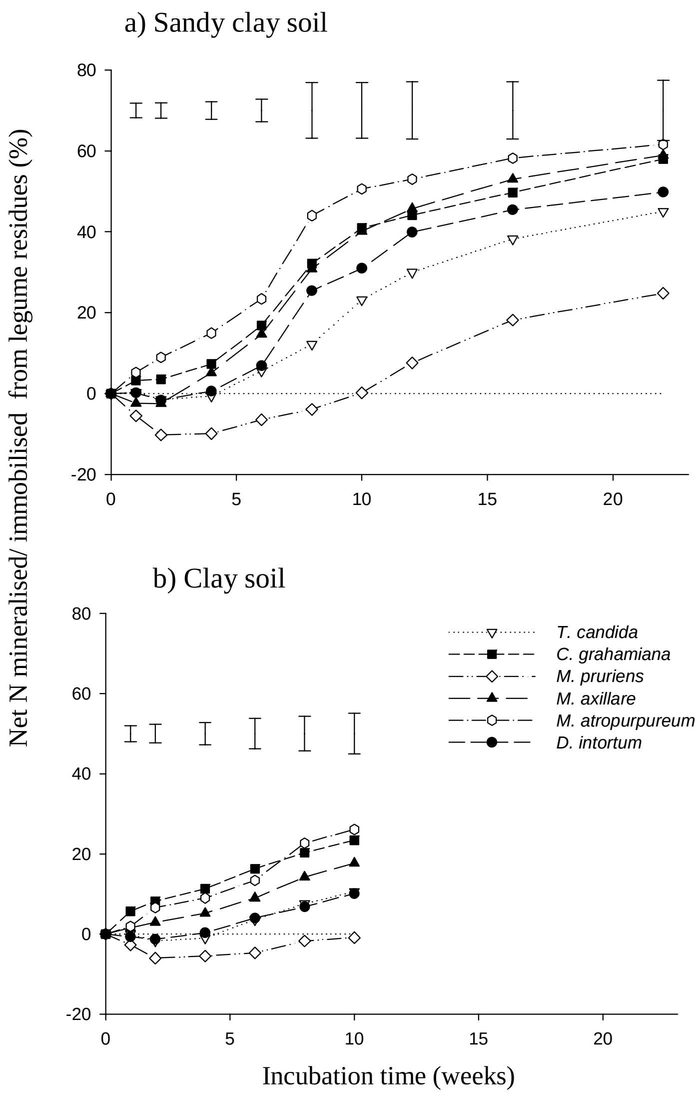

Figure 4.2 Cumulative net N (%) of the initial added N of various legume residues mineralised/immobilised in a) sandy clay soil and b) clay soil under leaching condition. Vertical bars are standard error of difference in treatment means (SED).

The proportions of N mineralised and the mineralisation rate constants (*k*) varied between legume residues and were in some cases significantly correlated with the legume quality attributes i.e. N, lignin, lignin-to-N ratio and (lignin + polyphenols)-to-N ratio (Table 4.3). Moreover, in both soils the proportions of N mineralised were more strongly correlated with the (lignin + polyphenols)-to-N ratio compared to other quality attributes (Figure 4.3). There were, however, differences in the coefficients for linear regressions between the N mineralised and the *k* values of legumes residues incubated in sandy clay and in clay soil. In sandy clay soil, the lignin-to-N ratio and the (lignin + polyphenols)-to-N ratio were more strongly related to the proportion of mineralised N than in the clay soil.

Table 4.3 Coefficients of determination (R^2) between quality variables of legume residues and their N mineralisation rate constants under leaching conditions over 22 weeks in a sandy clay soil, and 10 weeks in a clay soils.

Residue quality	Coefficient of determination (R^2) for			
	N mineralised in		N mineralisation rate constant (k) in	
	sandy clay soil	clay soil	sandy clay soil	clay soil
N (%)	0.78*	0.56	0.64	0.43
Lignin (%)	0.67*	0.73*	0.63	0.25
Lignin-to-N ratio	0.79**	0.65**	0.75*	0.26
(Lignin +polyphenols)-to-N ratio	0.83**	0.71**	0.73*	0.35

* Significant at $P < 0.05$, ** significant at $P < 0.01$.

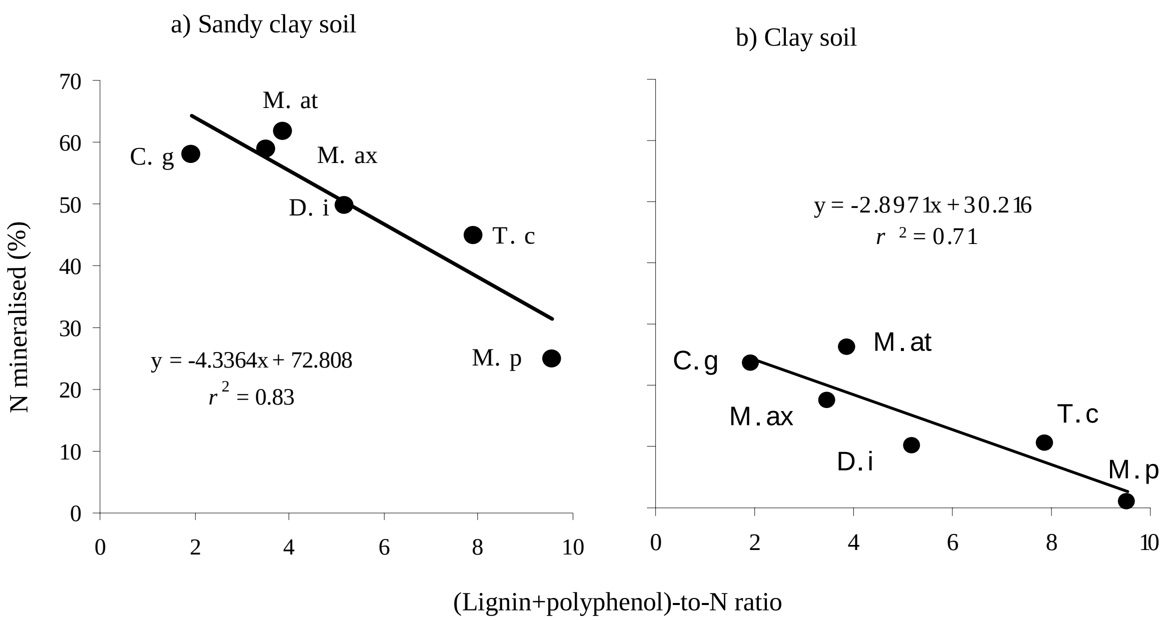

Figure 4.3 Relatioship between the proportion of legume residue N mineralised (%) and (lignin+polyphenol)-to-N ratio under leaching condition after (a) 22 weeks in a sandy clay soil and (b) 10 weeks in clay soil. Symbols represents; T.c = *T. candida*, C.g = *C. grahamiana*, M.p = *M. pruriens*, M.ax = *M. axillare*, M.p = *M. atropurpureum* and D.i = *D. intortum*.

4.3.2 Maize yield response to the application of mineral fertilisers and legume residues

In the first season, maize yield (grain + stover) increased with application of mineral fertilisers and legume residues (Tables 4.4, 4.5). On-station, the average total dry matter production in the control was 2 Mg ha^{-1} and 8.9 Mg ha^{-1} with application of 50 kg N ha^{-1} of mineral fertiliser. The mean total dry matter yield in the control was 30 and 34% of the maximum yield achieved with application of 50 kg N ha^{-1} of mineral fertiliser in the high and low rainfall zone, respectively. In the high rainfall zone, the total dry matter yield following application of *T. candida*, *C. grahamiana* and *M. pruriens* residues was 83%, 54% and 66% of the yield level with application of 50 kg N ha^{-1}of mineral fertiliser. The corresponding yields of similar treatments in the low rainfall zone were respectively, 86%, 56% and 74% and 65%.

Table 4.4 Effect of mineral nitrogen fertiliser application and incorporation of legume residues on maize yield at ARDI-Maruku. For legume species, the amount of N applied is the amount of N in residues produced on the site.

Treatment	Amount of N applied (kg ha^{-1})	Yield (Mg ha^{-1})	
		Grain	Total above ground [a]
Control	0	0.9	2.0
Mineral N fertiliser [b]	50	3.6	8.9
Tephrosia candida	129	2.5	6.2
Tephrosia vogelii	41	1.6	3.9
Crotalaria grahamiana	57	2.2	5.3
Mucuna pruriens	69	2.3	5.0
SED [c]		0.4***	0.9***

[a] Includes grain and stover.
[b] $Ca(NO_3)_2NH_4NO_3$; [c] Standard error of the difference in means, *** $P< 0.001$.

Maize yield varied between sites as demonstrated by yield ranges (Table 4.5). Without fertility amendment, the variation in yield among sites was explained by the initial soil N, r^2 = 0.54 (high rainfall zone) and 0.68 (low rainfall zone) and soil pH, r^2 = 0.65 (high rainfall zone) and 0.57 (low rainfall zone). This effect disappeared after application of legume residues and mineral N fertiliser. In the high rainfall zone, maize yield was positively correlated with the quantities of legume N and residues applied particularly those of *T. candida* and *C. grahamiana* (Figure 4.4). The relationship was weaker in the low rainfall zone except for *C. juncea* residues.

Table 4.5 Effect of mineral nitrogen fertiliser application and incorporation of legume residues on maize yield in the high and low rainfall zone of Bukoba District. Data in parentheses are ranges. For legume species, the amount of N applied equals to the amount of N in residues produced on the site.

Treatments	High rainfall zone			Low rainfall zone		
	Amount of N applied (kg ha^{-1})	Yield (Mg ha^{-1})		Amount of N applied (kg ha^{-1})	Yield (Mg ha^{-1})	
		Grain	Total above ground [a]		Grain	Total above ground [a]
Control	0	1.1 (0.7 - 1.7)	2.9 (1.8 - 4.4)	0	1.4 (0.5 - 2.5)	3.4 (1.4 - 6.4)
Mineral N fertiliser	50	3.8 (1.7 - 5.0)	9.9 (4.3 - 12.8)	50	3.8 (2.7 - 5.1)	9.8 (7.0 - 13.2)
Tephrosia candida	124 (38 - 224)	3.2 (1.2 - 4.5)	8.2 (4.0 - 11.7)	134 (50 -161)	3.3 (2.5 - 4.5)	8.5 (6.5 - 11.6)
Crotalaria grahamiana	33 (7 - 61)	2.0 (1.2 - 3.0)	5.3 (3.1 - 7.7)	22 (15 - 39)	2.2 (1.5 - 3.0)	5.7 (4.0- 7.7)
Crotalaria juncea	-	-	-	66 (26 - 96)	2.2 (1.5 - 3.1)	6.4 (3.7-11.8)
Mucuna pruriens	87 (25 -168)	2.5 (1.2 - 4.2)	6.5 (3.1 -10.9)	94 (17 - 274)	2.9 (1.3 - 4.8)	7.4 (3.4-12.3)
SED [b]		0.5***	1.2***		0.4***	1.1***

[a] Include grain and stover; [b] Standard error of difference in means, *** $P < 0.001$.

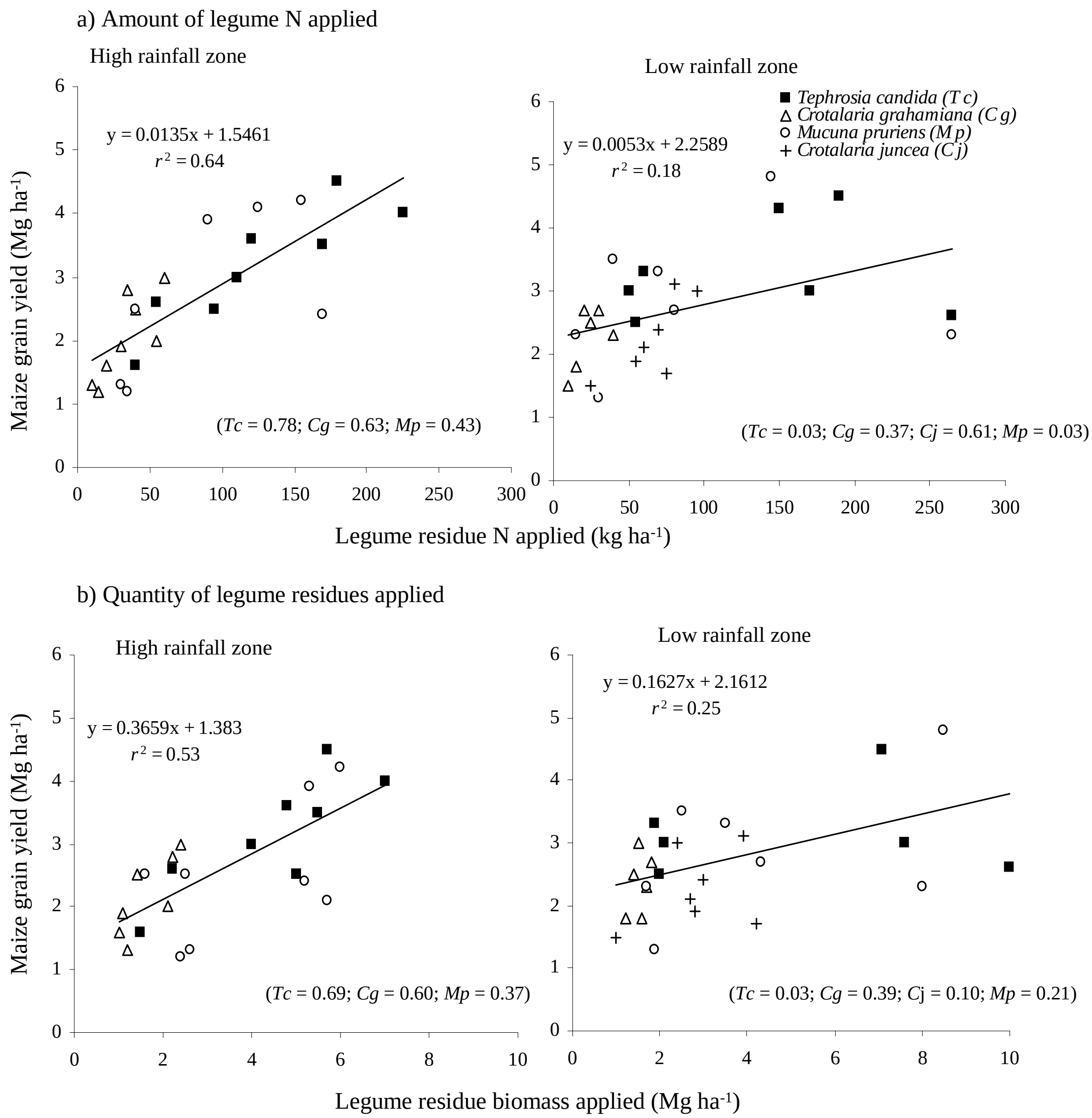

Figure 4.4 Relationships between (a) amounts of legume residue N applied and (b) and quantities of legume residue applied and observed maize grain yield in the high and low rainfall zones of Bukoba District.

Maize yields in the second season were poor compared with the first season, but the residual effect of mineral N fertilisers and legume residues was still strong (Figure 4.5). In this season, higher maize yields were obtained on legume residue applied plots compared with those receiving mineral N fertilisers although yields in plots previously applied with mineral N fertiliser were higher than in unfertilised controls. The highest yield was obtained with *T. candida* and *M. pruriens* residues applied, with the effect being generally stronger in the low rainfall zone than in the high rainfall zone.

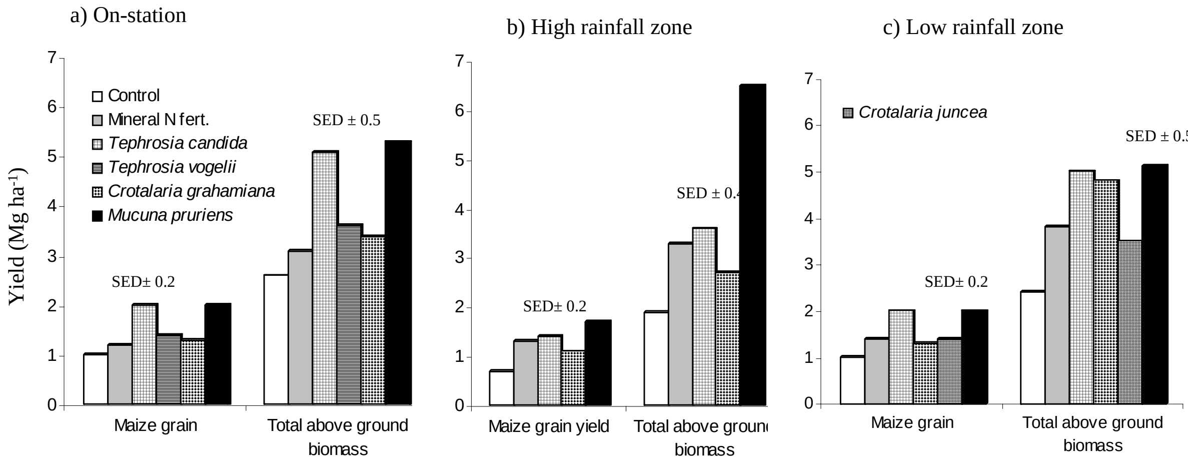

Figure 4.5 Effect of mineral fertiliser N application and N through incorporation of legume residues into the soil on grain and total above ground yield of the second season maize at a) on-station b) in the high rainfall zone and **c**) in the low rainfall zones. SED = Standard error of differences in treatment means.

4.3.3 Fertiliser equivalency (FE) values of legume residues

The FE ranged from 18 kg for *C. grahamiana* to 38 kg N ha^{-1} for *T. candida* (Table 4.6 and Figure 4.6)**.** The FE of the same legume residues applied in different zones showed only slight differences. A different pattern was obtained when the % FE was calculated (putting the amounts of residue N applied into account). In both zones, a higher % FE value was observed with *C. grahamiana* and a lower value with *C. juncea*. Generally, the %FE of the same residues applied in different zones showed only slight differences.

Table 4.6 N Fertiliser equivalence (FE) (kg N ha^{-1}) and percentage fertiliser equivalence (%FE) of legume residues.

Legume residue	High rainfall zone		Low rainfall zone	
	FE	%FE	FE	%FE
Tephrosia candida	38	31	33	25
Crotalaria grahamiana	18	55	13	59
Crotalaria juncea	-	-	13	20
Mucuna pruriens	27	31	28	30

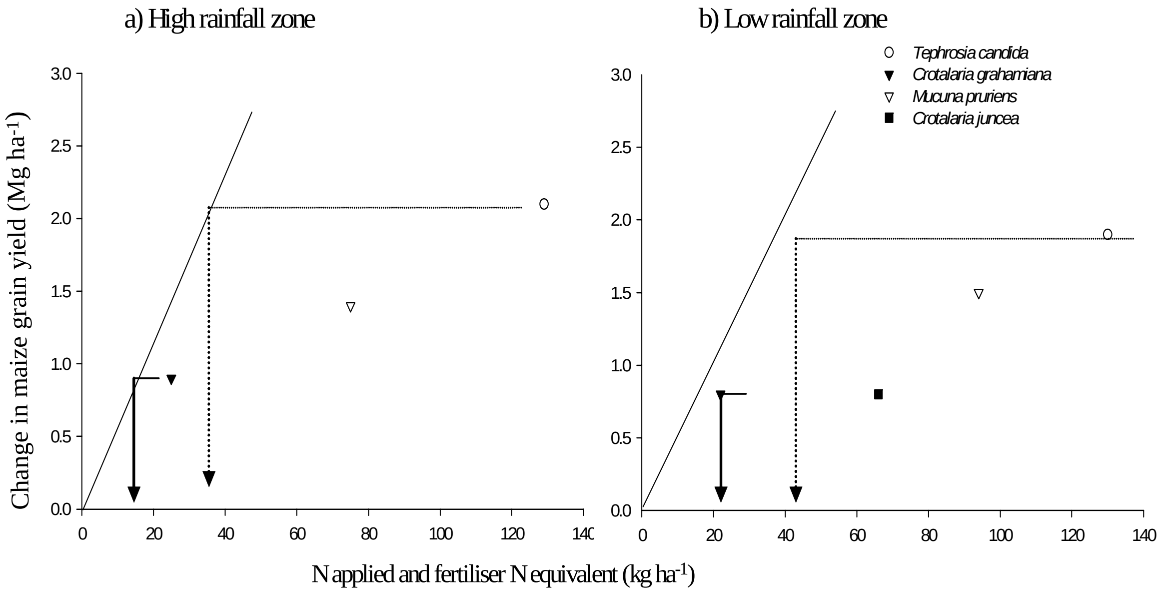

Figure 4.6 Relationship between change in maize grain yield and fertiliser N application in the (a) high rainfall zone and (b) low rainfall zone. The one to one lines present the linear response of maize to mineral N fertiliser. The horizontal lines compare the applied legume residue N at the same level of maize yield due to application of mineral N fertiliser. For the sake of legibility only two lines are shown.

4.3.4 Nitrogen uptake and use efficiency

Total nitrogen uptake by maize in the control plots ranged from 18 kg N ha^{-1} on station to 31 kg N ha^{-1} on-farm; in all cases more than 50% was taken up in the grain (Tables 4.7 and 4.8). With the application of mineral N fertiliser and legume residues, N uptake by maize was doubled to quadrupled with respect to the control. The efficiency of use of nutrients applied was higher for the mineral fertilisers than for legume residues. N from *C. grahamiana* residues was more efficiently used compared with N from residues of other legume species. Nitrogen utilisation efficiency by maize was not affected by the N source and was in the range of 57 and 69 kg of grain produced, and 97 and 115 kg for the total above ground biomass per kg N taken up. At harvest, the first maize season had recovered more than 100% of the applied mineral N fertiliser, 80% of being accounted for in the grain. N recoveries by maize from the applied residues were less than 50% of the N applied except for *C. grahamiana* from which more than 70% of the N was recovered in the high rainfall zone.

Table 4.7 N uptake and efficiency ratios of grain and total biomass yield for maize as a function of application of mineral N fertiliser and incorporation of legume residues at ARDI Maruku.

	N uptake (kg ha^{-1})		Fert. N use efficiency (kg kg N$_{applied}$$^{-1}$)		N utilisation efficiency (kg kg N$_{uptake}$$^{-1}$)		Nitrogen recovery efficiency (kg N$_{uptake}$ kg N$_{applied}$$^{-1}$)	
	Grain	Total above ground Biomass[a]	Grain	Total above ground Biomass[a]	Grain	Total above ground Biomass[a]	Grain	Total above ground Biomass[a]
Control	12	18	-	-	-	-	-	-
Mineral fertiliser	53	80	54	137	65	109	0.81	1.25
Tephrosia candida	35	55	8	35	68	113	0.20	0.32
Tephrosia vogelii	23	33	18	64	57	110	0.21	0.31
Crotalaria grahamiana	30	49	24	65	68	113	0.35	0.62
Mucuna pruriens	30	44	23	56	64	113	0.35	0.47
SED [b]	5***	8***	10**	25**	ns	ns	0.14**	0.22**

[a] Include grain and stover.
[b] Standard error of the difference in means, ** *P*< 0.01, *** *P*< 0.001, ns = not significant.

Table 4.8 N uptake and efficiency ratios of grain and total biomass yield for maize as a function of application of mineral N fertiliser and incorporation of legume residues in the high and low rainfall zones of Bukoba District; means are for data collected at 8 sites in the high rainfall zone and at 7 sites in the low rainfall zone.

Treatment	N uptake (kg ha^{-1})		N use efficiency (kg kg N$_{applied}^{-1}$)		N utilisation efficiency (kg kg N$_{uptake}^{-1}$)		Nitrogen recovery efficiency (kg N$_{uptake}$ kg N$_{applied}^{-1}$)	
	Grain	Total above ground biomass [a]	Grain	Total above ground biomass [a]	Grain	Total above ground biomass [a]	Grain	Total above ground biomass [a]
High rainfall zone								
Control	16	31	-	-	-	-	-	-
Mineral fertiliser	57	92	54	110	59	114	0.90	1.35
Tephrosia candida	45	74	18	45	69	108	0.26	0.42
Crotalaria grahamiana	29	47	30	78	68	100	0.43	0.73
Crotalaria juncea	nt	nt	nt	nt	nt	nt	nt	nt
Mucuna pruriens	37	58	22	58	62	115	0.33	0.50
SED[b]	6***	11***	8***	19***	ns	ns	0.11***	0.16***
Low rainfall zone								
Control	20	29	-	-	-	-	-	-
Mineral fertiliser	62	97	48	123	58	97	0.81	1.23
Tephrosia candida	49	78	18	47	69	116	0.20	0.23
Crotalaria grahamiana	33	51	38	110	65	114	0.35	0.42
Crotalaria juncea	35	54	14	47	64	110	0.23	0.38
Mucuna pruriens	42	63	24	63	63	111	0.35	0.47
SED [b]	7***	10***	10*	28*	ns	ns	0.16**	0.27**

nt = not tested

[a] Include grain and stover

[b] Standard error of the difference in means, * $P< 0.05$ ** $P< 0.01$ *** $P< 0.001$, ns = not significant.

4.4 Discussion and conclusions

4.4.1 N released from decomposing legume residues

The rates at which N was released from the decomposing legume residues (Figure 4.2) reflected their differences in chemical composition (Tables 4.1), and was most strongly related to lignin-to-N ratio and (polyphenols + lignin)-to-N ratio (Table 4.3, Figure 4.3). It has been shown that plant materials with lignin-to-N ratio above 6 and (polyphenols + lignin)-to-N ratio above 9 release N slowly in the initial stages (Palm et al., 2001). Lignin intertwines with the cell wall, physically protecting cellulose and other cell wall constituents from degradation (Chesson, 1997) whereas higher soluble polyphenols can form complexes with proteins and protect them from decomposition (Davies et al., 1964). This may possibly be the case in the present study as *M. pruriens* and *T. candida* which were slow in releasing N had lignin-to N ratio and (polyphenols + lignin)-to-N ratios above the critical values (Palm et al., 2001). To the contrary, rapid mineralisation of N from *M. atropurpureum, M. axillare* and *C. grahamiana* residues in the initial period was related to their relatively high N contents, low contents of soluble polyphenols and lignin making them easily decomposable.

Despite having higher N, low lignin and total soluble polyphenol contents, residues of *D. intortum* exhibited a short-term N immobilisation possibly due to the presence of polyphenolics in the form of condensed tannins (Getachew et al., 2000). According to Handayanto et al. (1997) the type of polyphenol compounds is a more important determinant in decomposition of plant residues than the absolute quantities.

Up to 10 weeks of incubation, the rates of N release from residues were higher in the sandy clay soil than in the clay soil. Similar trends, though with different residues have been reported in other studies (e.g. Jansen, 1994; Veen et al., 1985; Ehaliotis et al., 1996; Sakala et al., 2000). All authors argued that higher clay contents facilitate stabilisation of small residue particles, the microorganisms and their metabolites, thereby slowing the decomposition and N turnover. This was possibly the case in the present study as the N release patterns of residues were similar in both soils the differences being the rate of N release (Figure 4.2). Even though the process of immobilisation and stabilisation of decomposition products may be undesirable, it may facilitate a more prolonged N availability particularly in areas with high rainfall such as Bukoba District, where the mineralised N is liable to be lost by leaching if not immediately absorbed by crops.

Reports on N release patterns of legume species are scarce. However, in a similar leaching incubation experiment, *M. pruriens* decomposing in a sandy soil from Zimbabwe also showed a prolonged N immobilisation up to 20 weeks of incubation (Chikowo, 2004). Under field conditions, however, *M. pruriens,* and *M. atropurpureum* residues were found to release more than 50% of their N in less than 30 days (Ibewiro et al., 2000; Duda et al., 2003). Although the present results are difficult to extrapolate to field conditions, they shed light on the complex relationship between residue quality and N release of legume cover crops, which have been identified as useful species in the tropics.

4.4.2 Effect of legume application on maize yield and their % fertiliser equivalents

In the prevailing annual cropping system in Bukoba District, maize is cultivated after 5 to 6 months of weedy fallow or rotated with sweet potato in the same period. The natural potential N supply of these soils to the maize crop during the experiment was 31 and 29 kg N ha^{-1} in the high and low rainfall zone, respectively, as inferred from the N uptake in the control treatments (Table 4.8). This natural N supply resulted in average maize grain yields of 1.1 and 1.4 Mg ha^{-1} in the high and low rainfall zone, respectively, slightly higher than the district average which is given as 0.9 Mg ha^{-1} (Bukoba District Council, 2001). The slightly higher maize grain yields (of 0.2-0.5 Mg ha^{-1}) in our experiment may be a result of the combination of use of an improved maize variety and a good season.

Maize yield response to application of mineral N was higher compared to application of legume residues (Table 4.4 and 4.5) implying that application of legume residues alone cannot produce yields levels expected on Bukoban soils. The results suggest the need for an integrated system of soil fertility management that combines organic and inorganic N fertilisers (Giller et al., 1997). The observed increase in maize yield with application of legume residues compared with the control (Tables 4.4 and 4.5, Figure 4.5) demonstrate that legume residues make a significant contribution to crop production. The results further indicate that application of mineral fertilisers can be reduced if legume residues are applied. Similar results have been reported in the humid areas of Uganda (Wortmann et al., 1994), in the Kenya highlands (Niang et al., 2002) and in the moist savanna region of West Africa (Sanginga et al., 1998). The observed higher maize yield on control plots in the low rainfall zone could be a result of favourable soil pH and the availability of Ca and Mg compared with soils in the high rainfall zone (Table 4.1), and a good season. Overall, there was little difference in crop yield between the zones largely because of a good season (in terms of rainfall) for maize even in the low rainfall zone.

The corresponding amounts of N that would have been released from *T. candida*, *C. grahamiana* and *M. pruriens* were in the order of 38, 18 and 27 kg ha^{-1} in the high rainfall and 31, 13 and 21 kg ha^{-1} in the low rainfall zone, calculated based on the %FE values (Table 4.6). Considering the amount of residue N applied, the N mineralised from *C. grahamiana* residues was high compared with that from *T. candida* and *M. pruriens* residues. These results on %FE agree well with those of leaching incubation studies where N mineralisation was poor for *M. pruriens* and *T. candida* (Figure 4.2). The foregoing results and the varied correlation between the amounts of legume residue applied and maize yield (Figure 4.4) may indicate differences in the temporal pattern of N availability from legume resideues to the maize. The comparatively higher maize yields with application of legume residues in the first season were likely not only due to N contribution but also to other additional effects such as improved soil aeration, water infiltration and moisture retention (Myers et al., 1997; Giller, 2002).

4.4.3 Efficiency of use of Legume N by maize crop

N uptake by maize following application of mineral N fertiliser was higher than the amount applied (Tables 4.7 and 4.8). Applying 50 kg N ha^{-1} of mineral fertiliser resulted in maize crop mining an extra 20 kg N ha^{-1} probably due to better root growth and better soil N capture. The efficiency of use of mineral fertiliser N was high compared to legume residue N, implying that use of mineral fertilisers along with legume residues can increase the N use efficiency of crops. The first maize crop recovered about 30 to 70% of the legume residue N, which were two to threefold the recovery in the control (Tables 4.7 and 4.8). This is within the range of 27 to 70% recovery reported for legume cover crops (Harris and Hesterman 1990; Ibewiro et al., 2000; Giller, 2001). The contribution of below-ground residue N to maize yield was not accounted for, in this experiment, although other authors suggest that substantial amounts of N can be added belowground by legumes (McNeill et al., 1997; Peoples et al., 2001; Cadisch et al., 2002). Given the limited response seen to additions of aboveground legume materials in these experiments (Tables 4.4 and 4.5), we consider the belowground contribution of the legumes to be negligible. Roots are slow to decompose (Vanlauwe et al., 1997; Urquiaga et al., 1998, Cadisch, et al., 2002), thus they play a more important role in building of soil organic matter rather than in direct nutrient supply.

The results of this study show that application of legume residues can contribute significantly to the overall productivity in low-external input agricultural systems of Bukoban District, as they add nutrients and enhance efficient management and utilisation of soil resources by the plant. However, application of legume residues alone cannot achieve the potential crop yield on Bukoban soils unless managed with small doses of mineral fertilisers as top dressing in order to ensure synchrony with crop demand (Giller, 2002).

Owing to presence of organic resources with differential N release patterns, and the extremely poor resource base of many farmers in the district, more flexible guidelines for management of both organic and mineral fertilisers proposed by Palm et al. (2001) and Giller (2002) are important. In our previous study (Baijukya et al., submitted) farmers mentioned shortage of labour to grow and incorporate legumes (a factor, which was not accounted for in the present study) as a constraint to legume use. Therefore the net effect of labour requirement, economic benefits of legume use and legume residue interactions with mineral fertilisers need to be investigated with farmers to determine the appropriateness of the technology.

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Fast growing short-fallow legumes like mucuna and tephrosia produce large quantities of biomass in a short period, which in turn suppress the natural vegetation.

Chapter 5

Managing herbaceous legumes and their residues to enhance productivity of degraded soils in the humid tropics: A case study in Bukoba District, Tanzania

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Chapter 5

Managing herbaceous legumes and their residues to enhance productivity of degraded soils in the humid tropics: A case study in Bukoba District, Tanzania

Abstract

In degraded soils, establishment of soil-improving legumes can be problematic and requires investment of labour and other resources. We investigated various aspects of managing herbaceous legumes in farmers' fields in the high and low rainfall zones of Bukoba District, Tanzania. Biomass and N accumulation by *Crotalaria grahamiana* was 1.1 Mg ha^{-1} and 34 kg N ha^{-1} when established without farmyard manure (FYM) and 3.0 Mg ha^{-1} and 95 kg N ha^{-1} when established with 2 Mg FYM ha^{-1}. Growing *Crotalaria* with FYM gave an increment of 700 kg ha^{-1} of grain in the subsequent maize crop. Maize grain yield with *Tephrosia candida* residues ranged from 1.4 to 3.3 Mg ha^{-1} and from 2.0 to 2.8 Mg ha^{-1} in the high and low rainfall zone, respectively. Of the tested application rates (2, 4, 6, and 8 Mg ha^{-1} tephrosia biomass), 2 Mg ha^{-1} had no significant effect on maize yield whereas the 4, 6 and 8 Mg ha^{-1} treatments gave comparable yields. Apparent N recovery efficiencies at all rates of tephrosia residues were maximally 28% and 12% for the high and low rainfall zones, respectively. Mulching with *Mucuna pruriens* suppressed weeds (49% and 67%) compared with incorporated residues (20%), and increased maize yield by 64% and 100% compared with the unamended control in the respective zones. Incorporated residues demanded an extra (45) man days compared with removed residues (20) and mulched residues (23). Consequently the labour productivity of this treatment was poor (20 and 33 kg grain person-day^{-1}) compared with mulched residues (32 and 53 kg grain person-day^{-1}) in the high and low rainfall zone, respectively. These results have shown that if well managed, legume residues have potential to increase yield of subsequent maize crops in degraded soils. Because managing legumes and residues is resource demanding, a challenge remains as to how legumes should be mixed with other soil fertility management options so that smallholder farmers can optimise their resource use and meet their production objectives.

Key words: *Short fallow legumes; N depleted soils; Smallholder farms, Labour productivity, Bukoba, Tanzania*

5.1 Introduction

Improved fallows with herbaceous legumes are a promising option to improve crop productivity in the low-income agricultural systems of the humid and sub-humid tropics (Sanchez, 2002; Giller, 2001; Hartemink et al., 2000; Kwesiga and Coe, 1994). The benefits of this technology, however, are likely to be smaller on poor soils where the biomass and nitrogen accumulation by legumes may be limited (Uexküll and Mutert, 1994; Giller, 2001; Hounghandan et al., 2001). Prospects for improving the productivity of legumes on infertile soils are extensively discussed by Giller, (2001) and Hungria and Vargas (2000). However, most literature suggests the use of external inputs such as lime (in acidic soils), phosphate fertilisers and starter doses of nitrogenous fertilisers (e.g. Hounghandan et al., 2001; Sanginga et al., 1996; Uexküll and Mutert, 1994). Although mineral fertilisers are by far the most effective means of providing deficient nutrients in soils, organic resources, such as farmyard manure (FYM) can have additional benefits such as helping to raise the pH of acidic soils. Moreover, organic resources can increase the availability of nutrients like P, K, Mg and micronutrients that are essential for legume growth and N_2-fixation (Diels et al., 2002; Ridder and Keulen, 1990). However, there is insufficient knowledge on response of legumes to application of small quantities of FYM and the expected benefits from combined use of FYM and legume residues.

Legume residue management practices that retain organic matter and the embodied nutrients *in situ* are required in order to maximise the beneficial effect of improved fallows. Such alternatives to legume removal may include mulching or legume residue incorporation into the soil (Giller et al., 1997). In a recent development, a decision tree to guide the use of plant residues for soil amendment has been developed (Palm et al., 2001). Although the guide seeks to maximise the N use efficiency of organic resources, incorporation of residues into the soil may be difficult when productivity of labour invested is restricted (Roger, 1995). High rates of legume residues application may be uneconomical, especially when the corresponding yield increases are not substantial (Chapter 4; Bijukya et al., submitted (b)). This is of particular importance where there may be trade-offs associated with use of legume residues for different purposes such as providing fodder or green manure. These lead to a need for flexible guidelines for management of legume residues that take into account of residue availability, alternative uses and practices that demand less labour and result in higher labour productivity.

In light of the above knowledge gaps, three experiments were conducted in farmers' fields in Bukoba District with the objectives: *i*) to determine the effects of application of small quantities of FYM on biomass accumulation and N yield by legumes; *ii*) to examine whether extra benefits are realised from combined use of manure and legumes on maize yield; *iii*) to determine the optimum application rate of legume residues for maize production in Bukoba District; *iv*) to assess the effect of different legume management practices on weeds and maize yield; and *v*) to determine the labour cost and labour productivity of legume fallows with different legume residue management practices.

5.2 Materials and methods

5.2.1 Study area and legume species used

The experiments were conducted in the high and low rainfall zones of Bukoba District northwest Tanzania (1^{o}13'-1^{o}30' S, longitude 31^{o}19'-31^{o}52' E). Average annual precipitation ranges between 1500 and 2100 mm in the high rainfall zone and 750 - 1000 mm in the low rainfall zone. Soils at experimental sites are deep, well drained, sandy clay loam (Alumi-humic Ferralsol) in the high rainfall zone and clay loam (Humic Acrisols) in the low rainfall zone (FAO-UNESCO, 1988). The characteristics of soils at the experimental sites are given in Table 5.1. Detailed characteristics of the zones are described by Baijukya and Steenhuijsen Piters (1998). The rainfall data during the experimental periods are reported in Figure 5.1.

The test legumes were *Crotalaria grahamiana*, *Tephrosia candida* and *Mucuna pruriens*. These legumes had been selected by farmers on basis of their growth potential, also as most suitable for soil fertility improvement as well as fodder in the case of mucuna (Chapter 2; Baijukya et al., submitted (a)). Due to limited land (in farmer fields), different species were selected for use in different experiments. In previous experiments, *C. grahamiana* had high impact on maize productivity but its growth was restricted in poor soils, hence it was used in Experiment 1 where the effect of cattle manure on legume growth was examined. *T. candida* was chosen for Experiment 2 because of its ability to yield large amounts of biomass in different soils. *M. pruriens* was chosen for Experiment 3 because it gives rapid establishment of soil cover and its residues are relatively easy to handle as mulch.

Table 5.1 Topsoil (0-30 cm) characteristics at experimental sites; Data in parentheses are ranges.

Soil and corresponding sites and experiments	Zone	pH (H_2O)	OC [a] (g kg^{-1})	Total N (g kg^{-1})	Available P Bray (mg kg^{-1})	Exchangeable cations (cmol$_c$ kg^{-1})			Particle size (%)		
						Ca	K	Mg	Sand	Silt	Clay
Soil at sites used for Experiment 1	High rainfall (degraded soils)	4.4 (4.2-4.5)	13 (9-16)	0.9 (0.7-1.1)	6.9 (5.1- 8.7)	1.2 (1.1-1.3)	0.1 (0.1)	0.2 (0.1-0.3)	60 (58-62)	21 (20-22)	19 (18-20)
Soil at sites used for Experiment 2	High rainfall	5.4 (5.2-5.6)	23 (20-28)	1.3 (1.1-1.4)	15 (9-22)	2.8 (1.6-4.4)	0.3 (0.2-0.5)	0.2 (0.1-0.3	59 (56-63)	21 (15-28)	20 (17-25)
	Low rainfall	5.3 5.1-5.4)	16 (13-18)	1.2 (0.8-1.5)	6.6 (2.6-12.3)	3.9 (1.3-5.8)	2.8 (2.1-3.1)	0.1 (0.1-0.2)	29 (26-34)	26 (24-30)	47 (40-48)
Soil at sites used for Experiment 3	High rainfall	5.1 (4.9-5.2)	23 (17-29)	1.5 (0.9-2.0)	20.0 (5.1-25)	0.7 5 (0.4-2.1)	0.2 (0.2-3.6)	0.2 (0.1-0.3)	62 (60-64)	20 (16-24)	20 (18-22)
	Low rainfall	5.3 (5.2-5.4)	18 (12-31)	1.2 (0.8-2.7)	15.4 (10.2-20.6)	2.6 (1.8-2.8)	2.0 (0.8-2.2)	1.0 (0.8-1.2)	31 (26-32)	27 (24-30)	42 (34-48)

[a] Organic carbon

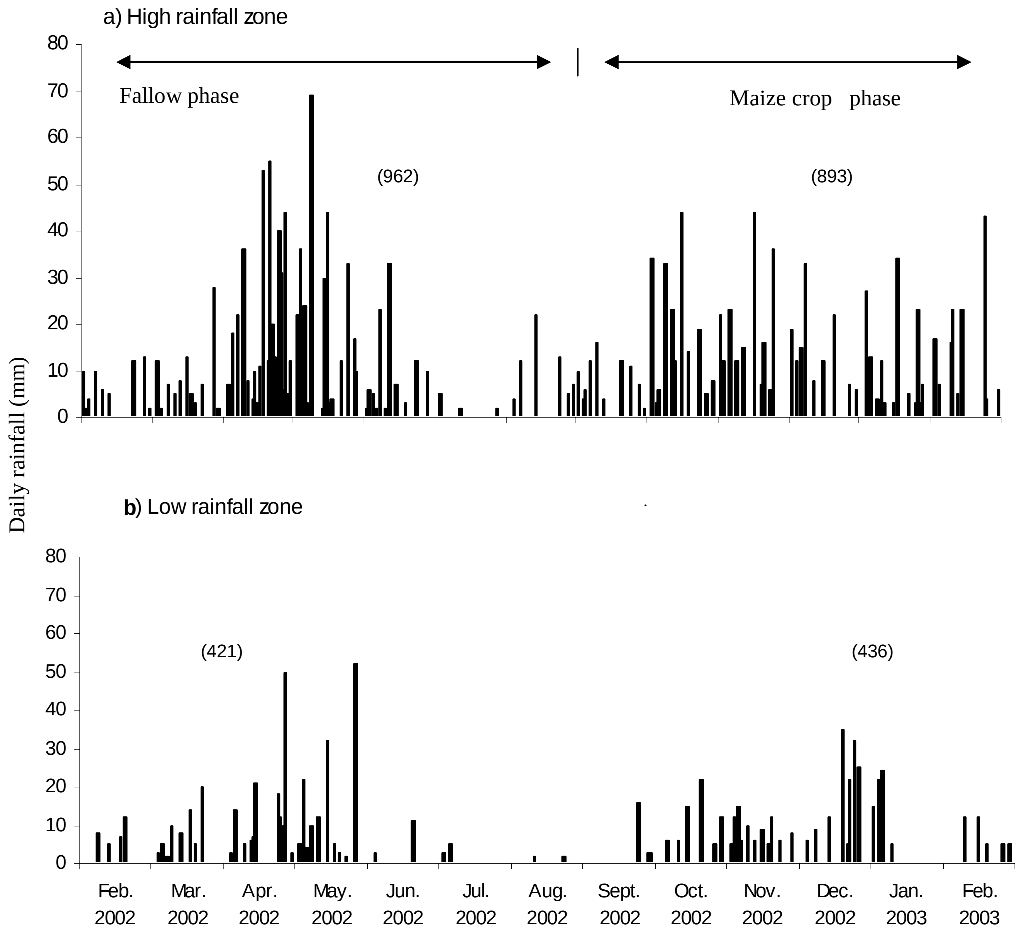

Figure 5.1 Daily precipitation during the maize growing seasons for the a) high rainfall zone and b) low rainfall zone. Data in parentheses are totals in respective seasons.

5.2.2 Experiment 1: Improving productivity of degraded soils by use of legumes and farmyard manure

To determine the effects of FYM on legume productivity and eventual impact on maize yield, a field experiment was conducted on two farmers' fields, in the villages of Butairuka and Kiilima between February 2002 and February 2003. The villages are separated by a distance of 15 km. Both sites had been abandoned for 1 year due to poor soil fertility and high infestation of couch grass (*Digitaria scalarum*).

After removing the couch grass, by hand cultivation and hand picking, two blocks each with 4 plots measuring 6 m by 13 m separated by 1 m paths, were randomly demarcated per site. Dry farmyard manure (FYM) was spread on two plots at a rate of

2 Mg ha^{-1} and ploughed under the soil (< 20 cm). *Crotalaria grahamiana* was sown in the third week of February 2002 in all FYM applied plots and on other 2 plots which did not receive FYM, at a seeding rate of 4 kg seeds ha^{-1}. Weeds were allowed to grow in other 2 plots in each block. The treatments were *i*) weed fallow *ii*) crotalaria established without FYM and *iii*) crotalaria established with FYM in a randomised complete block design with two replications. Harvest of fallows was done in the fourth week of August (6 months after planting) by cutting three quadrats (3 m^2) at ground level in each plot. Plant shoots were oven dried at 70^{o}C for 48 hours, weighed and sub-samples taken for N determination. Above ground biomass yields were estimated using the mean weight of samples taken at three locations and the final yield expressed in Mg ha^{-1}. The biomass yields and the N mass rations (% N) in plants tissues were used to estimate the N accumulation, which was expressed in kg ha^{-1}.

After harvesting the fallows, weeds were removed in weedy fallow plots as practiced by farmers. Dry FYM of the same quality as used before was spread and ploughed under the soil on the plots which were previously under weedy fallow, to simulate the condition where FYM is applied at the time of sowing maize. Crotalaria residues that were obtained on respective plots were chopped into smaller pieces (<15 cm long) and incorporated into the soil using a hand hoe. Maize, variety *Kilima*, was sown in all plots in the first week of September 2002 at a spacing of 0.75 m x 0.45 m, one week after application of treatments. Mineral N fertiliser in the form of calcium ammonium nitrate was applied to one of the blocks aat rate 50 kg N ha^{-1} (N_1) in split doses of 25 kg N ha^{-1}, at 4 and 7 weeks after maize emergence and the other block received no mineral fertiliser (N_0), resulting to the following treatments: *i*) control (no fertility amendment), *ii*) mineral N fertiliser at 50 kg N ha^{-1} (MF), *iii*) FYM, *iv*) FYM + MF, *v*) *C. grahamiana* (Cr), *vi*) *C. grahamiana* + MF (Cr + MF), *vii*) *C. grahamiana* + FYM (Cr + FYM) and *C. grahamiana* + FYM + MF (Cr + FYM + MF). The experimental design was a split plot design with four replications.

Maize, variety *Kilima*, was sown in the first week of September 2002 at spacing of 0.75 m x 0.45 m, one week after application of treatments. Mineral N fertiliser in the form of calcium ammonium nitrate was applied to + MF plots in two split doses of 25 kg N ha^{-1}, at 4 and 7 weeks after maize emergence (WAE). Maize plots were kept free of weeds. The final harvest of maize was done in the third week of February 2003 in three (3 m^2) quadrats in each plot. Maize cobs and stover were oven dried at 72^{o}C for 48 hr and re-weighed to determine their biomass contents and the final yield expressed in Mg ha^{-1}. Samples of grain and stover were taken for N determination.

5.2.3 Experiment 2: Determination of optimum rates of legume residues for maize production

The experiment was conducted in the villages of Kiilima (in the high rainfall zone) and Kabirizi (in the low rainfall zone) in the same period as the first experiment. Two sites previously planted with maize without any fertiliser amendment were selected per village. At each site a 13 m by 41 m plot was cleared and *Tephrosia candida* was established in the fourth week of February 2002 at a seeding rate of 4 kg seed ha^{-1}. *Tephrosia* was harvested in the second and fourth week of September 2002 in the high and low rainfall zone, respectively. The plots at each site were divided into six 6 m by 6 m plots (allowing for paths of 1 m) in which the following treatments were randomly assigned: *i*) no fertility amendment (control), *ii*) Mineral fertiliser at 50 kg N ha^{-1}, and *iii* - *vi*) *T. candida* residues applied at rates of 2, 4, 6 and 8 Mg ha^{-1}. *Tephrosia* residues were chopped into pieces (< 15 cm) and incorporated into the soil. The experiment was arranged in a completely randomised design with two replications.

Maize variety *Kilima* was sown in the first and fourth week of September 2002 in the high and low rainfall zone, respectively, one week after the residues were incorporated into the soil. Prior to sowing of maize, all plots received a basal fertiliser of 15 kg ha^{-1} P and 20 kg ha^{-1} K as triple super phosphate (46% P_2O_5) and muriate of potash (60% K_2O), respectively. Mineral N fertiliser in the form of calcium ammonium nitrate was applied to mineral fertiliser plot at a rate of 50 kg N ha^{-1} in the same way as in Experiment 1. Maize was harvested in the fourth week of February and processed as before. The N uptake in grain and stover from the individual treatments were estimated. The N use efficiency, apparent N recovery efficiency and N utilisation efficiency by maize of N in the applied legume residues was assessed using the following equations:

$$\text{N use efficiency} = \frac{kg\ yield}{kg\ N\ applied} \qquad (5.1)$$

$$\text{N recovery efficiency} = \frac{kg\ N\ uptake}{kg\ N\ applied} \qquad (5.2)$$

$$\text{N utilisation efficiency} = \frac{kg\ yield}{kg\ N\ uptake} \qquad (5.3)$$

Where *Yield* (Y) = ($Y_{fertiliser} - Y_{control}$); *N uptake* ($U$) = ($U_{fertiliser} - U_{control}$)

5.2.4 Experiment 3. Legume residue management practices and their effect on weeds, maize yield and labour productivity

The experiment was conducted in the same period as Experiments 1 and 2 in the same villages as Experiment 2, at three sites in each village. Three 6 m by 20 m plots and three 6 by 13 m plots, separated by 1 m paths, were demarcated at each site and cultivated to remove weeds and maize stover. *Mucuna pruriens* was sown in the 6 m by 20 m plots (mucuna fallow) in the fourth week of February 2002 at a spacing of 0.5 x 0.3 m by putting 2 seeds per planting hole. Weeds were left to grow in the 6 by 13 m plots (weedy fallow). Mucuna was harvested in the first week of September 2002 by cutting the stems at the soil surface. The weedy fallow was cultivated and weeds removed from the plots.

The respective weedy and mucuna fallow plots were sub-divided into 6 m by 6 m plots allowing for paths of 1 m between the plots. The treatments *i*) no fertility amendment (control) and *ii*) mineral fertiliser were randomly assigned to plots which were under weedy fallow whereas mucuna residues were either removed, incorporated into the soil or mulched on plots which were under mucuna fallow. This resulted in additional treatments of iii) removed residues, *iv*) incorporated removed and *v*) mulched removed. For both residues incorporated and residue mulched treatments, mucuna residues were applied at a rate of 5 Mg dry biomadd ha^{-1} (about 100 kg N ha^{-1}) within 3 to 5 days after harvest. The experiment was arranged in a randomised complete block design with three replications per site.

Maize variety *Kilima* was sown in the second week and fourth week of September 2002 in the high and low rainfall zones, respectively, at a spacing of 0.75 x 0.45 m, immediately after application of treatments (3 days after harvesting the fallow). Prior to sowing of maize, all plots received a basal application of P and K fertilisers as in Experiment 2. Mineral N fertiliser in the form of calcium ammonium nitrate was applied at a rate of 50 kg N ha^{-1} as in Experiments 1 and 2. Maize was weeded twice and weeds were retained in the plots. Harvesting of maize was done in the third week of February 2003 and yield data collected and processed as described before.

All field operations were done by a group of six farmers (for each village) aged between 25 and 48 years. The time spent by the group for each operation was recorded, summed per treatment and converted to person-day equivalents. In Bukoba District, 1 person-day (for work on the farm) is estimated to be 6 hours (Nkuba, 1997). Weed biomass in the respective treatments was assessed during the first and second weeding which was done at 5 and 9 weeks after sowing. Measurements were taken in

1 m^2 quadrats at three locations in each plot. Weeds were handpicked, oven-dried at 70º C for 48 hrs and DM determined.

5.2.5 Soil sampling

Composite topsoil (0-25 cm) samples were taken from each site at the beginning of each experiment. For Experiment 3, soil samples were taken at 0, 6, 12 and 18 weeks after planting (WAP) to study the dynamics of mineral N under each treatment. Sampling was done using augers in sections of 0-30, 30-60 and 60-90 cm. In each plot, soil was collected and bulked from three locations for each depth. Sub-samples were taken in polyethylene bags, stored in a refrigerator at 4º C and mineral N extracted within 1 day of collection. A sub-sample of each composite soil sample was dried (105ºC, 48 hrs) to determine the gravimetric water content and to calculate the oven-dry weight of extracted soil.

5.2.6 Analysis of soils, plant, mineral N and calculations

Soil pH was determined on H_2O (1:5 w/v), organic carbon by the Walkley-Black wet oxidation method and total N by the micro-Kjeldahl digestion method. Available P was determined by Bray I method (Murphy and Riley, 1962), exchangeable cations by ammonium acetate extraction with Ca and Mg estimated by the atomic absorption spectrophotometer (AAS) and K by flame photometer. Particle size distribution was analysed by standard hydrometer method (Page et al., 1982). Total N in legumes and maize (grain and stover) material was determined by the micro-Kjeldahl digestion method followed by distillation and titration (Okalebo et al., 1993).

For the soil mineral N analysis, 10 g of field-moist soil was extracted with 50 ml 0.5 M KCl by shaking the suspension for one hour at 150 reciprocations per min and subsequent gravity filtering using pre-washed Whatman 42 paper. Exchangeable NO_3-N (plus NO_2-N) was determined using the cadmium reduction method (Keeney and Nelson, 1982). Concentrations of soil NO_3-N per kg soil were calculated for the sampling depths from the mineral N concentration per unit of oven-dry soil weight and mean bulk density for each depth increment.

5.2.7 Data analysis

Data were analysed with GENSTAT (Genstat release 6.1 Lawes Agricultural Trust) statistical package. Standard errors of the differences between means were calculated. The correlation coefficients were calculated between the soil chemical parameters, the legume biomass, N applied and maize yield.

5.3 Results

5.3.1 Soil quality and rainfall during the experimental period

Based on the classification by Landon (1991), soils in the high rainfall zone were strongly acid, had medium organic carbon (OC) and available P and were poor in total N, Ca, available K and Mg (Table 5.1). Soils in the low rainfall zone were slightly acidic with medium contents of OC, available P and Ca, but poor in total N, available K and Mg. Within zones, soils at different sites varied in chemical characteristics mainly due to differences in past management, e.g. fertilisation, past crops grown, etc. The total amount of rainfall received during the experimental period (Figure 5.1) was considered adequate for optimum production of legume species and the maize crop.

5.3.2 Response of legume to FYM application

Application of FYM had no influence on the proportion (%) of N in crotalaria shoots (Table 5.2). Crotalaria established with FYM accumulated threefold higher biomass and N than crotalaria established without FYM. The biomass and N accumulated by crotalaria established with FYM was 51% and 86% higher than that of weedy fallow. Crotalaria established without amendment gave comparable biomass to weedy fallow but it accumulated twice as much N as the weeds.

Table 5.2 Total N, shoot biomass and N accumulation by six months old weedy fallow and *Crotalaria grahamiana* established without (-) and with (+) farmyard manure in farmer fields, in the high rainfall zone of Bukoba District.

Fallow type	Total N (%)	Biomass (Mg ha^{-1})	N accumulation (kg ha^{-1})
Weedy fallow	1.3	0.9	12
Crotalaria grahamiana - FYM	3.1	1.1	34
Crotalaria grahamiana + FYM	3.2	3.0	95
SED	1.3***	0.5***	16***

SED = Standard error of differences between means, ****P*< 0.001.

5.3.3 Maize response to mineral N fertiliser, legume residues, FYM and their combinations

Maize grain and total above ground biomass ranged from 0.8 to 3.1 Mg ha^{-1} and 1.9 to 7.9, respectively (Table 5.3) with higher yields observed in Cr + FYM + MF treatment and the lower yields in the control. Relative to the control, maize biomass and grain were increased substantially by all manure, fertiliser and legume treatments. Growing *Crotalaria* with manure added in the previous season gave comparable N uptake (67kg N ha^{-1}) and yield (6.2 Mg ha^{-1}) as manure plus mineral fertiliser in the same season (63 kg N ha^{-1} and 5.8 Mg ha^{-1}). Mineral fertiliser further increased maize aboveground biomass after crotalaria +FYM to 7.7 Mg ha^{-1}.

5.3.4 Maize yield response to different quantities of legume residues

Maize yield increased with increasing legume residue rates (Table 5.4), although the 2 Mg ha^{-1} rate had an insignificant influence on maize yield in both zones. In the high rainfall zone, yields in 4 and 6 Mg ha^{-1} treatments were not significantly different. The yields in 8 Mg ha^{-1} and 50 kg N ha^{-1} treatment were comparable. In the low rainfall zone, maize yields in 4, 6 and 8 Mg ha^{-1} treatment did not differ significantly, although the yield in the 8 Mg ha^{-1} treatment was comparable with the yield in the 50 kg N ha^{-1} treatment. Nitrogen uptake in grain and total aboveground biomass also increased with increasing residue rates and largely reflected the differences in yield. There were however, wide variations in yield between sites in both zones. These yield differences appeared to be explained by the initial soil organic carbon (OC) (r^2 = 0.35) and soil pH (r^2 = 0.65) in the high rainfall zone but only weakly by soil pH (r^2 = 0.20) in the low rainfall zone (graphs not shown). The general trend was that higher yields were found on soil with high OC contents and pH and *vice versa*.

The efficiency of use of N from *T. candida* residues by maize was poor compared with that of N from mineral fertiliser, and was not affected by the amount of legume residues applied (Table 5.5). This was also the case with apparent N recovery efficiency where maximum values of less than 27% and 13% were recorded for the total above ground biomass in the high and low rainfall zones, respectively. All treatments had comparable values of N utilisation efficiency except the 2 Mg ha^{-1} where response was poor. N use and recovery efficiency of mineral N fertiliser was high in the high rainfall zone (99 kg grain kg N^{-1}and 90%) compared with the low rainfall zone (39 kg grain kg N^{-1} and 52%).

5.3.5 Effect of mineral fertiliser and legume residue management practices on weeds in maize crop

Relative to the control, residue removal led to an increase in weed biomass in association with maize by 14% in the high rainfall zone but had a negligible effect in the low rainfall zone (Table 5.6). In both zones, incorporated residues reduced weed biomass by 20%. Mulched residues reduced weed biomass by 49% in the high rainfall zone and 67% in the low rainfall zone. Application of mineral N fertiliser increased weed biomass by 44% and 11% in the high and low rainfall zones, respectively.

Table 5.3 N uptake, grain and above ground yield of maize following application of FYM, residues of *C. grahamiana* grown with or without FYM in the previous season in combinations of without (N_0) and with application of 50 kg N ha^{-1} as mineral N fertiliser (N_1). Data are pooled results from two farmer fields in the high rainfall zone of Bukoba District.

Main plots treatment	N uptake (kg ha^{-1})						Yield (Mg ha^{-1})					
	Grain			Above-ground biomass			Grain			Above-ground biomass		
	N_0	N_1	Mean	N_0	N_1	Mean	N_0	N_1	Mean	N_0	N_1	Mean
Weedy fallow	11	27	19	18	45	32	0.8	1.7	1.2	1.9	4.3	3.1
FYM	20	39	30	34	63	49	1.4	2.3	1.9	3.41	5.8	4.6
Crotalaria	19	30	24	31	51	41	1.1	2.1	1.6	2.8	5.2	4.1
Crotalaria + FYM	42	50	46	67	81	72	2.5	3.1	2.8	6.2	7.7	6.9
Mean	23	37.0	30	38	60	49	1.5	2.3	3.8	3.6	5.6	4.7
SED treatments N_0, N_1		0.8***			1.2***			0.1***			0.49***	
SED main plots		3.1**			5.1**			0.2**			0.12 **	
SED (Main plot x treat. N_0, N_1		ns			2.3*			ns			ns	

SED = Standard error of differences between means, **P*< 0.05, ***P*< 0.01, ****P*< 0.001; ns = not significant.

Table 5.4 Nitrogen uptake and yield response of maize to application of mineral N fertiliser and different quantities of *T. candida* residues under farmer conditions in the high and low rainfall zones of Bukoba District.

Treatment	Amount of N applied (kg ha^{-1})	High rainfall zone				Low rainfall zone			
		Yield (Mg ha^{-1})		N uptake (kg ha^{-1})		Yield (Mg ha^{-1})		N uptake (kg ha^{-1})	
		Grain	Above-ground biomass	Grain	Above- ground biomass	Grain	Above- ground biomass	Grain	Above-ground biomass
Control	0	1.2	3.0	19	31	1.8	4.6	30	45
50 kg N ha^{-1}	50	3.2	7.9	50	76	3.1	7.8	49	71
2 Mg ha^{-1}	50	1.4	3.6	22	35	2.0	4.9	32	47
4 Mg ha^{-1}	100	2.4	5.9	37	57	2.5	6.1	39	58
6 Mg ha^{-1}	150	2.7	6.6	42	63	2.7	6.7	42	62
8 Mg ha^{-1}	200	3.3	8.2	51	78	2.8	6.9	41	64
SED		0.5***	0.5***	4***	5***	0.3**	0.8***	5***	7***

SED = Standard error of differences between means, $^{**}P < 0.01$, $^{***}P < 0.001$.

Table 5.5 Nitrogen efficiency ratios of grain and total above ground biomass for maize following application of mineral N fertilisers and different quantities of *T. candida* residues under farmer conditions in the high and low rainfall zones of Bukoba District.

Treatment	High rainfall zone						Low rainfall zone					
	N use efficiency (kg kg $N_{applied}^{-1}$)		N utilisation efficiency (kg kg N_{uptake}^{-1})		Apparent N recovery efficiency (kg N_{uptake} kg $N_{applied}^{-1}$)		N use efficiency (kg kg $N_{applied}^{-1}$)		N utilisation efficiency (kg kg N_{uptake}^{-1})		Apparent N recovery efficiency (kg N_{uptake} kg $N_{applied}^{-1}$)	
	Grain	Above ground biomass	Grain	Above ground biomass	Grain	Above ground biomass	Grain	Above ground biomass	Grain	Above ground biomass	Grain	Above ground biomass
Control	-	-	-	-	-	-	-	-	-	-		
50 kg N ha^{-1}	39	99	64	108	0.61	0.90	25	64	68	122	0.39	0.52
2 t ha^{-1}	4	14	58	67	0.05	0.09	4	9	42	87	0.09	0.11
4 t ha^{-1}	11	28	66	119	0.18	0.27	6	15	64	149	0.11	0.12
6 t ha^{-1}	10	24	63	135	0.15	0.22	7	15	62	124	0.10	0.13
8 t ha^{-1}	10	26	65	111	0.16	0.24	5	13	62	154	0.08	0.11
SED	2***	8***	5*	ns	0.05***	0.07***	3***	7***	23*	30*	0.05**	0.09***

SED = Standard error of differences in means, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$; ns = not significant.

Table 5.6 Effect of weed fallow, mineral N fertiliser and different management of mucuna residues on weed biomass (Mg DM ha^{-1}) associated with maize crop, observed in farmer fields at 5 and 9 weeks after sowing in the high and low rainfall zone of Bukoba District.

Management	High rainfall zone		Low rainfall zone	
	5 weeks after sowing	9 weeks after sowing	5 weeks after sowing	9 weeks after sowing
Weedy fallow	0.44	0.22	0.50	0.30
50 kg N ha^{-1}	0.65	0.30	0.58	0.31
Removed residues	0.52	0.23	0.47	0.29
Incorporated residues.	0.37	0.17	0.42	0.21
Mulched residues	0.22	0.12	0.17	0.09
SED	0.05***	0.04***	0.07***	0.06***

SED = Standard error of differences between means, ***$P< 0.001$.

5.3.6 Maize yield and N uptake under different types of Mucuna residue management

In the high rainfall zone, a yield increase of 30% and 36% in grain and of 32% and 35% in total aboveground biomass was recorded with incorporated residues and mulched residues, respectively (Table 5.7). Maize yields in removed residues and the control plots were comparable. Overall, the highest yield was obtained with application of mineral N fertiliser, which was 52%, 31% and 24% higher than the control, incorporated residues and mulched residues, respectively.

Table 5.7 Effect of weed fallow, mineral N fertiliser and different management of mucuna residues on N uptake and yield of maize under farmer conditions in the high and low rainfall zones of Bukoba District.

Management	High rainfall zone				Low rainfall zone			
	Yield ($Mg\ ha^{-1}$)		N uptake ($kg\ ha^{-1}$)		Yield ($Mg\ ha^{-1}$)		N uptake ($kg\ ha^{-1}$)	
	Grain	Above ground biomass	Grain	Above ground biomass	Grain	Above Ground biomass	Grain	Above ground biomass
Weedy fallow	1.4	3.4	20	31	2.0	5.1	30	45
50 kg N ha^{-1}	2.9	7.2	46	63	4.3	10.7	66	94
Residues removed	1.4	3.4	20	30	2.7	6.8	40	59
Residue incorporated	2.0	5.0	28	43	3.2	8.0	44	68
Residue mulched	2.2	5.2	31	45	4.2	10.4	61	89
SED	0.2***	0.5***	3***	4***	0.4***	0.9***	5***	8***

SED = Standard error of differences between means, ****P*< 0.001.

In the low rainfall zone, maize yield with the mulched residues and mineral N fertiliser treatments were not significantly different from each other but were 53% above the control. Incorporated residues increased grain yield by 38% whereas the removed residues increased yield by 26%. The total N uptake ranged between 31 and 45 kg ha^{-1} in the high rainfall zone and between 45 and 94 kg ha^{-1} in the low rainfall zone, with the treatment effect following a similar trend as for maize yield.

Maize grain and total aboveground biomass were positively correlated with N uptake (r^2 = 0.93 in the high rainfall zone and r^2= 0.86 in the low rainfall zone). However, wide variations in yield and N uptake were observed between sites and could be explained by the site differences in initial soil pH (r^2 = 0.64 and 0.56) and initial soil N (r^2 = 0.53 and 0.65) for the high and low rainfall zone, respectively.

5.3.7 Mineral N dynamics under different types of legume residue management and mineral N fertiliser

At fallow harvest, mean NO_3-N contents in the soil profile up to 0.9 m depth varied between 28 and 32 kg N ha^{-1} under weedy fallow and 20 and to 29 kg N ha^{-1} under mucuna fallow, in the high and low rainfall zones, respectively (Figure 5.2). At 6 WAP, NO_3-N content was 59, 11, 33 and 23 kg N ha^{-1} in the high rainfall and to 46, 9, 4 and 16 kg N ha^{-1} in the low rainfall zone in plots with mineral fertiliser, removed residues, incorporated residues and mulched residues, respectively. For all treatments, NO_3-N contents were highest in the 0-0.3 m depth, moderate in the 0.3-60 cm depth and lowest in the 0.6-0.9 m depth. At 12 WAP, NO_3-N in the soil varied between 5 and 55 kg N ha^{-1} in the high rainfall zone and 11 to 58 kg N ha^{-1} in the low rainfall zone. In all cases, the highest increase was observed with mineral N fertiliser and the lowest with the control. At 18 WAP, the control, residue removed and mineral fertiliser treatments had comparable NO_3-N concentrations at all depths, with similar trends for the high and low rainfall zone. In the same period NO_3-N concentrations were higher in residue incorporated and residue mulched plots but with the latter treatment showing slightly higher values in at the 0-30 cm depth.

5.3.8 Labour demand and productivity of legume fallow with different types of residue management

In the high rainfall zone, growing maize with incorporated residues required 26 and 27 more person-days compared with growing maize with removed residues and mulched residues (Table 5.8). A similar trend was observed in the low rainfall zone though with a slightly higher labour requirement per treatment. In both zones, growing maize with removed residues or mulched residues demanded about 22 person-days more compared with growing maize on a previously weedy fallow. In both zones, maize grown with mucuma residue removed or mulched demanded about 20 person-days more compared with maize grown with application of mineral N fertiliser. Growing maize with incorporated residues required about 40 and 45 person-days more compared with growing maize on a weedy fallow and with application of mineral N fertiliser, respectively, with the trend being the same in both zone.

Returns to labour ranged between 21 and 53 kg grain person-day^{-1} in the high rainfall zone and between 33 and 70 kg grain person-day^{-1} in the low rainfall zone, with the highest return observed with 50 kg N ha^{-1} treatment (Table 5.8), followed by mulched residues. In both zones removing and or incorporating residues gave comparable returns to labour invested. In the low rainfall zone, application of mineral fertiliser gave returns of 45%, 62%, 60% and 40% higher than the treatments control, removed

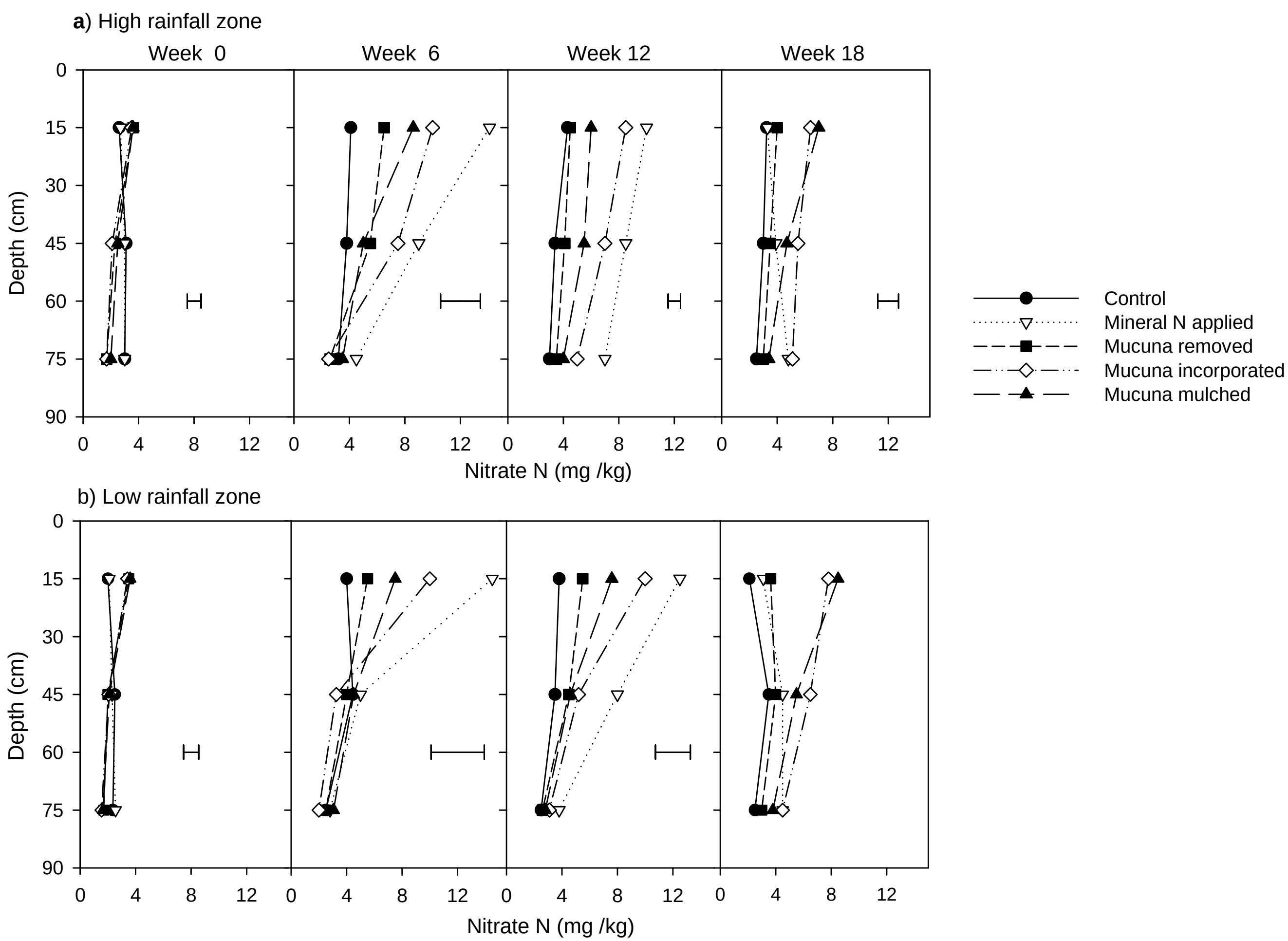

Figure 5.2 Soil NO_3-N in 0, 6, 13 and 18 week old maize established on a weedy fallow with and without application of mineral N fertiliser and under different type of mucuna residue management in a) high rainfall zone and b) low rainfall zone of Bukoba District. Horizontal bars are SED.

residues, incorporated residues and mulched residues, respectively. In the low rainfall zone, the returns to labour invested varied between 26 and 53% with the trend being the same as in the high rainfall zone.

Table 5.8 Estimated labour requirements (person days) and return to labour invested (kg /person day)under farmer conventional farming (weed fallow) in relation to use of mineral fertilisers and different management of mucuna residues in the high and low rainfall zones of Bukoba District.

Type of management	Type of field operation	High rainfall zone			Low rainfall zone		
		Labour required (pers.-day)	Total labour (pers-day)	Return to labour (kg pers-day^{-1})[a]	Labour required (pers.-day)	Total labour (pers. day)	Return to labour (kg pers. day^{-1})[a]
Weedy fallow	Land cultivation	33	49	29	33	58	43
	Weeding of maize	16			23		
50 kg N ha^{-1}	Land cultivation	33	55	53	35	61	70
	Fert. application	5			5		
	Weeding of maize	17			21		
Residues removed	Removing residues	4	70 [b]	20	5	81[b]	33
	Weeding maize	15			25		
Residues incorporated into the soil	Incorporating residues	32	96 [b]	21	30	101 [b]	36
	Weeding maize	13			20		
Residues mulched	Mulching residues	5	69 [b]	32	6	81 [b]	52
	Weeding maize	13			12		
SED			2***	5***		4***	10***

[a] Calculated as yield (kg) in Table 7 divided by total labour invested.
[b]Include labour for land cultivation, sowing and weeding (43), and uprooting mucuna (8).
SED = Standard error of differences between means, ****P*< 0.01

5.4 Discussion and conclusions

5.4.1 Effect of farmyard manure on biomass and N accumulation by crotalaria

Application of FYM on degraded soils increased the biomass and N accumulation by crotalaria (Table 2). The influence of FYM on crotalaria growth in degraded soils probably results from its liming effect ameliorating the problems of soil acidity and the supply of multiple nutrients (Bandyopadhay, 2003; Ridder and Keulen, 1990). The FYM used in the current experiment had N, P, Ca, K and Mg contents of 2.0, 0.5, 2.6 and 0.4% qualifying it as good quality when compared with other values for manure reported in Bukoba District (Kop, 1996). It is possible that a large proportion of N accumulated by the fertilised crotalaria was from N_2-fixation (Baijukya et al., submitted (b)).

5.4.2 Effect of application of FYM, crotalaria residues, mineral N fertiliser and their combination on maize development and final yield

Application of crotalaria residues and FYM in combination with mineral N fertiliser increased biomass accumulation and maize yields compared with the separate treatments and the control (Table 5.3). The yields obtained from FYM + MF (2.3 Mg ha^{-1}) treatment, was equal to the sum of the yield in the control (0.7), the yield response to FYM (0.7 Mg ha^{-1}) and the yield response to MF (1.0 Mg ha^{-1}). Likewise, yields obtained from Cr + MF (2.1 Mg ha^{-1}) were equal to the sum of the yield in the control (0.7), yield in the Cr treatment (0.4 Mg ha^{-1}) and yield in the MF treatment (1.0 Mg ha^{-1}), in both cases suggesting an additive effect of nutrients from these sources. A similar observation was reported in the humid tropics of West Africa when FYM was applied in combination with cowpea residues and or urea fertiliser (Iwuafor et al., 2002).

Combining crotalaria residues with FYM (Cr + FYM) and mineral fertiliser (Cr + FYM+ MF) resulted in an added increment of 700 kg and 300 kg of maize grain ha^{-1}, respectively. The most likely cause for the added benefits was the supply of multiple nutrients from the decomposing FYM. Under these conditions, the added benefits from the combined use of crotalaria residues and FYM can be considered sufficient to compensate for the cost of FYM even at a farm gate price equivalent to 100 kg grain per 1 Mg of dry FYM, which prevails in the region.

5.4.3 Maize response to the application of different quantities of T. candida residues

Biomass accumulation and maize yield increased with increasing application rates of *T. candid*a residues (Table 5.4). Given the poor N use and N recovery efficiency (Table 5.5), the observed increase in maize biomass could be attributed to better soil physical conditions, following application of residues which enhanced root growth and probably increased nutrient capture. However, the amounts of residues added were relatively small to have major effects on soil physical properties. The poor N recovery efficiency could be also a result of poor decomposability of *T. candida* residues as they are rich in reactive polyphenols and lignin (Chapter 4; Baijukya et al., submitted (b)). The observed low N utilisation efficiency at 2 Mg ha^{-1} residue application rate could be due to restricted root growth and poor uptake of nutrients. Maize yields in the high rainfall zone were comparable to yields in the low rainfall zone. This can be explained by regular rain distribution, avoiding excessive leaching in the high rainfall zone, and adequate rainfalls in the low rainfall zone during the experimental period (Figure 5.1 b).

The N use and N recovery efficiency in the current study are poor compared with those in earlier experiments conducted in the same zones (Chapter 4). This is due to differences in sites used as well as the weather conditions during the experimental period. The influences of site, weather and quality on decomposability of residues are discussed by Mafongoya et al. (1998). The lack of yield increase with application of 4, 6 and 8 Mg ha^{-1} implies that 4 - 6 Mg ha^{-1} may be an optimal rate of residue application in both the high and low rainfall zones, although this may vary with the type legume species used. As a general rule of thumb, only legumes producing above 2 Mg ha^{-1} of biomass (50 kg N ha^{-1}) would be expected to provide better yield response for maize in the following season (Gilbert, 2000). Although our results confirm the rule, they also indicate that the impact of residues is not necessarily from N provision as this depends on many factors including the quality of biomass in terms of N release and the management of residues.

5.4.4 Effect of legume residue management practices on weed biomass and maize yield

Weed biomass was highest in the mineral N fertiliser treatment compared with other treatments (Table 5.6) because of improved N availability to the weeds as well as lack of suppression by the residue mulch. Higher weed biomass in the control and mineral N fertiliser treatments could be attributed to seed dispersal from mature weeds that were in the weedy fallow. Maize in the incorporated residues established better and had good soil cover compared with treatments with removed residues, hence the lower weed biomass when residues were incorporated into the soil. The mulched residue treatment gave stronger weed suppression in the low rainfall zone than in the high rainfall zone. This was largely due to soil moisture conditions in the high rainfall zone (Figure 5.1) which allowed for fast decay of mucuna residues, which in turn created a more favourable environment for germination and establishment of weeds.

In the high rainfall zone, incorporated residues and mulched residues resulted in similar yields and N uptake by maize (Table 5.7), as well as similar NO_3-N in the topsoil with these two treatments (Figure 5.2). This indicates that under stable soil moisture and temperature conditions, decomposition and nutrient availability from mucuna residues was similar whether placed on the surface or incorporated into the soil. A similar observation was reported at Ibadan, Nigeria (Vine, 1953). Vanlauwe et al. (2001) also reported a minor difference in the total amount of mineral N between soil incorporated and surface applied mucuna residues. In a comparable experiment though under glasshouse conditions, Cobo et al. (2000), reported faster mineralization and higher N uptake by maize from surface applied than soil incorporated mucuna residues.

In the low rainfall zone, maize yield and N uptake with mulched residues were higher compared with incorporated residues, removed residues and the control, but less than mineral N fertiliser treatments. The observed higher yields and N uptake with mulch residues could largely be attributed to improved soil moisture conservation, which enhanced better establishment of maize. Moreover, maize plants in plots with mulched residues showed a longer duration, which is a sign of higher water availability in the rooting zone (Giller, 2002). The observed increase in maize yield and N uptake with removed residues compared with the control could be due to better root growth as a result of improved soil conditions and nutrient supply from the decomposing mucuna nodules and roots. The observed higher response of maize to mineral N fertiliser could be attributed to better supply of N at tasseling and at cob filling stages (at 6 and 12 WAP) which are peak periods of demand for N in maize (Keating et al., 1991).

5.4.5 Labour productivity of improved fallow with different legume residue management practices

Labour productivity was poor in residue removed and residue incorporated treatments compared with weedy fallow and mineral N fertiliser (Table 5.8). This is because of the extra labour required to establish, weed and incorporate residues into the soil. Our results are in agreement with the findings by Roger (1995), although his work was done in rice production systems and with different legume species. Mulched residues gave higher labour productivity than other types of legume management suggesting that the methods for managing legume residues could strongly determine the adoption of short fallow by smallholder farmers.

The observed low weedy biomass and subsequent low labour demand in mulched residue treatment suggests that the entry point of legumes into smallholder farms should not focus on improving soil fertility. Other immediate farmer problems which can be solved by planting of legumes e.g. labour in land preparation and weeding could lead to wider adoption of legumes as was the case with mucuna in Benin (Versteeg and Koudokpon, 1990). It can be concluded from this research that mucuna residues are more beneficial in smallholder farming if used as mulch as it impedes the growth of weeds, improves soil water conservation and supplies nutrients to crops when decomposing.

Results of this research suggest that if well managed, legume residues have potential to increase the yield of subsequent crops. However, the management practises discussed above are resource (labour, land, capital, FYM) intensive. Reducing labour spent on establishing and weeding legumes would improve labour productivity of all types of residue management. Relay-planting by under sowing legumes within maize crop after the second weeding, then allowing the legume to grow in the second season, is among the feasible approaches (Gilbert, 1998). Improved productivity of legumes in depleted soils will depend on availability of organic resources such as FYM, which is not within the reach of most smallholder farmers. The greatest challenge remains to determine the best mix of soil fertility management options that smallholder farmers, who are compelled to seek short-term gains when applying nutrients, may use to optimise their resource use and meet their production objectives.

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Legume establishment can be problematic in degraded soil. Application of small doses of manure can help to kick-start legume growth and improve production of subsequent crops.

Chapter 6

Exploring options for utilisation of herbaceous legumes in smallholder farms in banana-based farming systems of northwest Tanzania: Looking back to the system

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Chapter 6

Exploring options for utilisation of herbaceous legumes in smallholder farms in banana-based farming systems of northwest Tanzania: Looking back to the system

Abstract

An explorative study was conducted to identify rotations for using herbaceous legumes in smallholder farms in Bukoba District, Tanzania, to increase maize and manure production while maintaining positive partial N-balances in annual cropping fields. Explorations were done using a multiple goal linear programming model (MGLP). The maximum N-balances, maize and manure production without restriction on other objective functions (zero rounds) were: 55, 43 and 30 kg; 3430, 2674 and 1822 kg; and 3839, 2942 and 1942 kg per rotation period, for the resource-rich, medium and resource-poor households, respectively. Manure production conflicted with maize production and N-balances. The negative partial N-balance with manure production indicates that without external fertiliser inputs continued utilisation of *kikamba* for fodder production is not sustainable. At maximum maize production the model allocated 29%, 38% and 40% of *kikamba* of resource-rich, medium and resource-poor household in that order, to the green manure legume *Tephrosia candida* in rotation with maize. A similar land allocation was proposed when N-balance was maximised without restrictions of other objective functions but the area under *T. candida* was increased to 45%, 44% and 42% for the respective household categories. When manure production was maximized without restrictions of other objective functions, the model allocated 81%, 73% and 72% of *kikamba* of the resource-rich, medium and resource-poor households respectively, to the fodder legume *Desmodium intortum*. By imposing restriction on manure production or N-balances, the rotations with a mixture of green manure and fodder legumes were selected with the proportions of fodder legumes increasing with increasing levels of manure production. It is concluded from the results that there are opportunities for farmers to increase maize production at moderate levels of manure production while maintaining or improving N-balances of *kikamba*.

Key words**:** *Explorative study; Crop rotations; Maize and manure production; Nitrogen balances*

6.1 Introduction

Agricultural development in sub-Saharan Africa is constrained by a range of problems including decline in soil fertility (Eicher and Carl, 1982; Sanchez and Leakey, 1996). The evidence that traditional practices of managing soil fertility are no longer sustainable and that smallholder farmers cannot afford to use mineral fertilisers, has necessitated investment in developing cheap technologies to improve soil fertility including use of N_2-fixing legumes (Giller, 2001). The potential contributions of herbaceous legumes to the soils N-levels and their contribution to crop and livestock production have been covered in detail in a number of reviews (e.g. Snapp et al., 1998; Giller, 2001). However, authors also mention disappointingly low adoption rates of legume-based technologies. It is generally conceived that legumes would only be adopted by smallholder farmers if they could be grown on land that had no opportunity cost or intercropped with other crops (e.g. Gachene et al., 1999), if they could involve no extra labour and out of pocket cash expense and if they could guarantee some other benefits besides fertile soil (Versteeg et al., 1998; Giller, 2001; Bunch, 2002).

Whilst these propositions may have a predictive value also in Bukoba District, there are indications that individual farmers would adopt and use legumes in different ways depending on the available resources and production goals (Chapter 3). Earlier studies which focused on the role of herbaceous legumes for soil amendment (Becker et al, 1995; Giller and Cadisch, 1995) or as fodder (Ikwuegbu et al., 1995) indicate the need for detailed studies to investigate how legumes can best be used by smallholder farmers taking into account the trade-offs of their alternative uses (e.g. food, soil fertility improvement, fodder, soil erosion, weed control).

We developed a multiple goal linear programming model (MGLP) to explore options for using herbaceous legumes to meet farmers' objectives of increasing maize yields and manure production while achieving the environmental objective of positive N-balances in annual cropping fields (*kikamba*). The specific objectives of this study were to: *i*) identify combinations of crop activities and land use options in *kikamba* that give optimal maize yield, manure production and positive N-balances in smallholder farms, *ii*) assess the trade-offs between achieving the economic objectives of increasing maize and manure production and the environmental objective of achieving positive N-balances.

6.2 The approach

6.2.1 Multiple goal linear programming (MGLP)

To investigate the various options, multiple goal linear programming (MGLP) was used as an optimisation technique. MGLP is a multi-criteria analysis method composed of production techniques (in this case crop rotations), constraints, and more than one objective for which the model is optimised. The various objectives are optimised for a mix of production techniques subject to a set of constraints. The production techniques are defined by quantifying their outputs and required inputs. The inputs utilise resources that are limited and may therefore be constraining for the selection of production techniques.

The degree to which an objective is realised is expressed by its value in the optimisation procedure. In each iterative run, the MGLP model is optimised for one of the objective functions with upper or lower bounds on the other objectives (thus, the latter goals are used as constraints). In this way, the consequences of tightening one objective, in terms of others are revealed, i.e. the trade-offs between the objectives become visible. The result is a feasible combination of the values of the objective variables and the associated mix of production techniques. For a more detailed description of MGLP and its application in agricultural planning we refer to Wit et al. (1988), Ittersum et al. (1998), Hengsdijk and Ittersum (2003) and Dogliotti (2003).

In Chapters 3, 4 and 5 data on different aspects of legume management and productivity were collected from experiments conducted in the high and low rainfall zones of Bukoba District. However, in this chapter we restricted our analyses to the high rainfall zone, where information that we could not collect in the previous chapters, but which were necessary to run the model, were available from other studies.

6.2.2 Crop activities in the kikamba

The boundaries of the system that was modelled are the *kikamba*. The *kikamba* is used for cultivation of crops under various rotations. The crop activities were defined and quantified for different crop rotations. Two food crops (maize and sweet potato), six herbaceous legumes (*Tephrosia candida*, *Crotalaria grahamiana*, *Mucuna pruriens*, *Macrotyloma axillare*, *Macroptilium atropurpureum* and *Desmodium intortum*) and weedy fallow were considered in the rotations. Weedy fallow was regarded a crop because weeds are a significant component of fodder.

The rotations were defined by crop type, season, soil fertilising technique and crop residue management strategies. In Bukoba, rainfall follows a bimodal pattern with the short rains (SR) occurring between August-January and the long rains (LR) between March-July. One rotation cycle is completed after four seasons (2 years). Soil fertilisation techniques include zero N-inputs (farmer practice), application of mineral N-fertilisers at a rate of 50 kg N ha^{-1} (current fertiliser recommendation), the proposed incorporation of legume residues in the soil and soil coverage with legume residue mulch. Because of the possibilities that farmers would grow legumes in one field and use residues on another fields (biomass transfer), residue removal was also considered among the soil fertilisation strategies. Crop residue strategies include retaining residues in the field or removing them for use as mulch in *kibanja* or as fodder.

The definition criteria and the maximum number of variants that could define rotations (Hengsdijk and Ittersum, 2002, 2003) in *kikamba* are shown in Table 6.1. Theoretically, the four definition criteria for crop activities can be combined in any form with 4 types of seasons, 9 types of crops, 14 types of soil fertilising techniques and 3 types of crop residue strategies to give 1512 unique crop rotations. However, not all combinations are feasible. For example, the long rain season is unsuitable for maize production and farmers do not use mineral fertiliser on sweet potato or legumes. Moreover, legume residues are not used to fertilise sweet potatoes. Therefore, the number of rotations was reduced to 50 (Appendix 6.1), representing those that are technically feasible. These are comprised of rotations that are practised by farmers and the proposed alternatives which involve use of legumes.

6.2.3 Input-output coefficients of crop rotations

The input-output tables (Appendices 6.1 and 6.2) for the crop rotations were quantified using information gathered in Chapters 2, 3, 4 and 5, as well as from past studies conducted in the study area.

Inputs

The inputs considered were limited to nutrient N and labour. Nitrogen inputs in the crop rotation were calculated as the sum of N applied (kg ha^{-1}) in the form of organic and mineral fertilisers to individual crops. The application rate of 50 kg N ha^{-1} as mineral fertilisers was considered although farmers apply much lower doses (Chapter 2). Sweet potato receives about 4 kg N ha^{-1} in the form of weeds which are composted in the mounds as the crop grows. Maize is usually planted after sweet potato to utilise the residual effect of the decomposing weeds.

Table 6.1 Definition criteria and distinguishing variants per criteria for the crop rotations in *kikamba.*

Activity	Definition criteria	Maximum number of variant
Crop rotation	1. Number of seasons per rotation	4 (short rain 1, long rain 1, short rain 2, long rain 2)[1]
	2. Crop type	9 (maize, sweet potato, weed fallow, 6 types of legume species)
	3. Fertilisation technique	14 (zero inputs, mineral fertilisers, residues of 3 legume species incorporated in the soil or mulched [2], residues of 6 legumes species removed from the field [3])
	4. Crop residue use strategy	3 (Fed to dairy cattle, applied in *kibanja*, left in the field)

[1] The rotation is completed in two years, with one year having a short and a long rain season;
[2] These include *Tephrosia candida, Crotalaria grahamiana, Mucuna pruriens*;
[3] These include *Tephrosia candida, Crotalaria grahamiana, Mucuna pruriens, Macrotyloma axillare, Macroptilium atropurpureum and Despmodium intortum*.

The proposed alternatives of supplying N to maize is by use of legume residues. The amounts of legume N applied depend on the quantity and quality of legume residue used. The N input under different fertilisation strategies is presented in Table 6.2. In Chapter 3, the legume species *T. candida*, *C. grahamiana*, *M. pruriens*, *M. axillare, M. atropurpureum and D. intortum* were reported to fix on average 70, 63 and 78, 102, 61 and 109 kg ha^{-1} respectively, under production levels given in Table 6.2. These amounts of fixed N were considered as inputs.

Labour input was calculated as the sum of labour requirement (hours) per field operation for implementation of all field operations in a rotation (i.e. field preparation and planting (FPP), first weeding (W_1) second weeding (W_2) and harvesting (H) per period with periods of different lengths depending on the type of rotation. The information on labour required to grow maize under different soil fertilisation techniques including use of herbaceous legumes was reported in Chapter 5. Labour requirements for growing sweet potato were obtained from Kapinga et al. (1998).

<u>*Outputs*</u>

Crops and crop residues

The outputs from the *kikamba* include consumed or marketed crop products (maize grain and tubers), crop residues, weeds, and legume residues. The individual outputs were expressed in kg ha^{-1} of dry matter. Mean yields of crops and their residues as observed under farmer’s conditions are summarised in Table 6.2. The corresponding crop and crop output per rotation are presented in Appendix 6.2. In cases where maize is grown after sweet potato, the yield is 10% higher compared with yield under

Table 6.2 Production techniques, N inputs, N content, yield and total N of yield components of crops in *kikamba* (Data summarised from Chapters 2, 3, 4 and 5).

Crop	Fertilisation strategy	N input (kg ha^{-1})	%N (in maize grain, sweet potato tubers or legume residues)[a]	Biomass yield (kg ha^{-1} ± s.d.)		Total N in whole crop (kg ha^{-1})[b]
				Maize grain or sweet potato tubers	Stover of maize, sweet potato or legume residues	
Maize	No fertiliser amendment	0	1.2 (0.5)	1100 ± 400	1800 ± 560	22
	Mineral fertiliser (50 kg N ha^{-1}) [c]	50	1.4 (0.6)	3800 ± 600	6100 ± 700	90
	After sweet potato	-	1.2 (0.6)	1210 ± 250	1980 ± 480	26
	Soil incorporated residues of legume 1	97	1.3 (0.5)	3200 ± 700	5000 ± 980	67
	Soil incorporated residues of legume 2	32	1.2 (0.5)	2000 ± 300	3300 ± 730	41
	Soil incorporated residues of legume 3	62	1.4 (0.6)	2500 ± 550	4000 ± 630	59
	Mulched residues of legume 3	62	1.2 (0.5)	2200 ± 360	3000 ± 710	41
	Legume residues removed from field [d]	-	1.0 (0.7)	1400 ± 640	2000 ± 345	28
Sweet potato	Soil incorporated weeds	4	0.6 (1.0)	2400 ± 800	3056 ± 1020	17
Weeds	no fertiliser amendment	-	1.0	-	2000 ± 300	20
Legume 1	No fertiliser amendment	-	2.9	-	5500 ± 610	160
Legume 2	No fertiliser amendment	-	2.8	-	2100 ± 360	59
Legume 3	No fertiliser amendment	-	2.1	-	3700 ± 476	78
Legume 4	No fertiliser amendment	-	3.2	-	5800 ± 780	186
Legume 5	No fertiliser amendment	-	3.2	-	5100 ± 560	163
Legume 6	No fertiliser amendment	-	3.2	-	5000 ± 784	160

[a] Data in parenthesis are for maize and sweet potato stover; ± s.d. = Standard deviation, values are means of samples equal to the respective number of cases; [b] Excludes he below grounds parts of maize, legumes and non-harvestable roots of sweet potato;
[c] Current recommended application rate of mineral N fertilisers; [d] Apply to removal of residues of all six legume species from the field.
Legume 1 = *T. candida*, Legume 2 = *C. grahamiana*, Legume 3 = *M. pruriens*, Legume 4 = *M. axillare*, Legume 5 = *M. atropurpureum*.

zero input due to the residual effect of decomposing weeds in the previous crop (sweet potato). Maize and sweet potato residues can be used as mulch in the *kibanja* or as fodder. The legumes *T. candida* and *C. grahamiana* can be used as green manure in the *kikamba* or as mulch in the *kibanja*. Residues of *M. pruriens* can be used as green manure in *kikamba*, as mulch in *kibanja* or as fodder. The legumes *M. axillare*, *M. atropurpureum* and *D. intortum* are exclusively grown for use as fodder. The N outputs following removal from the *kikamba* of the respective residues of legume species were calculated as the mass fraction of the N content of the total dry biomass removed.

Manure

Cattle management in Bukoba District is changing from extensive (free grazing) to intensive (zero grazing) as more dairy cattle are introduced (Chapter 2). Over 80% of fodder fed to dairy cattle is collected from the *kikamba* in the form of crop residues and weeds. In this farming system, the main reason for farmers to keep cattle is to obtain manure to fertilise the *kibanja* (banana fields), thus manure is hardly returned back to the *kikamba* and we consider it as an output. The amount of manure obtained by feeding cattle with a certain type of fodder depends on quantities of fodder ingested and its digestibility, which also depends on nitrogen contents of ingested materials. Information on the qualities of fodder materials considered in the present study (Table 6.3) was obtained from previous studies (Kabatange and Shayo, 1997; Mwita, 2003; Nyambati and Sollenberg, 2003) and partly from Chapters 2 and 3. In the high rainfall zone of Bukoba, there seems to be no variation in quality of fodder materials between the seasons (Mwita, 2003). However, it was assumed that only 80% of legume residues and 50% of crop residues are consumed by cattle. The rest of materials are left in *kikamba*, wasted during collection and transportation or considered as refused by cattle. The amount of manure produced was estimated using the relationship developed by Lascano et al. (1992) as:

$$\text{Manure produced (kg)} = DM_{ingested} - D\left(\frac{DM_{ingested}}{100}\right) \qquad (6.1)$$

Where: $DM_{ingested}$ = dry matter of feed materials (kg) ingested and D = digestibility of feed materials (%).

Table 6.3 Quality of fodder materials produced in *kikamba* as considered in this study.

Fodder material	No. of samples	Digestibility (%) (± s.d.)	N content mg kg^{-1} of DM (± s.d.)	Source of information
Weeds	12	34 ± 3.1	1.2 ± 0.4	Mwita (2003)
Maize stover	10	49 ± 5.8	0.6 ± 0.1	Kabatange and Shayo(1997)
Sweet potato stover (vines)	8	63 ± 6.8	1.4 ± 0.3	Mwita (2003)
Residues of *M. pruriens*	4	62 ± 4.6	2.4 ± 0.4	Nyambiti and Sollenberg (2003)
Residues of *M. axillare*	6	64 ± 2.5	3.2 ± 0.5	Mwita (2003)
Residues of *M. atropurpureum*	6	68 ± 2.4	3.2 ± 0.6	Mwita (2003)
Residues of *D. intortum*	6	56 ± 1.8	3.2 ± 0.4	Mwita (2003)

DM =Dry matter; ± s.d. = Standard deviation, values are means of respective number of samples.

Nitrogen

The nitrogen outputs of rotations were calculated as the sum of the crop yield components removed from the field (grain or residues), multiplied by their respective N mass fractions. Values of nitrogen contents and probable N outputs of crops grown under different soil fertility management are indicated in Table 6.2. The total N outputs from the different crop rotations are presented in Appendix 2. These outputs are considered as losses to the *kikamba* in calculating its N-balance.

6.2.4 Constraints

The constraints considered in the model are land and labour availability. For each household category, the *kikamba* area occupied by crops must be less or equal to the area available, which is 0.51, 0.42 and 0.31 ha for resource-rich, medium and resource-poor households, respectively (Chapter 2). However, in any particular season of the year, each household has to produce at least 50 kg (dry weight) of sweet potato for food security reasons (Kapinga et al., 1998). Therefore, in each season, a certain area of *kikamba*, sufficient to produce at least 50 kg of sweet potato has to be reserved and this constrains the availability of land for cultivations of other crops.

Labour requirements for field operations depend largely on the type of crop, soil fertilisation technique and the yield achieved. Different field operations are carried out in a specific period of the year (Table 6.4). Thus, labour demand for such operations should not exceed the labour available. Estimations of labour available for crop activities in *kikamba* were based on FSRP (1990) and ARI-Maruku (unpublished). In these studies, availability of labour for crop activities was differentiated for women and men (Table 6.4). In the mode, the available labour for different household categories was related to the number of working persons; i.e. 2 women and 1.6 men for the resource-rich households, 1.5 women and 1.3 men for the medium-resource and 1 woman and 1 man for the resource-poor household (Nkuba, 1997).

6.2.5 Objective functions

The objective functions in the model were selected based on the outcome of the land use and nutrient balance study (Chapter 2), and on farmer's expectations from use of herbaceous legumes (Chapter 3). They relate to optimisation of:

- maize production (kg for whole *kikamba* area over a complete rotation cycle)
- manure production (kg for whole *kikamba* area over a complete rotation cycle) and
- N balance (kg for whole *kikamba* area over a complete rotation cycle)

Although the *kikamba* was also indicated to have negative balances of P and K (Chapter 2), in the present study only N was considered because it is the only nutrient that can be externally added to the system by herbaceous legumes through biological N_2-fixiation. In the present study, the N balance was partial and defined as the difference between the N inputs (through mineral and organic fertilisers) and outputs (harvested crops and crop residues removed from the field) in the crop rotation.

6. 3 Optimisation results

6.3.1 The maximum attainable N balances, maize and manure production

The maximum attainable N balances with no restrictions on the other objectives, in the so called zero rounds (Veeneklaas, 1990), were 55, 44 and 30 kg per rotation for the resource-rich, medium and resource-poor households, respectively (Table 6.5). The corresponding maize production at these N balances was 3106, 2530 and 1763 kg per rotation while manure production was 762, 624 and 442 kg for the respective household categories (Optimisation 1). The maximum attainable maize production without restrictions on other objectives was 3430, 2674 and 1822 kg for resource-rich, medium and resource-poor household, respectively. In this situation, positive N-balances of 25, 35 and 28 kg and manure production of 895, 705 and 459 kg per rotation were achieved by the respective household categories (Optimisation 2). The maximum manure production with no restrictions on the other objectives was 3839 kg for the resource-rich, 2942 kg for medium-resource and 1942 kg for the resource-poor household (Optimisation 3). These levels of manure production corresponded to N-balances of -93 for the resource-rich, -76 for medium-resource and -50 kg for the resource-poor households.

Table 6.4 Available labour for a full time farmer categorised for women and men for agricultural activities in the *kikamba* during different periods of the year and labour requirements for maize produced with different soil fertilisation techniques, sweet potato and legume cover crops (Data for available labour are means of 66 women and 54 men; from ARI-Maruku, Unpublished; data for labour requirements are from Chapter 5 for maize and legumes and from Kapinga et al., (1998) for sweet potato).

Season	Period in a year (dekad)	Type of field operation	Available labour (hours)		Labour requirements (hours ha^{-1}) for different crops						
			Women	Men	Maize-1	Maize-2	Maize-3	Maize-4	Maize-5	Sweet potato	Legumes
Short rain season	4	H	20	11	35	49	49	49	35	-	-
	6-7	FPP	19	15	-	-	-	-	-	308	245
	11	W_1	53	40	-	-	-	-	-	63	56
	15	W_2	-	16	-	-	-	-	-	42	-
Long rain season	23-25	FPP	33	11	245	245	294	105	98	308	-
	29	W_1 + fert. applic.	75	49	70	77	56	42	70	63	-
	33	W_2	57	14	49	56	35	21	49	42	-

FPP = Field preparation and planting; W_1 = First weeding; W_2 = Second weeding, H = harvesting.
Maize-1 = Maize with no fertility amendment; Maize-2 = maize with mineral N fertiliser applied; Maize-3 = Maize with incorporated legume residues; Maize-4 = Maize with legume residue mulched; Maize-5 = Maize with legume residue removed. Note: Sweet potatoes are harvested piece-meal, hence, labour for harvesting is not accounted for; Maize is only grown in the short rain season, whereas legumes are only grown in the long rain season.

Table 6.5 Maximum values of three objectives optimised (**bold**) and the associated values of the other objectives variables for *kikamba* of three household categories with the restriction that the *kikamba* should produce at least 50 kg DM of sweet potato per season.

Household category, (available land and labour)	Optimisation number	Goal variable			Maize production (kg)	Manure production (kg)	N-balance (kg)
		Maize production	Manure production	N- balance			
Resource-rich	1	Free	free	maximized	3106	762	**55**
(land = 0.51 ha)	2	Maximized	free	free	**3430**	895	25
(labour = 3.4 persons)	3	Free	maximized	free	390	**3839**	-93
Medium- resource	1	free	free	maximized	2530	624	**44**
(land = 0.42 ha)	2	Maximized	free	free	**2674**	705	35
(labour = 2.8 persons)	3	Free	maximized	free	385	**2942**	-76
Resource-poor	1	free	free	maximized	1763	442	**30**
(land = 0.31 ha)	2	Maximized	free	free	**1822**	459	28
(labour = 2.0 persons)	3	Free	maximized	free	281	**1942**	-50

6.3.2 Solution areas and trade-offs among objective functions

The maximum values of each single objective in Table 6.5 defined the outer boundaries of the solution areas. In subsequent iterations, the solution area for each household category was established by optimising maize production and progressively tightening restrictions for N-balance and manure production in steps of 1 unit. The results are given in Figure 6.1, where the N-balance (*x*-axis) and manure production (*y*-axis) are connected by labelled iso-maize production lines (*z*-coordinate). The solution areas for the three household categories have the same shape but the opportunities, as defined by the size of the solution areas are higher for the resource-rich household and less for the resource-poor-household. Due to similarities in shapes, Figure 6.1 is explained using results of the resource-rich household (Figure 6.1 A), but the same reasoning is applicable to Figure 6 B and 6 C.

The value at each point in the solution area represents a unique combination of the three objective variables. Numbers 1, 2 and 3 in Figure 6.1 correspond to optimisation numbers in Table 6.5. The area at the right of the broken line connecting points 1 and 3, represents the efficient or "Pareto" optimal solutions such that an increase in the value of one of the objectives is achieved by degrading the value of other objectives. The rest of the areas in the figure represent the non-Pareto optimal solutions. Operating in the Pareto optimal solution area means that overall each kg of increase in manure production leads to a decrease in 0.9 kg of maize. Also, each 25 kg of produced manure leads to 1 kg decline in N-balance. Restricting the N-balance to a minimum of -10 kg N, the maize production in the Pareto optimal solution area at point *a*, is 1230 kg below that at optimum maize production (point 2) whereas the manure is 1500 kg above that obtained in Optimisation 2. Consequently, the N-balance at this rate of manure production is 45 kg N less that with Optimisation 2. In general, maximisation of manure production conflicts with maize production and N-balances, and *vice versa*. However, there seems to be little conflict between maize production and N-balances. Reducing manure production to 1250 kg raises maize production to 3200 kg (point *b*). However, a further reduction in manure production to levels below that obtained at maximum maize production e.g. to 350 kg, result in a concomitant reduction in maize yield to 1200 kg, whereas nothing is gained in the N-balance (point *c*).

Analyses along the horizontal lines, which show a constant manure production and increasingly tighter restrictions on N-balances, indicate that within the non-Pareto

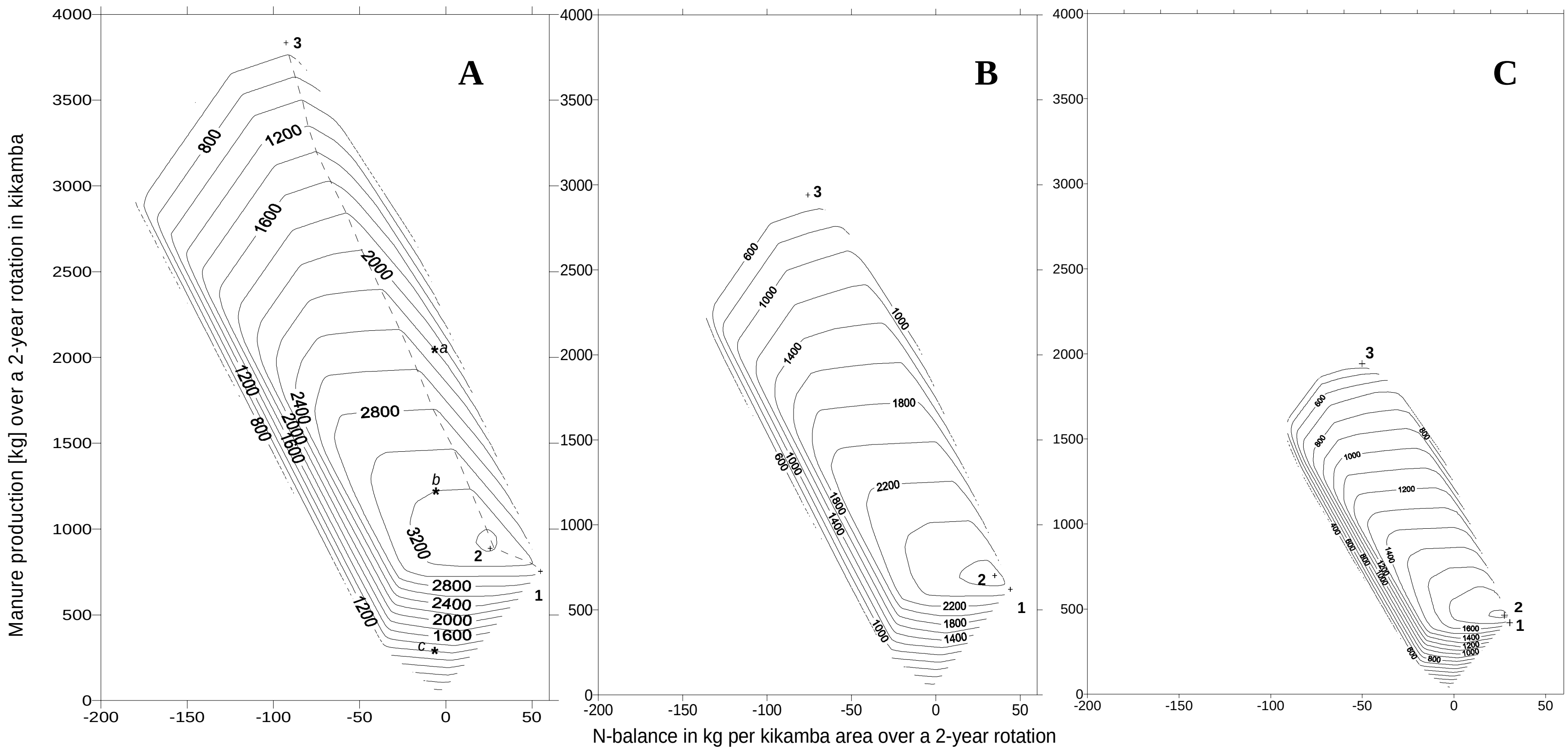

Figure 6.1. The solution area for cropping in *kikamba* as defined by optimisation of N-balance, maize and manure production for the three household categories; the resource-rich (A), medium-resource (B) and resource-poor (C). Labelled lines are iso-maize production, numbers 1-3 refer to optimisations and letters a-c are points of interest as explained in the text.

solution area, improving N balance gradually increases maize production, and reaches a threshold where any further improvement in N-balance hardly improves maize yield. For example, at fixed manure production of 1700 kg, maize yields of between 2800 and 2850 kg are obtained at N-balances ranging from -10 to -60 kg N ha^{-1}. Thus, at fixed levels of manure production and slight changes in maize production a farmer has opportunities to improve the N-balances by choosing alternative crop rotations. Generally, the denser the maize iso-production lines in the non-Pareto optimal solution area the higher the rate of decline in maize production becomes for a slight change in N-balance. Although it sounds futile to operate in this area, the majority of farmers in Bukoba do so as they hardly apply nutrients to improve N-balances. In the following sections the configuration and crop rotations as depicted by the points in Figure 6.1 will be analysed in more detail to reveal the influence of the herbaceous legumes.

6.3.3. Crop rotations and land allocation of kikamba when maximising maize production with no restriction on N balance and manure production

Maximizing maize production on poor soil requires supply of nutrients including N. At maximum maize production the model allocated 33%, 39% and 40% of the *kikamba* area of resource-rich, medium and resource-poor households, respectively, to green manure legumes in the long rain season, in rotation with maize in the short rain season (Table 6.6). The remaining land was allocated to weedy fallow which is rotated with sweet potato and maize. In this situation, maize occupies 43, 48 and 46% of the *kikamba* area for the resource-rich, medium and resource-poor household, respectively. The model proposed application of mineral N-fertiliser to maize growing on land that had not been under legumes. In all cases, *T. candida* was chosen as green manure legume, with its residues incorporated into the soil before maize was planted. A similar configuration of *kikamba* was proposed when N-balance was maximised without restrictions on other objectives. However, in this case, the area under *T. candida* increased to 45%, 44% and 42% for the resource-rich, medium and resource-poor household in that order. The area under weedy fallow and sweet potato decreased slightly. When manure production was maximized without restrictions of other objectives, the model allocated 91%, 87% and 84% of the *kikamba* of the resource-rich, medium and resource-poor households respectively, to fodder legumes, mainly to *D. intortum*. Ten to fourteen percent of *kikamba* was allocated to the fodder legume *M. axillare* in the long rain season, to be rotated with maize in the short rain season. The rest of the land was equally allocated to weedy fallow and sweet potato in the long rain season, followed by maize and sweet potato in the short rain season. The proposed land allocation to crops in the specific seasons at maximum N-balance, maize and manure production is presented in Table 6.7.

Table 6.6 Land allocation when optimising respectively N balance, maize yield and manure production with no restrictions on the other objectives, for *kikamba* of different household categories. All figures pertain to an average *kikamba* size for the respective households.

Production characteristic	Resource-rich household			Medium-resource household			Resource-poor household		
	Maximum maize production	Maximum N-balance	Maximum manure production	Maximum maize production	Maximum N- balance	Maximum Manure production	Maximum maize production	Maximum N- balance	Maximum manure production
Goal									
N balance (kg N)	25	55	-93	35	44	-76	28	30	-50
Maize production (kg)	3430	3106	390	2674	2530	385	1822	1763	281
Manure production (kg)	895	762	3839	705	624	2942	459	442	1942
Land allocation to crops (%)									
Weedy fallow	11	2	3	7	2	6	5	5	6
Sweet potato	13	5	4	6	7	5	9	8	6
Maize + mineral N-fert.	10	3	2	9	3	2	6	3	4
Maize / leg. residues inc.	33	45	0	39	44	0	40	42	0
Green manure legume	33	45	0	39	44	0	40	42	0
Fodder legume/ maize	0	0	10	0	0	14	0	0	12
Fodder legume	0	0	81	0	0	73	0	0	72

6.3.4. Crop rotations and land allocation of kikamba when maximizing maize production with restriction on manure production

When optimising maize production with manure production restricted at 1500 kg, the area under rotation of *T. candida* and maize decreased from 45 to 21% if the N-balance is restricted at ≥ 1 kg for the resource-rich household, 38% to 20% if the N-balance is restricted at ≥ -12 kg for medium-resource household and from 40% to 19% if the N-balance is restricted at ≥ 20 kg for the resource-poor household (Table 6.8). The model results indicated that 13%, 9% and 3 % of *kikamba* of resource-rich, medium-resource and resource-poor households, respectively, had to be under a fodder legume *M. axillare* in the long rain season, and then rotated with maize in the short rain season. The model also proposed 14%, 26% and 44% of the *kikamba* to be under permanent cultivation of a fodder legume *D. intortum*. Given these restrictions area allocated to maize is reduced, but yields are maintained by application of mineral N-fertilisers. At more extreme negative N balances e.g. at -150 kg for resource-rich household, -130 kg for the medium resource household and -80 kg for the resource-poor households, area under the weedy fallow and fodder legume increased and for medium and resource-poor households, the area under maize produced without mineral N fertilisers increased. In this situation, *D. intortum* was proposed as the fodder legume to grow.

In the previous experiments (Chapters 3), *T. candida* yielded higher biomass and accumulated larger amount of N. In addition to these characteristics, incorporated residues of *T. candida* gave higher maize yields than when other type of residues were used (Chapter 4), hence this legume species was selected by the model. On the other hand, *D. intortum* was selected by the model despite yielding lower biomass and N compared to *M. axillare* and *M. atropurpureum*. This could be explained by lower digestibility of *D. intortum* due to high tannin contents (Chapter 4). Plants containing higher proportion of tannins are often found to be relatively resistant to degradation in the rumen (Deshpande and Salunkhe, 1982), hence large proportions of such materials come out of the animal in the form of faeces. Although, our interest was to optimise manure from legumes, this may conflict with other farmer objectives of improving animal nutrition and production.

6.3.5. Labour demand and availability for crop activities at maximum N balance, and at maximum maize and manure production

Optimisation results showed that labour is not limiting in periods when legumes are to be planted (FPP in long rain season), weeded (W_1 in long rain season) or incorporated into the soil (FPP in short rain season) (Table 6.9). Consequently, the

Table 6.7 Land allocation of *kikamba* to crops for different household categories to achieve the maximum N balance, maize and manure production in different seasons in a rotation. Land units are ha.

Household category	Crop activity	Maximum maize Production				Optimum N balance				Maximum manure production			
		LR1	SR1	LR2	SR2	LR 1	SR1	LR2	SR2	LR1	SR1	LR2	SR2
Resource-rich	Weedy fallow	0.19	0.00	0.04	0.00	0.00	0.00	0.04	0.00	0.02	0.00	0.04	0.00
	Sweet potato	0.02	0.02	0.17	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Maize with no input	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.10	0.00	0.10
	Maize + mineral N-fert.	0.00	0.19	0.00	0.19	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02
	Maize / leg. residues inc.	0.00	0.30	0.00	0.30	0.00	0.47	0.00	0.45	0.00	0.00	0.00	0.00
	Green manure legume	0.30	0.00	0.30	0.00	0.47	0.00	0.45	0.00	0.00	0.00	0.00	0.00
	Fodder legume	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.37	0.45	0.37
Medium-Resource	Weedy fallow	0.00	0.02	0.04	0.02	0.00	0.00	0.04	0.02	0.04	0.00	0.04	0.00
	Sweet potato	0.10	0.00	0.06	0.00	0.04	0.02	0.02	0.02	0.04	0.04	0.02	0.04
	Maize with no input	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.07	0.00	0.07
	Maize + mineral N-fert.	0.00	0.08	0.00	0.08	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.02
	Maize / leg. residues inc.	0.00	0.32	0.00	0.32	0.00	0.38	0.00	0.36	0.00	0.00	0.00	0.00
	Green manure legume	0.32	0.00	0.32	0.00	0.38	0.00	0.36	0.00	0.00	0.00	0.00	0.00
	Fodder legume	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.29	0.34	0.29
Resource-poor	Weedy fallow	0.00	0.01	0.04	0.01	0.00	0.01	0.04	0.01	0.05	0.02	0.05	0.02
	Sweet potato	0.06	0.02	0.02	0.02	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Maize with no input	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01
	Maize + mineral N-fert.	0.00	0.03	0.00	0.03	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02
	Maize / leg. residues inc.	0.00	0.25	0.00	0.25	0.00	0.26	0.00	0.25	0.00	0.00	0.00	0.00
	Green manure legume	0.25	0.00	0.25	0.00	0.26	0.00	0.25	0.00	0.00	0.00	0.00	0.00
	Fodder legume	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.24	0.24	0.24

All column groups fall under the heading "Objective".

LR1= Long rain season 1, LR2= Long rain season 2, SR1 = Short rain season 1, SR2 = Short rain season 2.

Table 6.8 Land allocation when optimising maize production without and with restriction on manure production (1500 kg) and restrictions on N balances for the resource-rich, the medium and the resource-poor household at respectively, 1 and -150 kg N, -12 and -130 kg N, and -20 and -80 kg N. All figures pertain to average *kikamba* sizes for the respective households.

Characteristic	Resource rich household			Medium resource household			Poor resource household		
	Not restri-cted	Restricted at 1500 kg manure		Not restri-cted	Restricted at 1500 kg manure		Not restri-cted	Restricted at 150 kg manure	
		N ≥1	N ≥-150		N ≥-12	N ≥-130		N ≥-21	N ≥-80
Goal									
N balance (kg N)	55	1	-150	44	-12	-130	30	-20	-80
Maize production (kg)	3106	2975	1225	2530	1955	618	1763	937	308
Manure production (kg)	762	1500	2720	624	1500	2100	442	1500	1220
Land allocation to crops (%)									
Weedy fallow	3	2	16	6	3	13	5	4	17
Sweet potato	4	10	7	9	8	5	9	7	7
Maize with no fertiliser	0	0	0	0	0	6	0	0	11
Maize + mineral N-fert.	3	19	9	9	14	5	6	4	2
Maize / leg. residues inc.	45	21	0	38	20	0	40	19	0
Green manure legume	45	21	0	38	20	0	40	19	0
Fodder legume/ maize	0	13	4	0	9	4	0	3	0
Fodder legume	0	14	64	0	26	67	0	44	63

Table 6.9 Available labour (hours) for resource rich, medium and resource poor households and labour demand for implementation of different field operations in the long rain and short rain seasons to achieve the maximum N balances, and maximum maize and manure production. Bold values indicate labour limitations (i.e. labour demand equals labour available).

Season	Field operation	Resource- rich household				Medium resource household				Resource- poor household			
		Avail.Labour	Labour demand for maximum:			Avail. Labour	Labour demand for maximum:			Avail. Labour	Labour demand for maximum:		
			Maize prod.	N-bal.	Manure prod.		Maize prod.	N-bal.	Manure prod.		Maize prod.	N-bal.	Manure prod.
LR1	FPP	189	79	127	37	144	0.9	105	27	98	80	79	19
LR1	W_1	38	18	29	28	30	24	24	21	22	18	18	14
LR1	W_2	21	1	2	21	16	4	2	16	11	3	2	11
LR1	H	21	0	0	20	16	0	0	15	10	0	0	9
SR1	FPP	208	141	149	111	159	120	123	89	111	86	86	18
SR1	W_1	34	34	29	34	26	26	25	26	18	18	18	18
SR1	W_2	32	21	18	29	24	16	15	21	17	11	11	15
SR1	H	57	24	24	25	44	20	20	20	31	14	14	13
LR2	FPP	189	126	116	28	144	97	97	18	98	67	67	10
LR2	W_1	38	28	26	26	30	22	22	21	22	15	15	14
LR2	W_2	21	7	1	21	16	2	1	16	11	1	1	11
LR2	H	21	0	0	20	16	0	0	15	10	0	0	9
SR2	FPP	208	141	147	28	159	120	120	22	111	86	87	64
SR2	W_1	34	34	30	34	26	26	25	26	18	18	17	18
SR2	W_2	32	21	18	29	24	16	16	22	17	11	11	14
SR2	H	57	24	24	25	44	20	20	19	31	14	14	13

R1 = long rain season 1, LR2 = long rain season 2, SR1 = short rain season 1 SR2 = short rain season 2.
FPP = field preparation and planting, W_1 = first weeding, W_2 = second weeding, H= harvesting.

rotations comprising legumes and residue management requiring more total labour but which are more efficient in the short rainy season when maize is grown. This results in higher maize and manure production and more positive N-balances the reason why these rotations were selected. However, labour was limiting in the short rain season (SR1 and SR2) when maize is grown at the first weeding period (W_1) and in the long rain season (LR1 and LR2) at the second weeding period (W_2) although less frequently.

6.4 Discussion and conclusions

6.4.1 Objective functions and household resources

The focus of this study was to explore the scope for improving maize and manure production, and N balances through use of herbaceous legumes in smallholder farms in Bukoba District. The results of explorations with MGLP model show that at present endowment, all household categories are able to increase maize and manure production or achieve positive N-balances of the *kikamba* if they adopt the herbaceous legumes (Table 6.5). We have shown that, through a step-by-step tightening of manure production or N balances, the acceptable area, i.e. the area where the combination of maize, manure production and N balances to each of the farmer household category can be established. However, depending on the farmer's emphasis on a specific goal, the characteristic combinations and area occupied by the crops in the particular season may vary and hence will lead to differences in scenarios for *kikamba* use.

At all levels of combinations of the objectives, similar crop activities are selected for all three household categories, the difference being on area of land occupied by different crops. This is because labour was equally available to all households, as all have a land-to-labour ratio of 0.2. It may be concluded from these results that for Bukoba District where land holdings are small, labour should not be seen as constraint to adoption of legume technology as long as there are no opportunities for its use in other sectors off-farm.

6.4.2 Sustainable integration of herbaceous legumes in the kikamba

Sustainable use of N in *kikamba* soils as defined in the present study (partial N-balance) is assured at maximum maize production and maximum N-balances. In these two situations, both the N_2-fixed from the atmosphere and the N sourced from the soil is retained in the field, and the loss that occurs through removal of crop residues is returned in the form of mineral fertilisers. However, the sustainability is jeopardised when the *kikamba* is left to produce the fodder crops. This is because the fodder legume exports both the fixed-N and N sourced from the soil. Contrary to the situation in central Kenyan highlands where manure is returned back to the plots where fodder and crop residues are produced (Lekasi et al., 1994), manure use in Bukoba is used selectively in the banana plots (*kibanja*). The strategies to sustain fodder production from *kikamba* would be to bring back part of manure or increase application of mineral fertilisers. However, the current price ratios of fertiliser and animal products e.g. milk are hardly conducive to fertiliser utilisation (Omolo et al., 1999). Thus, the key parameter for future cattle production in banana based systems in Bukoba District is apparently not the land availability but the price ratio between inputs and outputs.

6.4.3 Application of the approach in an innovation process

This explorative model was developed to explore strategic opportunities and possible consequences of introducing legumes into smallholder farms rather than to study tactical decision making. The results obtained allow a basis for strategic discussions among farmers, extension staff and researchers on the sustainable use of *kikamba* and support the design of alternative crop rotations before they are implemented. The proposed crop rotations should be tested on-farm as proposed by Makowski et al. (2000) and the results obtained from such experiments could be used to build confidence in, and/ or improve, the model.

Models always simplify reality, thus, some relationships not defined in the model are excluded. Therefore the presented results must be considered within the limits defined for the system being modeled. All calculations were made using the averages of crop yields, N inputs, probable manure production and mean values of farmer resources (labour and land). As mentioned before, the present study only took the *kikamba* into consideration which is one of many dynamic related elements of the smallholder farms in these banana-based systems. It is most likely that by including other components of the farm, as well as the institutional arrangements and markets, the outcome of the model will change. The model described has a flexible structure which allows for extension to consider additional goals, production techniques and restrictions.

Appendix 6.1 Rotations considered in the study and the associated N and labour demand. Abbreviations of crops in the rotations are Wef = weedy fallow, Maiz = maize, Sp = Sweet potato, Tc = *Tephrosia candida*, Cg = *Crotalaria grahamiana*, Mp = *Mucuna pruriens*, Max = *Macrotlyloma axillare*, Mat = *Macroptilium atropurpureum*, Di = *Desmodium intortum*.

Crop rotation	N inputs (kg ha^{-1})	Labour demand (hours ha^{-1}) for a rotation
Wef-Maiz-Wef-Maiz	0	784
Sp-Maiz-Sp-Maiz	15	1470
Wef-Maiz-Wef-Maiz	100	854
Sp-Sp-Wef-Maiz	65	1253
Mp-Maiz-Mp-Maiz	124	1470
Sp-Maiz-Sp-Wef	15	1148
Sp-Wef-Sp-Wef	15	826
Sp-Maiz-Sp-Wef	65	1253
Sp-Wef-Sp-Maiz	15	1148
Wef-Maiz-Wef-Maiz	8	1057
Wef-Sp-Wef-Maiz	8	735
Wef-Maiz-Wef-Sp	8	735
Sp-Maiz-Wef-Maiz	8	1057
Sp-Maiz-Wef-Sp	15	1057
Wef-Maiz-Sp-Maiz	108	1267
Wef-Sp-Wef-Maiz	58	840
Wef-Maiz-Wef-Sp	58	840
Sp-Maiz-Sp-Maiz	115	1267
Sp-Maiz-Wef-Maiz	108	1267
Sp-Wef-Sp-Maiz	65	1253
Sp-Maiz-Sp-Wef	65	1253
Sp-Maiz-Wef-Sp	65	1253
Mp-Maiz-Sp-Maiz	70	1470
Sp-Maiz-Mp-Maiz	70	1470
Mp-Maiz-Mp-Maiz	124	1036
Mp-Maiz-Sp-Maiz	70	1253
Sp-Maiz-Mp-Maiz	70	1253
Tc-Maiz-Sp-Maiz	105	1470
Tc-Maiz-Tc-Maiz	194	1470
Tc-Maiz-SP-Maiz	105	1267
Sp-Maiz-Tc-Maiz	105	1267
Sp-Maiz-Tc-Maiz	105	1470

Appendix 6.1 continued…..

Cg-Maiz-Cg-Maiz	129	1470
Cg-Maiz-Sp-Maiz	40	1470
Sp-Maiz-Cg-Maiz	40	1470
Max-Maiz-Max-Maiz	204	951
Max-Maiz-Sp-Maiz	102	1347
Sp-Maiz-Max-Maiz	110	1347
Mat-Maiz-Mat-Maiz	122	1224
Mat-Maiz-Sp-Maiz	61	1347
Sp-Maiz-Mat-Maiz	69	1347
Di-Maiz-Di-Maiz	218	1224
Di-Maiz-Sp-Maiz	109	1347
Sp-Maiz-Di-Maiz	117	1347
Mp-Maiz-Mp-Maiz	124	1224
Max continuous	436	959
Mat continuous	244	959
Mp continuous	248	1064
Di continuous	436	959

Appendix 6.2 Outputs (kg DM ha^{-1}) of weeds, maize, sweet potato, legume residues from the *kikamba* under specific crop rotations and the associated manure production (kg ha^{-1}) and N (kg ha^{-1}). Intercrop management refers to soil fertility management when maize is grown; A = No fertility amendment, B = Mineral N fertilizer, C = legume residues incorporated, D = legume residues mulch, E = legume residues removed). All data are over the cropping rotation in kg ha^{-1}. For abbreviations in crop rotation see Appendix 1.

Crop rotation	Inter-crop manage-ment.	Weeds	Maize grain	Maize stover	S. potato tubers	S. potato residues	Legume residues	Manure	N output
Wef-Maiz-Wef-Maiz	A	4000	2200	3600	0	0	0	551	75
Sp-Maiz-Sp-Maiz	A	0	2420	4158	5000	6111	0	1201	70
Wef-Maiz-Wef-Maiz	A	4000	7600	7859.4	0	0	0	1867	162
Sp-Sp-Wef-Maiz	B	2000	3800	6100	5000	6111	0	1499	102
Mp-Maiz-Mp-Maiz	C	0	5000	8000	0	0	7400	1224	83
Sp-Maiz-Sp-Maiz	A	2200	1210	2178	5000	6111	0	899	61
Sp-Wef-Sp-Wef	A	4400	0	0	5000	6111	0	565	52
Sp-Maiz-Sp-Wef	B	2200	3800	6710	5000	6111	0	1592	104
Sp-Wef-Sp-Maiz	A	2200	1210	2178	5000	6111	0	899	61
Wef-Maiz-Wef-Maiz	A	2000	2310	3978	2500	3056	0	891	73
Wef-Sp-Wef-Maiz	A	4200	1100	1800	2500	3056	0	558	80
Wef-Maiz-Wef-Sp	A	4200	1100	1800	2500	3056	0	558	54
Sp-Maiz-Wef-Maiz	A	2000	2310	3978	2500	3056	0	891	73
Sp-Maiz-Wef-Sp	A	2000	1210	2178	5000	6111	0	899	60
Wef-Maiz-Sp-Maiz	B	2000	7980	12810	2500	3056	0	2243	163
Wef-Sp-Wef-Maiz	B	4200	3800	6100	2500	3056	0	1216	108
Wef-Maiz-Wef-Sp	B	4200	3800	6100	2500	3056	0	1216	108
Sp-Maiz-Sp-Maiz	B	0	7980	13420	5000	6111	0	2619	160
Sp-Maiz-Wef-Maiz	B	2000	7600	12810	2500	3056	0	2243	158
Sp-Wef-Sp-Maiz	B	2200	4180	6710	5000	6111	0	1592	108
Sp-Maiz-Sp-Wef	B	2200	3800	6710	5000	6111	0	1592	104
Sp-Maiz-Wef-Sp	C	2000	3800	6710	5000	6111	0	1592	103
Mp-Maiz-Sp-Maiz	A/C	0	3710	4678	2500	3056	3700	998	73
Sp-Maiz-Mp-Maiz	A/C	0	3710	6178	2500	3056	3700	1228	76

Appendix 6.2 continued …..

Mp-Maiz-Mp-Maiz	D	0	5000	8000	0	0	7400	1224	83
Mp-Maiz-Sp-Maiz	A/D	0	3710	4678	2500	3056	3700	998	73
Sp-Maiz-Mp-Maiz	A/D	0	3710	6178	2500	3056	3700	1228	76
Tc-Maiz-Tc-Maiz	C	0	6400	10000	0	0	11000	1530	73
Tc-Maiz-Sp-Maiz	AC	0	4410	7178	2500	3056	5500	1381	71
Tc-Maiz-Tc-Maiz	D	0	4410	4356	0	0	11000	949	169
Tc-Maiz-Sp-Maiz	A/D	0	4410	10000	2500	3056	5500	1813	78
Sp-Maiz-Tc-Maiz	D	0	4410	7178	2500	3056	5500	1381	71
Sp-Maiz-Tc-Maiz	C	0	4410	7178	2500	3056	5500	1381	71
Cg-Maiz-Cg-Maiz	C	0	4000	6600	0	0	4200	1010	119
Cg-Maiz-Sp-Maiz	A/C	0	3210	5478	2500	3056	2100	1121	62
Sp-Maiz-Cg-Maiz	C	0	3210	5478	2500	3056	2100	1121	62
Max-Maiz-Max-Maiz	E	0	2800	4000	0	0	11600	4788	426
Max-Maiz-Sp-Maiz	A/E	0	2610	4178	2500	3056	5800	3010	240
Sp-Maiz-Max-Maiz	A/E	0	2610	4178	2500	3056	5800	3010	248
Mat-Maiz-Mat-Maiz	E	0	2800	4000	0	0	10200	3876	368
Mat-Maiz-Sp-Maiz	A/E	0	2610	4178	2500	3056	5100	2554	212
Sp-Maiz-Mat-Maiz	A/E	0	2610	4178	2500	3056	5100	2554	219
Di-Maiz-Di-Maiz	E	0	2800	4000	0	0	10000	5012	364
Di-Maiz-Sp-Maiz	A/E	0	2610	4178	2500	3056	5000	3122	210
Sp-Maiz-Di-Maiz	A/E	0	2610	4178	2500	3056	5000	3122	217
Mp-Maiz-Mp-Maiz	E	0	2800	4000	0	0	7400	3424	202
Max continuous	E	0	0	0	0	0	24200	8712	723
Mat continuous	E	0	0	0	0	0	21200	6784	665
Mp continuous	E	0	0	0	0	0	18600	7068	334
Di continuous	E	0	0	0	0	0	20400	8976	645

A

B

The *kibanja* is the most sustainable system in Bukoba where soil nutrients are prone to leaching due to high rainfall. However, profitable marketable bananas can be sustained with application of large quantities of manure.

A: A kibanja and the homestead.

B: Bananas at the market.

Chapter 7

General discussion

Chapter 7

General discussion

7.1 Introduction

The overall goal of this study was to explore the potentials and opportunities for integrating herbaceous legumes in the deteriorating banana-based farming systems in Bukoba District, Tanzania, to revitalize soil fertility, and accordingly improve their productivity. In this chapter we draw major conclusions and discuss the main results from the previous chapters.

7.2 Farming system dynamics

In Chapter 2, we presented results of the study on the evolution of soil fertility management practices by farmers in Bukoba District over 39 years. It was indicated that the ecological balance between the home gardens (*kibanja*) and the grasslands (*rweya*) has been lost in unprecedented socio-economic changes since independence, resulting in expansion of annual cropping fields (*kikamba*). The general impact of the changes on soil fertility management is summarised as follows:

a) The divergence in soil fertility management strategies for *kibanja* according to household resources. This encompasses two opposing trends: *i*) gradual restriction of cattle keeping to wealthier households, obtaining sufficient quantities of manure to maintain their *kibanja* and *ii*) gradual increase in the number of poor households with no access to manure, practicing minimal soil fertility management, experiencing a gradual decline in fertility of their small-sized *kibanja*.
b) The decline and disappearance of long-term natural fallows as farmers increasingly exploit short-term fallows in *kikamba.*
c) Intensification in livestock management by the wealthier households resulting in increased utilization of crop residues and weeds from *kikamba* as source of fodder but without any corresponding intensification of manure use in *kikamba*.

The above trends present a particular difficult problem. The point of concern is that the ecologically refined *kibanja* in the of the majority poor households is disintegrating, yet the local conditions do not favour a simple transition to a different cropping pattern that does not require external inputs.

We have indicated in Chapter 2 that population growth is not the only factor for an overall decline in soil fertility as a part of the prevailing generalised view of the poor region’s resource base (Stoorvogel and Smaling, 1990; Sanchez and Leakey, 1996).

Other factors play a role as well including poor prices of cash crops in the world market, and increased social differentiation of farm households. Few wealthier households intensifying livestock management maintain *kibanja* management because they have off-farm opportunities rather as a response to population growth. This implies that the generalised remedies researchers offer in the region such as application of farmyard and mineral fertilisers (Mgenzi and Mbwana 1999; Mowo et al., 1993) ignore crucial relationships between people and their environment. Our observations support the recommendations that social differentiation and its implications have to be recognised and factored into research (FSRP, 1990; Nkuba, 1997).

7.3 Adaptability and productivity of herbaceous legumes

In low-external input agriculture where soil N is deficient, legumes are an option to improve human nutrition, to improve crop and fodder situation. The ability of legumes to fix atmospheric N_2 and thereby add external N to the soil-crop or soil-crop-livestock production systems is a distinct benefit. Other added benefits include among others, suppression of weeds and, conservation of soil moisture when legume residues are used as mulch (Adetunji, 1997). The ability of legumes to grow and fix N_2 in the field is strongly influenced by the prevailing conditions (Giller, 2001; Niang et al., 2002). With great diversity in tolerance to agro-ecological conditions, the performance of the legume species varied. Results in Chapter 3 indicated that the variability was largely reflected in biomass production, N accumulation as well as tolerance to pests and diseases. In the high and low rainfall zones, higher biomass and N accumulation was consistently found with the non-forage legume *Tephrosia candida* (4.5-5.3 Mg ha^{-1}; 125-143 kg N ha^{-1}), with a dual purpose legume *Mucuna pruriens* (3.7-5.1 Mg ha^{-1}; 78-103 kg N ha^{-1}) and with the fodder legumes *Macrotyloma axillare* (3.3-5.8 Mg ha^{-1}; 92-186) and *Macroptilium atropurpureum* (3.2-5.1 Mg ha^{-1}; 77-163 kg N ha^{-1}). *Desmodium intortum* performed well in the high rainfall zone but poorly in the low rainfall zone. To the contrary, *Crotalatia juncea* performed well in the low rainfall zone but poorly in the high rainfall zone. The rest of the tested species performed poorly in both zones, largely due to susceptibility to pests and diseases. These results emphasize that while screening legume species for biomass and nutrient yields, prevailing climatic conditions during the fallow phase, especially rainfall as well as soil conditions, should be taken into account.

In this study, the biomass and N accumulation by legumes was affected by soil pH and low levels of soil N. For instance, in the high rainfall zone, *T. candida* accumulated less than 2 Mg of biomass ha^{-1} in soils with pH levels below 4.2, but the performance was good in soils with pH above 4.2. Similarly, in the low rainfall zone, *T. candida* accumulated less than 2 Mg of biomass ha^{-1} in soils with available N below 1 g/kg soil. In Bukoba, most of the *kikamba* soils, where legumes are targeted, are acidic and extremely deficient in N (Touber and Kanani, 1994). Such conditions are prevalent in most of the *kikamba* of resource-poor households. Although such hostile conditions can be reduced by application of small doses of farmyard manure (Chapter 5), it is unlikely that poorer farmers will afford to do. Under this condition it might be important to test new species that are adapted to low N and pH. Generally, the biomass and N accumulated by *T. candida*, *M. pruriens*, *C. grahamaiana*, *M. axillare*, *M. atropurpureum* and *D. intortum*, within a period of 5 months can be considered as reasonably high. The levels of N in the tissue of these legumes were in the range reported to most tropical annual herbaceous legume species, being 20-250 kg ha^{-1} (Becker et al., 1995; Giller, 2001). Thus the N in the test legume were as variable as with others (plant growth conditions > higher biomass > higher N). However these legume species derived more than 50% of their N from N_2-fixation (Chapter 3) making them a potential source of N if integrated in low-input agricultural systems with similar conditions as in Bukoba District.

7.4 Legume residue quality

It is widely recognised that the main chemical factors determining the quality of plant materials as green manure, is their rate of decomposition and N release, which are governed by the initial N, lignin and polyphenol contents (Mafongoya et al., 1998). These plant litter quality characteristics play an important role on nutrient supply and soil organic matter formation, as well as determine the pattern of nutrient release (Palm, 1995; McDonagh et al., 1995). In Chapter 4, the most sensitive indicator for N release from biomass of tested legumes was the (polyphenol+ lignin) to N ratio. For the green manure legumes, the (polyphenol + lignin) to N ratios were 9.6, 2.7 and 10.7 for *T. candida*, *C. grahamiana* and *M. pruriens*, respectively. On this basis, *C. grahamiana* would be the most suitable legume species for use in improved fallows. However, *T. candida* and *M. prurience* accumulated more biomass and N compared to *C. grahamiana* and had a greater residual effect on maize (see 7.3). This appears to suggest that some species with different litter quality could be grown together in mixtures to yield a basket of better quality biomass, and hence optimise crop response. This was demonstrated in a fallow study in nearly western Kenya which showed that a mixture of legumes species with different rooting pattern and residue qualities enhanced maize yield more than single legume species (Gathumbi et al., 2002). Using several legumes species in mixture can also provide several benefits (e.g. fodder mulch, soil fertility improvement).

7.5 Maize response to fallow biomass application

The primary objective of improved fallow is to achieve recovery of soil fertility within a short time. This can be reflected by the increased yield of the crop after planted fallow (Hartemink et al., 2000). In our study, two seasons maize yield data demonstrated that it is possible to double or triple maize yield in the short rain season with improved fallows (Chapters 4 and 5). However, there was no clear evidence that the yield increase by application of *T. candida* and *M. pruriens* was related to the amount of residue N applied. This indicates that besides the amount of N, residue quality may determine the net N- release as pointed out by Mafongoya et al. (1998). In this study, application of mineral N at a current recommended rate of 50 kg N ha^{-1} was superior to legume residues. This observation implies that using herbaceous legumes to replace weedy fallows could increase yields of subsequent maize crop and intensify crop production, but further improvement can be reached. To bridge yield gaps between mineral fertilisers and legume residues, small quantities of mineral fertilisers can be applied. It has been revealed from other studies that in situations where farmers want to optimise yields, the legumes should be used to provide a starter, subsequently top-dressed with mineral N fertilisers (Giller, 2002; Vanlauwe et al., 2002). However, it is worth noting that although organic input from planted fallows can add enough N for crop growth to the system, they cannot add sufficient amounts of other nutrients like P, K, Ca and Mg which are also limiting in Bukoba soils. As such, additions of these nutrients in the form of mineral fertilisers may alleviate their limitations and optimise crop yields benefits after the fallows.

7.6 Management of legume residues

Legume residues management means returning residues to the soil either by incorporation or as mulch. The main purpose is to conserve nutrients embodied in the residues. In most environments, apart form the quality aspect discussed above, the effect of applied residues will also depend on the quantity applied. In this study, maize yield increased with increasing application rates of *T. candid*a residues to the optimum of 6 Mg ha^{-1} (Chapter 5). This implies that higher rates of application of legume residues may be not economic, when corresponding yield increase is not substantial. In circumstances where a farmer has portions of infertile land, as is in the majority of poor households, the production of residues can be optimised on fertile soil and excess residues used to improve the poor soil.

Among the benefits associated with use of legumes residues is weed suppression. In most studies, the effect of legume residues on weeds has been assessed during the fallow phase (e.g. Akobundo, 1983, Akanvou, 2001). In the present study, the effect of legume residue management practices on weed incidences was assessed during the subsequent maize growth phase. In both the high and low rainfall zones, the mulched residue treatment gave stronger weed suppression in comparison to residue incorporation (Chapter 5). In addition to weed suppression, residue incorporation and mulching gave similar yields and N uptake in the high rainfall zone. This indicates that under stable soil moisture and temperature conditions, decomposition and nutrient availability from legume residues would be similar whether placed on the surface or incorporated into the soil (Vanlauwe et al., 2001). In the low rainfall zone, where the moisture was limiting at the initial maize growth stage, mulched residues gave higher yields compared to incorporated residues. Overall, residue removal performed equally to the control, indicating that significant effect of below-ground parts of the legumes should not be expected.

7.7 Potentials for utilisation of legumes

Increased adoption of legume technology requires the recognition of farmer socio-economic conditions (Becker et al., 1995; Giller and Cadisch, 1995). Much of the information provided in this thesis was based on the results of experiments conducted with farmer participation. Labour and land availability are recurrently mentioned as key factors limiting the adoption of legume technology in smallholder farming systems (e.g. Raquet, 1990; Roger, 1995). It was indicated in Chapter 5 that the labour problem can be reduced by practicing residue management options that have higher labour productivity, in this case, using legume residues as mulch. Moreover, the explorative study (Chapter 6) indicated that farmer's objectives of increasing maize and manure production can be met if legume residues are used. Whether or not the legumes are utilised will largely depend on farmers perception of balances between the positive and negative aspects. The negative aspects include loss of land for other activities in short fallows. However, participatory development with farmers has guaranteed that the technology fits well within their customs and work calendar and reduces possible other negative aspects of developed technology.

7.8 Conclusions

The major conclusions of the studies described in this thesis can be summarised as follows:

(1) The principal strategy used by farmers to cope with the decreasing size of homegardens (*kikamba*) and their associated poor productivity is to transform part of it into annual cropping field (*kikamba*) and/ or extend the annual cropping into the grassland (*rweya*).

(2) The *kikamba* is increasingly becoming an important land use system for cultivation of food crops and for provision of fodder, hence manure for use in the *kibanja*. Therefore, the future production of *kibanja* and livestock will largely depend on the productivity of the *kikamba*.

(3) Application of residues of herbaceous legumes can double or triple the yield of the subsequent maize crop and have a profound influence upon yield to at least six months later, making them a potential source of N in low-input agriculture but external inputs are necessary to maintain balanced nitrogen, phosphorus, potassium, calcium and magnesium stocks in the *kikamba* soils.

(4) Herbaceous legumes may play a potential role as a source of fodder for livestock. However, for sustainable production, the manure produced should be returned to the field where the fodder was collected, or mineral fertilisers should be applied to maintain N and P balances when manure is applied elsewhere.

(5) Low soil pH and available N in pose are the major environmental stresses that limit the growth and N_2- fixation of herbaceous legumes in Bukoba District.

(6) Application of large quantities of herbaceous legumes with low-quality does not necessarily transform to maize yield of the subsequent maize crop.

(7) Availability of productive land and labour is the major household related limiting factor to utilisation of legumes.

(8) In view of the fact that farming households are diverse in terms of resources and production objectives, blanket recommendations or technology packages are unlikely to provide effective solutions to problems faced by farmers. Farmers' interests will be best served by using a participatory approach to develop technology that addresses the need and specificity of each different household class.

Sustainable production can only be triggered in the region by external inputs. However, the current price of fertilisers and animal feeds are hardly conducive to use of extensive inputs. The Government should therefore deliberately formulate comprehensive policies that will make farming profitable. Such policies should (among other things) focus to improve farmers accessibility to inputs, better access to markets and reduce farming risk through provision of safety nets.

7.9 Way forward

The legume technology described in this thesis is knowledge intensive because of the complex interactions between soil and legume plants, and soil and residue management options. Therefore adoption of this technology will require systematic dissemination of information through discussions and training programs for farmers and extension staff. Such discussions and training could be based on the results of the explorative model described in Chapter 6.

In this study, the impact of legume technology was considered within the limits of a sub-system of the farm (*kikamba*). As the *kikamba* is among the many components of the farm, and from the fact that household decisions take into account all farm activities, the potential impact of legumes can best be revealed if the results are up-scaled to the farm level. Then, the household decision for allocating labour and land to cultivation and use of legumes can be best revealed. Such analysis is embedded in the African-NUANCES project (Nutrient Use Efficiency in Animal and Cropping Systems-Efficiency and Scales) which will operate in the study area in the near future.

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Summary

Indigenous soil fertility management strategies in the banana-based farming systems of northwest Tanzania have largely depended on the mobilisation of nutrients from large areas of grassland *(rweya)* to the home gardens *(kibanja)* where the banana is cultivated. Cattle have acted as the main concentrators and transporters of nutrients from the grassland to the home gardens in the form of manure. The shrinkage of grasslands due to expansion of cultivated lands, the general loss of productivity in the natural ecosystem and the increasing demand of nutrients due to increased number of farming households have resulted in a critical scarcity of traditional sources of nutrients. This instigated the present project in which the potentials and possibilities of introducing N_2-fixing herbaceous legumes were investigated.

Firstly, the objective of the research was to document and understand changes that have occurred in the farming system over the past 50 years. Furthermore, the objective was to determine the potential and options of introducing herbaceous legumes in these farming systems. These legumes could contribute to improved soil fertility and increased production of staple foods through their capacity of biologically fixing N_2.

The project started with assessment of the spatial and temporal changes of land use, cropping patterns and cattle keeping for the period 1961-1999, in order to understand the type and magnitude of changes, the causal factors behind the changes, the impact of changes on soil fertility management practices by farmers and the sustainability of the farming system (Chapter 2).

The results indicated that the area of grassland declined by 40% whereas the area under annual cropping fields *(kikamba)* increased by 225%. The cropping pattern changed from a predominance of banana as a main food crop to include root crops (sweet potato, yams and cassava) and maize. The population of indigenous cattle decreased by 50% but an equal percentage of dairy cattle was introduced. However, cattle-owning households decreased by 85%. Nutrient balances of the home gardens were between -27 and 17, -1 and 7 and -5 and 12 kg ha^{-1} yr^{-1} for N, P and K, with the positive balances achieved by resource-rich households. Nutrient balances of crops in pure stand ranged between -15 and -2 kg ha^{-1} yr^{-1} for N , -2 and -1 kg ha^{-1} yr^{-1} for P and -14 to -1 kg ha^{-1} yr^{-1} for K, with more negative balances observed with maize, implying that soil stocks are decreasing.

Increasing population density, coupled with an unequal distribution of resources among households, land tenure, economic policies and poor markets for inputs and crop produces were identified as major causal factors of the above changes.

To assess productivity, N_2-fixation and adoptability of herbaceous legumes by farmers, field experiments were conducted in two agro-ecological zones (Chapter 3). The legumes studied include the non-fodder species; *Tephrosia candida, Tephrosia vogelii, Crotalaria grahamiana, Crotalaria paulina* and *Crotalaria juncea* and fodder species; *Lablab purpureus, Mucuna pruriens, Macrotyloma axillare, Macroptilium atropurpureum* and *Desmodium intortum*. Estimates of N_2-fixation were done using the ^{15}N natural abundance and N difference methods. A participatory assessment of adoptability of legumes by farmers was done using a gender analysis matrix (GAM) and the matrix ranking method.

Shoot biomass, nitrogen (N) accumulation in this biomass and N_2-fixed varied between legume species and sites. Shoot biomass and N yields (in parentheses) ranged between 0.3 and 5.5 Mg ha^{-1} (8 to 143 kg N ha^{-1}) and 0.8 and 5.6 Mg ha^{-1} (8 and 186 kg N ha^{-1}) for the non-fodder and forage legumes, respectively. The N_2-fixed was in the range of 11 to 106 kg N ha^{-1} for non-fodder legumes and 14 to 109 kg N ha^{-1} for fodder legumes. The N accumulation by legumes was related to the biomass production which in turn was related to soil N and pH. The non-forage and forage legumes species fixed between 15 and 20 kg shoot N for every Mg of shoot biomass. The species *T. vogelii, C. paulina, C. juncea* and *L. purpureus* were susceptible to attack by pests and diseases hence performed poorly. On the other hand *T. candida, C. grahamiana, M. pruriens and M. axillare* showed better performance at most sites and, hence, were selected by farmers.

The results indicate that the cultivation of legumes is a technical option that can lead to extra fodder and green manure. Farmers indicate, however, that adoption in their systems depends on efficiency improvement in use of land, labour and cash.

The impact of herbaceous legumes as green manure is also determined by the decomposition process in the soil. During this process nutrients are released and become available in mineral form (mineralization). The rate of decomposition depends on the quality of the material: lignin, polyphenols and nitrogen contents in the plant material are the quality indicators. The mineralization of leguminous plant material in the subsequent season determines to a large extend the production of the crop.

The nitrogen release patterns from decomposing shoot residues of *T. candida, C. grahamiana*, *M. pruriens, M. axillare, M. atropurpureum* and *D. intortum* were studied in the laboratory for a period of 22 weeks in a sandy clay soil and 10 weeks in a clay soil using a leaching tube technique. In addition, the residual effect of soil incorporated shoot residues of *T. candida*, *T. vogelii, C. grahamiana, M. pruriens* and *C. juncea* on maize yield was evaluated in the high rainfall zone (mean precipitation 2100 mm year^{-1}) and low rainfall zone (mean precipitation 800 mm yr^{-1}). These treatments were compared with the traditional practice: cultivation of maize after weed fallow in the previous season, the control. Currently, the advice to farmers is to add 50 kg N ha^{-1} as inorganic fertiliser. This treatment was included in the experiments as well (Chapter 4).

N mineralised from the legume residues ranged from 24 to 61% of the initial N after 22 weeks in a sandy clay soil and –1 to 34% after 10 weeks in a clay soil. The N mineralization rates of the residues decreased in the order *M. atropurpureum* > *M. axillare* > *C. grahamiana* > *D. intortum* > *T. candida* > *M. pruriens* and were in both soils most strongly related to (polyphenols + lignin)-to-N ratio, lignin-to-N ratio and lignin content of the legume residues. Relative to the control, legume residues resulted in two and three-fold increase in maize grain yield, from 1.1 to 3.2 Mg ha^{-1} and from 1.4 to 3.8 Mg ha^{-1} in the high and low rainfall zone, respectively. However, maize yield response to legume residues was limited in comparison to application of 50 kg N $ha^{-1}$of mineral fertiliser. The % fertiliser equivalency (%FE) of legumes ranged between 25% and 59% with higher values recorded for *C. grahamiana*. At harvest, apparent N recoveries in maize ranged between 23 and 73 % of the N applied in the legume residues. Highest recovery was found from application of *C. grahamiana* and least recovery from *T. candida* residues.

The results indicate that the effect of herbaceous legumes used as green manure on the subsequent maize crop is varying. As fertiliser they work less effective compared to inorganic fertilisers. The quality of the plant material used and the related rate of mineralization explain to a large extend the affectivity of this technology.

Production increase in maize does not only depend on the quality of the green manure but also on its quantity and the way of application. Labour efficiency can be improved considerably if the appropriate quantities can be determined. Land efficiency can be improved if establishment of legumes can be improved on degraded soils. In degraded soils, establishment of soil-improving legumes can be problematic.

Field experiments were conducted to investigate these various aspects of managing herbaceous legumes in farmers' fields in the high and low rainfall zones (Chapter 5). The management includes boosting legume growth (in this case *C. grahamiana*) by use of farmyard manure (FYM), varying application rates of legume residues (2, 4, 6 and 8 Mg ha^{-1}) applied as mulch (in this case *T. candida*), and different ways of application (5 Mg ha^{-1}), i.e. applied as mulch, incorporated in the soil or removed from the fields (in this case *M. pruriens*). These treatments were compared to the current practice, cultivation of maize after a weed fallow in the previous season (control).

The biomass and N accumulation by *C. grahamiana* on degraded soils was 1.1 Mg ha^{-1} and 34 kg N ha^{-1} when established without farmyard manure (FYM) and 3.4 Mg ha^{-1} and 95 kg N ha^{-1} when established with 2 Mg FYM ha^{-1}. Growing *C. grahamiana* with

FYM gave an increment of 700 kg ha^{-1} of grain in the subsequent maize crop. Maize grain yield with *T. candida* residues ranged from 1.4 to 3.3 Mg ha^{-1} and from 2.0 to 2.8 Mg ha^{-1} in the high and low rainfall zone, respectively. Application of 2 Mg ha^{-1} of *T. candida* biomass had no significant effect on maize yield whereas the same material applied at 4, 6 or 8 Mg ha^{-1} gave highest but comparable yields. Apparent N recovery efficiencies at all rates of *T. candida* residues were 28% and 12% for the high and low rainfall zones, respectively. Mulching with *M. pruriens* suppressed weeds in the maize crop with 49% in the high rainfall zone. This effect was higher (67%) in the low rainfall zone. Incorporating residues demanded extra person days (45) compared to removing residues (20) and mulched residues (23). This resulted to lower labour productivity of the latter treatments (20 and 33 kg grain person-day^{-1} in the high and low rainfall zones, respectively) compared to mulched residues (32 and 53 kg grain person-day^{-1} in the high and low rainfall zones, respectively).
It was concluded that also on degraded soil legumes can be grown if farmyard manure is applied to improve establishment. Land use efficiency on the farm is then improved. The quantity of green manure is minimally 2 Mg ha^{-1}; higher quantities do not result to significant higher maize production and is inefficient from that point of view. Although the production of green manure demands labour input, efficiency of labour is improved because more grain per labour unit is produced. The most efficient way of applying green manure is in the form of mulch because labour for weeding in the maize crop is substantially decreased.

The project was completed by an explorative study to identify options to including herbaceous legumes in the *kikamba* which increase maize and manure production for smallholder farms while maintaining positive partial N balances in these annual cropping fields (Chapter 6). A multiple goal linear programming model (MGLP) was developed. Household differences with high-, medium- and poor-resource endowments (labour availability and land size) were taken into account. A large number of existing and alternative rotations are quantified. Alternative rotations contain legumes as a green manure or fodder corp. For the quantification, results of the previous chapters are used completed with data from previous studies in the zone. The model generates optimal solutions selecting rotations and land allocation in dependence of the priorities set on objectives.
In so-called zero-rounds, each objective is optimised without setting limitations to the other objectives. The optimum values then obtained for N balances over the rotation period (2 year and 4 seasons) per *kikamba* are 55, 43 and 30 kg N for the resource-rich (0.51 ha and 3.6 persons), medium-resource (0.42 and 2.8 persons) and resource-poor (0.31 and 2 persons) households, respectively. The optimum values for maize and

manure production were 3430 and 3839, 2674 and 2942, and, 1822 kg and 1942 kg for resource-rich, medium-resource and resource-poor households, respectively. At maximum maize production the model allocated 29%, 38% and 40% of *kikamba* of resource-rich, medium-resource and resource-poor household, respectively, to the green manure legume *T. candida* in rotation with maize. A similar land use allocation was proposed when the N balance was maximised without restrictions on other objective functions. However, the area under *T. candida* was significantly increased. It was further indicated that maximizing manure production without restrictions on other objectives, 81%, 73% and 71% of *kikamba* of the resource-rich, medium-resource and resource-poor households respectively, would be allocated to the production of the fodder legumes *D. intortum*. With farmer wanting to meet all objectives, the rotations with both green manure and fodder legumes were selected with the proportions of fodder legumes increasing with increased manure production. Because the produced legumes are removed from the *kikamba* as fodder to produce manure, the N-balance of the *kikamba* becomes negative. Furthermore, all the land is then cultivated with fodder legumes leaving little land for maize production. Thus, manure production is in conflict with maize production and a positive N balance.

These results gave strengths to the observations made in Chapters 3, 4 and 5; cultivation of herbaceous legumes in the *kikamba* would be an option for farmers to produce manure for the *kibanja*, but this is a trade-off against the maize production and reverse of the present trend of increasingly negative N balances in the *kikamba*.

In Chapter 7, the results presented in previous chapters are placed in a general context and discussed. The focus of this study was to explore opportunities for integrating herbaceous legumes in the deteriorating banana-based farming system in northwest Tanzania to improve and maintain soil fertility, to produce fodder, increase manure and maize production. The current study revealed that farmers have different preferences for legumes, with the reasoning for preferences ranging from weed suppression to improved fodder availability. Therefore, the choice of legumes to be introduced in the farming system should be based on farmer production objectives. The legume technology described in this thesis is knowledge intensive. For it to be adopted, systematic dissemination of information through discussions with farmers, extension staff and researchers is needed. The possible solutions generated by the model could be a guide for discussions with farmers.

It is, however, recommended to upscale the results obtained for the *kikamba* to the farm scale level in order to reveal the potentials of legumes in the farm context.

Samenvatting

Aanpassen aan veranderingen in landbouwbedrijfssystemen in noordwest Tanzania die bananen als een hoofdgewas telen: de mogelijke rol van kruidachtige vlinderbloemigen.

Het beheer van de bodemvruchtbaarheid op landbouwbedrijfssystemen in noordwest Tanzania berust nog steeds op de strategie van transport van nutriënten van de uitgestrekte graslanden *(rweya)* naar de erftuinen *(kibanja)* rondom de boerderij. In deze erftuinen, meestal minder dan een hectare groot, worden bananen als hoofdgewas geteeld. Daarnaast kent het bedrijfssysteem nog akkerbouwland *(kikamba)* waar vooral maïs wordt geteeld. Door begrazing van de graslanden concentreert het vee nutriënten in de vorm van mest en urine, en deponeert deze voor een belangrijk deel in de stallen bij de erftuinen waar het vee gedurende de nacht verblijft. De afname van graslanden tengevolge van de uitbreiding van akkerbouwland, de afnemende productie van de graslanden en de toename in vraag naar nutriënten door een groeiend aantal huishoudens met erftuinen hebben tot een kritieke schaarste in de traditioneel beschikbare nutriënten geleid. Deze problematiek gaf aanleiding tot uitvoering van het voorliggende onderzoek.

Het doel van het onderzoek was veranderingen in het landgebruiksysteem, die over de laatste 50 jaar hebben plaats gevonden, vast te leggen en de aanleiding tot deze veranderingen te begrijpen. Het volgende doel was vast te stellen wat het potentieel en de mogelijkheden van de introductie van vlinderbloemigen in deze bedrijfssystemen zijn. Door hun capaciteit tot biologische binding van N_2 zouden deze een bijdrage kunnen leveren aan een verbeterde bodemvruchtbaarheid en een verhoogde productie van voedselgewassen.

Het onderzoek is begonnen met het vaststellen van de ruimtelijke en temporele veranderingen in landgebruik, veranderingen in bouwplan van gewassen en de wijze van houden van het vee, die over de periode van 1966 tot 1999 hebben plaatsgevonden. Dit om te kunnen vaststellen wat de mate en richting van veranderingen zijn, welke causale factoren achter deze veranderingen zitten, welke uitwerking deze veranderingen op het door boeren gevoerde beheer van bodemvruchtbaarheid hebben en om de mate van duurzaamheid van het bedrijfssysteem te kunnen bepalen (Hoofdstuk 2).

Uit de resultaten blijkt dat het areaal aan graslanden flink is afgenomen (45%), terwijl het akkerbouwareaal, dat met éénjarige gewassen wordt verbouwd, zeer sterk is toegenomen (225%). Het bouwplan veranderde van één gedomineerd door bananen, het belangrijkste voedselgewas, naar één waarbij ook knol- en wortelgewassen (zoete aardappel, yam en cassave) en maïs worden geteeld. De populatie van inheems vee is afgenomen (50%), maar een gelijk aantal stuks melkvee van externe herkomst heeft die plaats weer ingenomen. Echter, het aantal huishoudens dat vee bezit is sterk afgenomen (85%). Berekende nutriëntenbalansen voor erftuinen variëren sterk (tussen -27 en 17 kg N ha^{-1}, -1 en 7 kg P ha^{-1} en, -5 en 12 kg K ha^{-1}), waarbij erftuinen van de rijkere huishoudens een meer positieve balans hebben. Op plaatsen waar alleen éénjarige gewassen worden verbouwd, variëren de nutriënten balansen afhankelijk van het gewas (tussen -15 en -2 kg N ha^{-1}, -2 en -1 kg P ha^{-1} en -14 en -1 kg K ha^{-1}). Maïsteelt resulteert in een meer negatieve balans dan de teelt van andere éénjarige gewassen.

In alle gevallen impliceert een negatieve balans dat de bodemvoorraden aan nutriënten worden uitgeput. De toenemende bevolkingsdruk, gekoppeld aan een onevenredige verdeling van middelen over huishoudens, rechten op land, de gevoerde economische politiek en slecht functionerende markten voor productiemiddelen en producten zijn de belangrijkste factoren die aanleiding hebben gegeven tot bovenstaande veranderingen.

Ten einde de productiviteit en de mate van biologische N_2 vastlegging van kruidachtige vlinderbloemigen vast te stellen en de adoptiemogelijkheden door boeren van de teelt van deze vlinderbloemigen te verkennen, zijn in twee agro-ecologische zones veldproeven uitgevoerd (Hoofdstuk 3). De vlinderbloemige soorten die bestudeerd zijn, zijn de groenbemesters *Tephrosia candida*, *Tephrosia vogelii*, *Crotalaria grahamiana*, *Crotalaria paulina* en *Crotalaria juncea* en de voedergewassen *Lablab purpureus*, *Mucuna pruriens*, *Macrotyloma axillare*, *Macroptilium atropurpureum* en *Desmodium intortum*. Biologische N_2 vastlegging is geschat door gebruik te maken van (1) een methode die de dichtheid van de van nature voorkomende ^{15}N meet in planten en het verschil daarvan berekent tussen planten die wel en geen N_2 vastleggen, en (2) een methode die het verschil in totale N meet tussen planten die wel en geen N_2 vastleggen. De adoptiemogelijkheden van de teelt van vlinderbloemigen zijn op een participatieve wijze met boeren vastgesteld gebruikmakend van een volgens geslacht ingedeelde matrix analyse (Gender Analysis Matrix: GAM) en een op volgorde van belang geplaatste matrix methode.

Het bovengrondse geproduceerde plantmateriaal, de stikstof (N) accumulatie hierin en de mate van biologische N_2-vastlegging varieerden tussen vlinderbloemige soorten en locaties. Het geproduceerde bovengrondse plantmateriaal en de N opbrengst (de getallen tussen haakjes) varieerden tussen 0.3 en 5.5 Mg ha^{-1} (8 tot 143 kg N ha^{-1}) bij groenbemesters en tussen 0.8 en 5.6 Mg ha^{-1} (8 en 186 kg N ha^{-1}) bij voedergewassen. De biologisch vastgelegde hoeveelheid stikstof varieerde tussen 11 en 106 kg ha^{-1} bij groenbemesters en tussen 14 en 109 kg ha^{-1} bij voedergewassen. De accumulatie van N door vlinderbloemigen was afhankelijk van de hoeveelheid bovengronds materiaal die op zijn beurt weer afhankelijk was van de N in de bodem en de pH van de bodem. Beide type vlinderbloemigen, groenbemesters en voedergewassen, legden tussen de 15 en 20 kg stikstof per Mg bovengronds plantmateriaal vast. De soorten *T. vogelii, C. paulina, C. juncea* en *L. purpureus* waren gevoelig voor aantasting door ziekten en plagen en presteerden daardoor slecht. Maar, *T. candida, C. grahamiana, M. pruriens* en *M. axillare* presteerden beter op de meeste locaties en werden daarom door de boeren gekozen. De boeren gaven aan dat de beschikbaarheid aan land, arbeid en geld de belangrijkste sociaal-economische factoren zijn die bepalen of zij vlinderbloemigen zullen adopteren.

Uit de resultaten blijkt dat het telen van vlinderbloemigen in technische zin een optie is die leidt tot extra voer en (groen) bemesting. Boeren geven echter aan dat de werkelijke introductie van vlinderbloemigen in hun bedrijfsvoering afhangt van efficiëntie verbetering bij inzet van arbeid, land en geld.

Het effect van vlinderbloemigen als groenbemester wordt mede bepaald door het afbraakproces in de bodem waarbij de nutriënten in minerale vorm beschikbaar komen voor het volggewas (mineralisatie). De afbraaksnelheid is afhankelijk van de kwaliteit van het plantenmateriaal: lignine, polifenolen en stikstof in het materiaal spelen daarbij een rol. De mineralisatie in het volgende seizoen stuurt in belangrijke mate de productie van het volggewas.

Mineralisatiepatronen van de stikstof in het bovengrondse plantenmateriaal van *T. candida, C. grahamiana, M. pruriens, M. axillare, M. atropurpureum* en *D. intortum* zijn in laboratoriumproeven over een periode van 22 weken in een zandgrond en 10 weken in een kleigrond gevolgd. Daarbij is gebruik gemaakt van uitspoelingkolommen. In de hoge regenvalzone (gemiddelde neerslag van 2100 mm per jaar) en de lage regenvalzone (gemiddelde regenval van 800 mm per jaar) van noordwest Tanzania, is het residuen effect van het inbrengen van bovengronds plantenmateriaal van *T. candida, T. vogelii, C. grahamiana, M. pruriens* en *C. juncea* op de opbrengst van het vervolggewas, maïs, bepaald. Deze behandelingen zijn vergeleken met de opbrengst van het maïsgewas, dat volgt op een seizoen traditionele braaklegging. In dat geval groeit er in het voorgaande seizoen een natuurlijke onkruidvegetatie in plaats van vlinderbloemigen (de controle). Het huidige advies aan boeren is het maïsgewas met 50 kg N in de vorm van kunstmest te bemesten. Deze teeltwijze is als laatste behandeling toegevoegd (Hoofdstuk 4).

De gemineraliseerde N van het plantenmateriaal van vlinderbloemigen bedroeg na 22 weken in een zandgrond tussen de 24 en 61% van de initieel beschikbare stikstof. Deze waarden lagen tussen de -1 en 34% na 10 weken in een kleigrond. De snelheid van mineralisatie van dit plantenmateriaal nam af in de volgorde *M. atropurpureum* > *M. axillare* > *C. grahamiana* > *D. intortum* > *T. candida* > *M. pruriens*. In beide bodemsoorten was de snelheid van mineralisatie sterk gerelateerd aan de verhoudingen tussen (polifenolen + lignine) en N, tussen lignine en N, en aan de absolute hoeveelheid lignine in het plantenmateriaal van de vlinderbloemigen. Gebruik van plantenmateriaal van vlinderbloemigen leidde, in verhouding tot de controle plots, tot een twee tot drievoudige verhoging van de maïsopbrengst. De opbrengst nam in de hoge regenval zone toe van 1.1 tot 3.2 Mg ha^{-1} graan. In de lage regenval zone nam de opbrengst toe van 1.4 tot 3.8 Mg ha^{-1}. Maar, in vergelijking tot bemesting met 50 kg N ha^{-1} in de vorm van kunstmest is de opbrengstverhoging van maïs door groenbemesters duidelijk minder. De efficiëntie van groenbemesters is minder dan kunstmest: de opbrengstverhoging in maïs als gevolg van toediening van N via vlinderbloemigen was tussen 25% en 59% lager dan wanneer dezelfde hoeveelheid N via kunstmest zou zijn gegeven. *C. grahamiana* bereikte de hoogste waarde en was nog het meest vergelijkbaar met kunstmest. Het percentage van de stikstof, gegeven via vlinderbloemigen, dat is opgenomen door de maïs op het oogsttijdstip varieerde tussen de 23% en 73%. De hoogste fractie werd gevonden bij toediening van plantenmateriaal van *C. grahamiana* en de laagste bij *T. candida*.

De resultaten geven aan dat het effect van vlinderbloemigen, gebruikt als groenbemester op het volggewas (maïs) wisselend is. Als meststof werken vlinderbloemigen minder effectief dan kunstmest. Kwaliteit van het plantenmateriaal en daarmee samenhangende mineralisatie verklaart in belangrijke mate de mate van effectiviteit.

De opbrengstverhoging van maïs hangt niet alleen af van de kwaliteit van de groenbemester maar ook van de hoeveelheid die wordt toegediend en de wijze waarop deze wordt toegediend. Het vinden van de juiste hoeveelheden kan de efficiëntie van arbeid sterk verbeteren. Deze efficiëntie kan ook worden verbeterd als op gedegradeerde bodems de vestiging van vlinderbloemigen, die soms zeer moeizaam is, kan worden verbeterd. Om deze verschillende aspecten van het gebruik van vlinderbloemigen in de praktijk te onderzoeken, zijn veldproeven uitgezet op boerenbedrijven in zowel de hoge als de lage regenvalzone (Hoofdstuk 5).

Het toedienen van dierlijke mest (2 Mg ha^{-1}) geproduceerd op het bedrijf ten einde de vestiging en groei van vlinderbloemigen (in dit geval *C. grahamiana*) op gedegradeerde bodems te stimuleren werd onderzocht. Verder werd het effect van verschillende hoeveelheden plantenmateriaal (2, 4, 6 en 8 Mg ha^{-1}) van vlinderbloemigen (in dit geval *T. candida*), toegediend als strooisel, op de graanoogst van het volggewas, maïs, onderzocht om de optimale hoeveelheid te bepalen. Ook werd het effect onderzocht wanneer het plantenmateriaal (nu van *M. pruriens*; 5 Mg ha^{-1}) als strooisel op de bodem werd gelegd, werd ingewerkt in de bodem of wanneer het plantenmateriaal werd verwijderd. Deze behandelingen werden vergeleken met de op dit moment voorkomende teelt: maïs op grond die in het voorgaande seizoen braak heeft gelegen en waarop een onkruidvegetatie was ontwikkeld (de controle).

De geproduceerde *C. grahamiana* biomassa en de daarin geaccumuleerde N was 1.1 Mg ha^{-1} en 34 kg N ha^{-1} wanneer geen organische mest werd gebruikt en 3.4 Mg ha^{-1} en 95 kg N ha^{-1} wanneer wel organische mest werd gebruikt. Het gebruik van *C. grahamiana* als groenbemester, leverde een toename van 700 kg graan per hectare op in het volggewas, maïs. Toediening van *T. candida* plantenmateriaal als strooisel resulteerde in een opbrengst van graan in het volggewas (maïs) variërend van 1.4 tot 3.3 Mg ha^{-1} in de hoge regenvalzone en van 2.0 tot 2.8 Mg ha^{-1} in de lage regenvalzone. De mate van opbrengstverhoging is afhankelijk van de hoeveelheid toegediend materiaal. Bij toediening van 2 Mg ha^{-1} was er geen significant effect op de maïsopbrengst. Toediening van 4, 6 of 8 Mg ha^{-1} gaf wel een opbrengstverhoging maar deze verschillende hoeveelheden leidden niet tot significante verschillen in maïs opbrengst. De fractie van de toegediende stikstof in *T. candida* groenbemester, die is opgenomen door de maïs, was bij alle toegediende hoeveelheden in de hoge regenvalzone hoger (28%) dan in de lage regenvalzone (12%). In de hoge regenvalzone, onderdrukte het gebruik van *M. pruriens* strooisel de onkruiden in het volggewas minder sterk (49%) dan in de lage regenvalzone (67%). Bij inwerking van het strooisel was de onkruidonderdrukking lager (20%). De onkruiddruk in het maïsgewas was het hoogst in de controle plots. Wanneer het plantenmateriaal als strooisel wordt toegediend, werd, in vergelijking tot de controle velden, de maïs opbrengst in de hoge regenvalzone met 64% verhoogd en met 100% in de lage regenvalzone. In vergelijking tot de controle plots, vroeg het gebruik van vlinderbloemigen als groenbemester extra arbeid. In het voorgaande seizoen, wanneer in de controle plots de velden braak lagen, moeten in de overige behandelingen de vlinderbloemigen worden geteeld en daarna als groenbemester volgens verschillende methoden worden toegediend. In de hoge regenvalzone, kostte het telen en verwijderen van de plantenresten van vlinderbloemigen 21 mensdagen per hectare extra, het telen en vervolgens inwerken van de groenbemester in de grond kostte 47 mensdagen extra en het telen en opbrengen van het materiaal als strooisel kostte 20 mensdagen extra. In de lage regenvalzone waren deze getallen achtereenvolgens 23, 43 en 23 mensdagen.

De conclusie was dat ook op gedegradeerde gronden groenbemester kan worden geproduceerd waarbij de efficiëntie van landgebruik binnen het bedrijf kan worden verhoogd. De hoeveelheid groenbemester die moet worden toegediend is minimaal 2 Mg ha^{-1}; meer groenbemester geeft geen significante verhoging van graanopbrengst tot gevolg en is vanuit dat oogpunt niet efficiënt. Hoewel de productie van groenbemester arbeid kost, wordt de efficiëntie van gebruik van arbeid beter doordat meer graan per eenheid arbeid wordt geproduceerd. De meest efficiënte toedieningsmethode van de groenbemester is in de vorm van strooisel, vooral omdat de arbeid voor wieden in het vervolggewas afneemt.

In het laatste deel van het onderzoek is op bedrijfsniveau een verkennende studie uitgevoerd om na te gaan of de teelt van vlinderbloemigen in de velden waar éénjarige gewassen worden geteeld (*kikamba*) kan leiden tot een verhoogde maïs- en mestproductie terwijl de N balansen op peil gehouden kunnen worden (Hoofdstuk 6).

Er is een lineair programmeringmodel met meervoudige doelen (MGLP) ontwikkeld. Daarbij is rekening gehouden met de middelen (land- en arbeidsbeschikbaarheid) die voor huishoudens verschillen. Huishoudens met veel, gemiddeld en weinig beschikbare middelen zijn onderscheiden. Een groot aantal van bestaande en nieuwe rotaties is gekwantificeerd waarbij in de nieuwe rotaties een stikstofbindend gewas voorkomt als groenbemester of voedergewas. Hiervoor zijn getallen uit voorgaande hoofdstukken gebruikt, aangevuld uit andere studies die eerder in dit gebied zijn uitgevoerd. Het model genereert optimale oplossingen waarbij het rotaties en bijbehorende areaal selecteert afhankelijk van de prioriteiten die aan de verschillende doelen worden gesteld.

In de zogenaamde nulronden wordt een doelstelling geoptimaliseerd zonder beperkingen op de overige doelstellingen te leggen. De beste waarden voor de N balans, gerekend over een complete rotatie (2 jaar met 4 regen seizoenen) en voor het gehele areaal van de *kikamba*, waren 55, 43 en 30 kg voor huishoudens, die veel (0.51 ha en 3.6 personen), gemiddeld (0.42 ha en 2.8 personen) of weinig (0.31 ha en 2 personen) middelen beschikbaar hebben. De maximale productie aan maïs en mest waren 3430 en 3839 kg voor een huishouden dat veel middelen beschikbaar heeft. Deze waarden waren voor een huishouden met een gemiddelde beschikbaarheid aan middelen 2674 en 2942 kg en voor een huishouden met weinig middelen 1822 en 1942 kg. Bij een maximale maïsproductie wees het model aan dat een huishouden met veel middelen 29% van het *kikamba* areaal onder de rotatie groenbemester (*T. candida*) gevolgd door maïs zou moeten zetten. Voor huishoudens met gemiddelde beschikbaarheid aan middelen was het 38% en voor huishoudens met weinig middelen 40%. Wanneer een positieve N balans werd nagestreefd, dan wees het model het gebruik van dezelfde rotaties aan. Echter, in dit geval was het areaal onder de rotatie van *T. candida* met maïs significant groter. Dit gaf aan dat er een beperkte competitie was tussen de doelstellingen maximale N balans en maximale maïsproductie. Dit beeld veranderde wanneer de mestproductie werd gemaximaliseerd. Dan wees het model aan dat op 91% van het areaal van de *kikamba* van bemiddelde huishoudens met voedergewassen (*D. intortum*) zou moeten worden verbouwd. Dit percentage was 87% bij huishoudens met een gemiddelde beschikbaarheid aan middelen en 86% bij huishoudens met beperkte middelen. Omdat voor mestproductie de geproduceerde voeders worden afgevoerd ontstond een negatieve N balans. En, omdat vrijwel het gehele areaal gebruikt wordt voor voederproductie is er geen ruimte meer voor maïsproductie. Er bestond dus een duidelijk conflict tussen enerzijds de doelstelling om mest te produceren en anderzijds om maïs te produceren met een positieve N balans. In de analyse van de mogelijke uitruil tussen doelstellingen bleek, dat wanneer aan alle doelstellingen in enige mate moet worden tegemoet gekomen, het model koos voor een combinatie van een groenbemester en een voedergewas in de rotaties, waarbij het areaal met het voedergewas toenam bij oplopende mestproductie ten koste van de maïsproductie en de N balans.

De resultaten van deze verkennende studie bevestigden de waarnemingen zoals weergegeven in de Hoofdstukken 3, 4 en 5: verbouw van kruidachtige vlinderbloemigen kunnen een optie zijn voor boeren om de mestproductie voor de *kibanja* (bananen productie) te verhogen waarbij er wel op moeten worden gelet dat dit niet ten koste gaat van de maïsproductie en de N balans in de *kikamba*.

In hoofdstuk 7, worden de verschillende deelonderzoeken in een algemeen kader geplaatst en besproken. De kern van de studie was het verkennen van mogelijkheden om kruidachtige vlinderbloemigen te integreren in de boerenbedrijfssystemen van noordwest Tanzania, zodanig dat de bodemvruchtbaarheid kan worden verbeterd en onderhouden en leidend tot een verhoogde productie van mest en voedselgewassen.

De huidige studie gaf aan dat boeren verschillende voorkeuren hebben wanneer het gaat om de redenen waarom zij vlinderbloemigen zouden willen gebruiken. Deze redenen varieerden van betere onkruidonderdrukking in het volggewas en hogere productie van voedselgewassen tot verbeterde voerbeschikbaarheid voor het vee. Daarom moet de keuze van de vlinderbloemige en de wijze waarop deze in het systeem kan worden ingezet, worden gebaseerd op de doelstellingen die boeren hebben.

De beschreven technologieën die gebruik maken van vlinderbloemigen zijn zeer kennis intensief. Om de kans op adoptie door boeren te vergroten dient de informatie systematisch door middel van discussies met boeren, voorlichtingsstaf en onderzoekers te worden verspreid. Daarbij kunnen modelresultaten als een leidraad dienen.

Het is aan te bevelen dat de resultaten die op akkerniveau (*kikamba*) worden verkregen verder worden bekeken op het niveau van een geheel bedrijf.

Curriculum vitae

Frederick Baijukya was born on 8th June, 1965 in Bukoba Tanzania. He studied at Mzumbe High School in Morogoro, Tanzania, where he obtained his advanced secondary diploma in physics, chemistry, biology and applied mathematics in 1987. Between 1987 and 1988 he followed the National Service Course (JKT) at Mlale in Ruvuma region and at Mlalakuwa in Dar es Salaam. He studied at the Sokoine University of Agriculture (Tanzania) from 1989 to 1991 where he graduated with a BSc. degree in agriculture. From December 1991 to August 1992 he worked as agricultural research officer in the Department of Research and Training of the Ministry of Agriculture. In September 1992 he continued his studies at the Sokoine University of Agriculture where he obtained his MSc. degree in soil science and land management in 1994. After his graduation, he worked as soil scientist at Ilonga Agricultural Research Institute in Morogoro, Tanzania before he was transferred to the Lake Zone Agricultural Research and Development Institute- Maruku, in July 1996. At Maruku, he continued his research in soil fertility and land use, coordinated research at the institute and the applied soil fertility research programme funded by the Dutch Government through the Rural Development Programme. In March 2001, he started a 'sandwich' PhD programme with the Plant Production System Group of Wageningen University. Currently, he is working for the Lake Zone Agricultural Research and Development Institute-Maruku as a soil scientist and continues to do research in collaboration with the Plant Production Systems Group within the framework of the Africa-NUANCES programme. Frederick is married to Pudensiana Rwezaula and has three children, Marygoreth, Prudence and Franklin.

PE&RC PhD Education Statement

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature

- Nitrogen contribution by short fallow legumes to the banana-based agro-ecosystems of Northwest Tanzania (2000-2001)

Post-Graduate Courses

- Agro-forestry for sustainable land use (2001)
- Modelling techniques and systems engineering (2002)
- How to manage diversity in living systems? (2002)
- Scientific presentation skills (2004)

Deficiency, Refresh, Brush-up and General courses

- Nutrient management for sustainable soil fertility (2002)
- Quantitative evaluation of soil fertility management and response to fertilisers (2002)

PhD discussion groups

- Sustainable land use and resource management with focus on the tropics (2002 -2004)
- Plant soil relations (2002-2004)

PE&RC annual meetings, seminars and Introduction days

- Public sector research on rice must continue (2004)
- Fertility management of tropical soils (2004)

International symposia, workshops and conferences

- Integration of soil research activities in East and Southern Africa (Tanzania, 2001)
- The role of soil science for development of sustainable agriculture in East Africa (Tanzania, 2001)
- Development strategies for less favoured area (the Netherlands, 2002)
- Improvement of common bean (*Phaseolus vulgaris*. L.) in low fertile soils (Ethiopia, 2003)
- Improving human welfare and environmental conservation by empowering farmer to combat soil fertility degradation (Cameroon, 2004)

Laboratory training and working visits

- Evaluation of agroforestry tree species (ICRAF/KEFRI Maseno, Kenya, 2002)
- Application of GIS in land evaluation (Soil & Land Use Institute of Tanzania, 2003)

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