Farm management in mixed crop-livestock systems in the Northern Highlands of Ethiopia

Assefa Abegaz

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Assefa Abegaz

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To
My mother, Menen Amede
and
to the memory of my father, Abegaz Yimer and godfather, Mekonnen Seyoum

Abstract

In the Northern Highlands of Ethiopia, one of the least-favored areas in East Africa, farming systems are characterized by the integrated management of crop and livestock components, in which resources, such as nutrients and energy are cycled within the system. The overall objective of this study was to increase insight in the functioning of these farming systems, with special attention for the heterogeneity among farm households and farm fields, and the influence of farm management regimes on soil nutrient dynamics and livestock production, as a basis for formulation of recommendations for technological innovation leading to increased farm productivity, conservation of the natural resources and improved livelihoods for the farming population.

Crop production is limited by indigenous soil nutrient supply and water availability, as concluded from the results of an on-farm field study on barley on three soils classified as Cambisol, Luvisol-1 and Luvisol-2. Results of this study were also used to calibrate the QUEFTS model that can serve as a tool to quantify indigenous soil nutrient supply as a basis for determination of the best fertilizer combinations for targeted (barley) yields in the Northern Highlands of Ethiopia.

To quantify the possibilities for animal production, knowledge of on-farm available feed resources and their quality is fundamental. Our results show that crop residues comprise the major source of animal feed, in addition to roughage from natural pastures. Availability and quality of forage and hence live weight dynamics of the animals show a distinct seasonal pattern. In the late wet season, September to November, cattle graze natural pasture, and the high availability and quality of this feed resource is reflected in high rates of live weight increase. Starting December, cattle graze aftermath in crop fields, and the lower feed availability (in both quantity and quality), results in lower live weight gains. From April onwards, animals loose live weight, with the maximum loss observed in August.

Observed live weight gains (LWG) were close to the potential for well-endowed farm households, implying favorable nutritional conditions, whereas for medium and poor farm households they were significantly lower, associated with low quality feed.

The relationships between feed availability (quantity and quality) and feed intake on the one hand and animal performance, in terms of live weight and milk production, manure production and draught power, on the other, indicate that currently manure and draught power are the major production targets, attained by maximizing herd size (HS). Our results suggest that maximum live weight production and milk production would be associated with selective use of the better feeds at strongly reduced HS.

Partial balances of the macronutrients, nitrogen (N), phosphorus (P) and potassium (K) were studied at farm level, and the results indicate that soil nutrient depletion proceeds at an alarming rate at both ‘farm field’ and plot scales. Nutrient depletion rates differ significantly among farmer wealth groups, with the highest rates recorded for the rich farm group, followed by the medium and poor farm groups.

Current levels of organic fertilizer input are much lower than required to maintain a dynamic equilibrium in soil organic matter content. Thus, availability of organic inputs is a crucial constraint for attaining sustainability in terms of nutrient elements.

Results of a simulation study on long-term dynamics of soil C, N and P and the consequences of alternative farm management practices for crop-available N and P indicate that to maintain current levels of soil N, organic carbon and P, external inputs in the form of inorganic fertilizers and/or animal feed (concentrates) are indispensable.

In this study, attention focuses on the bio-physical aspects of sustainability in terms of soil qualities, with special attention for nutrient elements. Adoption of more sustainable farm management practices however, is constrained by the (socio-) economic environment.

Key Words: *nutrient dynamics, fertility management, feed availability and quality and livestock production, Northern Highlands of Ethiopia*

Contents page

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Chapter 1

General introduction

General introduction

1 Introduction

All around the globe, the agricultural systems in use by farmers today are different from those used some time ago (Herdt and Steiner, 1995). In this process of transition, in the Sub-Saharan African (SSA) countries, agricultural systems are showing disequilibrium dynamics; outflows particularly of nutrients, from the system exceeding inflows into the system. Consequently, cereal yields in this region have been growing slowly or in some cases declining over the past decades and are well below the levels attained in other parts of the world (Pender et al., 1999; Ramisch, 1999). On the other hand, population continues to grow fast and to meet the demands of the growing population, households are forced to expand cultivation to marginal lands, rangelands and forest areas, resulting in ecological degradation. Stagnating or declining food crop and livestock production, natural resources degradation and poverty are interrelated problems in less favored areas, such as the Northern Highlands of Ethiopia where this study was carried on.

Sustainability of agriculture has become a major concern in the contemporary research and development agenda and scientists and other stakeholders in the rural development arena have voiced concern about the management of continuously changing agricultural systems (Brady, 1990). Although sustainability has many dimensions that remain subject of debate in the development scene, it has been widely accepted that the dynamics of the major nutrients in the soil, nitrogen (N), phosphorus (P) and organic matter/carbon (OC) represent major soil quality indicators. That aspect of sustainability of agriculture systems can be assessed by examining the consequences of current management regimes and exploring options for alternative management regimes on soil nutrient dynamics.

Sustainability of farm management systems can be evaluated at different spatial scales (Lopéz-Ridaura et al., 2005a), varying from the agricultural plot (field), via farm (household), village, region and national to supranational scale. Selection of one or a combination of two or more spatial scales depends on the objectives of the study. Some variables and processes may be important at one spatial level, but not at others (Lopéz-Ridaura et al., 2005b; Schipper et al., 2000; Kruseman, 2000). For instance, at field and farm scales the relations between soils and crops, plant and animal growth, and nutrient balances are relevant characteristics. The farm/household scale is the focal point where biophysical and economic variables and their interactions can be clearly treated (Kruseman, 2000) and where the ultimate decisions on land use are being made. The spatial scales selected in this study include the plot, farm and village, selection being governed by the specific objectives of the study, and taking into account the interactions among soil, crop and livestock subsystems.

The temporal dimension in the assessment and exploration of farm management regimes is another important issue. In descriptive studies, the current status of the system is the starting point (Kruseman, 2000) and the time horizon is relatively short, i.e. from 2-5 years, whereas that of explorative studies is usually over 10 years (van Ittersum et al., 2004). The time scale selected and hence the type of model used are again dictated by the objectives of the study. Some models are static, some are comparatively dynamic and some others are more dynamic, depending on the degree to which changes over time are tracked in the analysis (Kruseman, 2000). In this study the current farm management system has been evaluated applying static models, as a basis for exploration, using dynamic simulation, of long-term effects of alternative management regimes on agricultural resource quality, focusing on N, P and OC dynamics and the consequence for crop-available N and P.

The selection of focus in modelling of agricultural development processes is subject of ongoing debate, because of the strong inter-relations between the agro-ecological and socio-economic environment in which agricultural systems operate. In the past decades, bio-economic modelling has been developed as a tool to include both biophysical and socioeconomic characteristics of the farming environment (Kruseman, 2000; van Keulen et al., 1998; Hengsdijk and Kruseman, 1993). Such an approach allows integration of various processes operating within and upon the system; however, it is almost inevitable that in particular studies either the biophysical or the socioeconomic environment is emphasized.

Therefore, this study focused on the biophysical environment of the region and its role in the development possibilities of the region, while, the socio-economic environment of the study area is subject of a companion PhD-study in the RESPONSE[1] program.

2 Tigray: Physical environment and resource potential

Location

Tigray is situated in the Northern Highlands of Ethiopia, stretching from 12^{0} 15’ to 14^{0} 57’N and 36^{0} 27’ to 39^{0} 59’E. The region is bordered in the north by Eritrea, in the west by the Sudan, in the south by Amhara region, and in the east by Afar region (Figure 1A).

Teghane is located in the eastern administrative zone of Tigray in the district “Atsbi-Wonberta” (Figure 1B (BFEDTR, 2003)). The main district town is Atsbi, about 70 km north of the capital of Tigray, Mekelle. Teghane micro-catchment is located 2 km north of Atsbi town. The catchment of Teghane is situated between 13^{0} 52' 53" and 13^{0} 53' 37" N and between 39^{0} 42' 05" and 39^{0} 43' 57" E, covering an area of 13.56 km^2. Its altitude ranges from 2710 to 2899 m above mean sea level.

Relief

The relief of Tigray is rugged, with altitudes that range from < 500 m above sea level (asl) in the eastern lowlands, to 4000 m in the southern part (Figure 2). This marked variation in altitude results in a distinct spatial distribution of temperature and rainfall.

[1]A collaborative research program on *Regional Food Security Policies for Natural Resource Management and Sustainable Economies* (RESPONSE). This program is jointly managed by the Graduate Schools for Social Sciences (Mansholt Institute) and Production Ecology and Resource Conservation (C.T. de Wit Institute) of Wageningen University (The Netherlands) in cooperation with the International Food Policy Research Institute (IFPRI) at Washington D.C.. The program aims to identify feasible options for agricultural and rural development in less-favoured areas and critical incentives for enabling rural household to invest in efficient and sustainable natural resource management.

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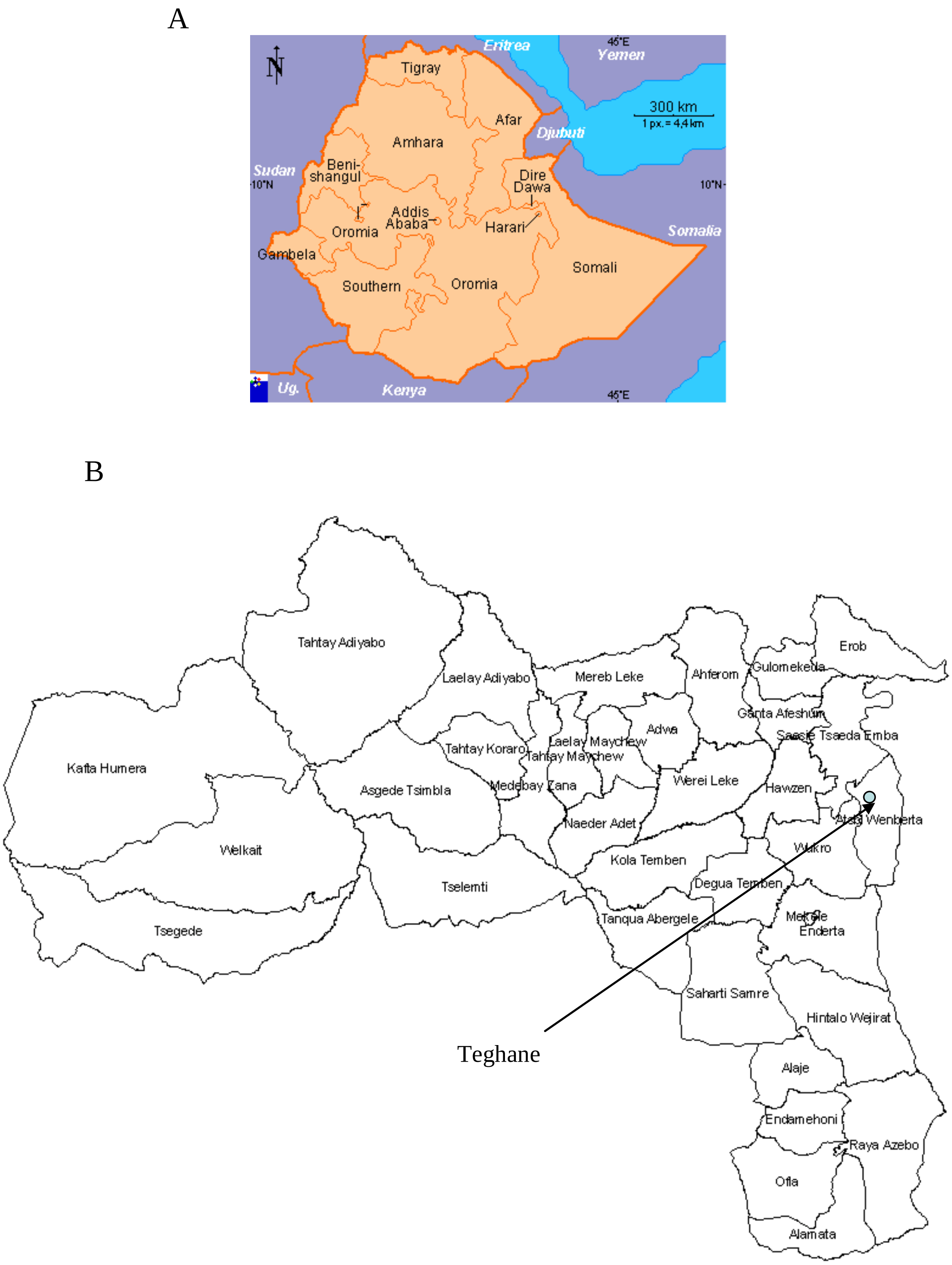


Figure 1. Geographical map of Ethiopia (A) and Tigray and Teghane (B)

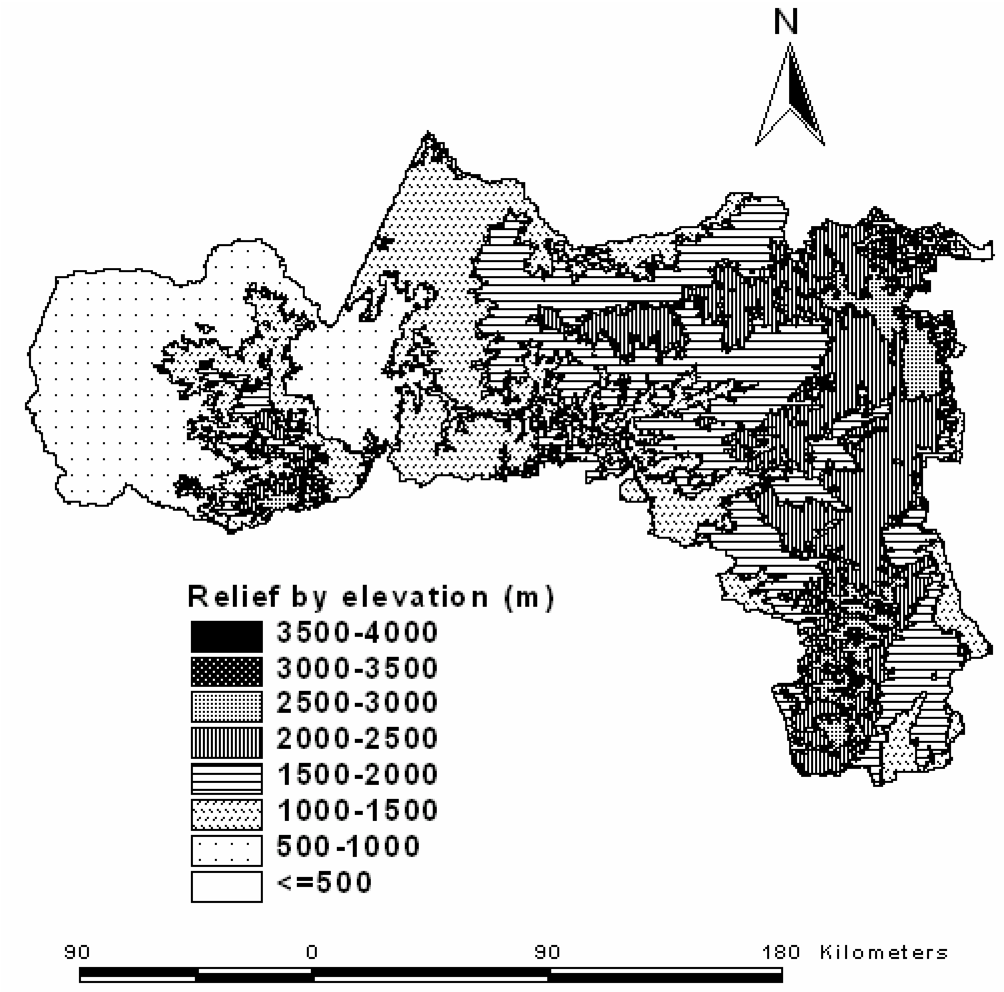


Figure 2. Relief of Tigray by elevation (m above sea level) (WBISPPO, 2002)

Rainfall

Average annual rainfall varies from 200 mm in the eastern lowlands to over 1800 mm in the western highlands (Figure 3). Rainfall is erratic and variable, which results in strong variation in yields of crops and livestock. For example, in Teghane, annual rainfall varied between 204 mm in 1902 and 1675 mm in 1954 (Figure 4A). Most of the rain is concentrated in summer (July to September). For example, the annual rainfall pattern in Teghane (Figure 4B) is monomodal, from July to September of 541 mm yr^{-1} (for the period 1901-2002, coefficient of variation 53%, at a location near Teghane at 14^0 N and 40^0 E (Viner, 2003)). For the period 2000-2004, average rainfall was 532 mm (Atsbi World Vision, 2004), comparable to the long-term average.

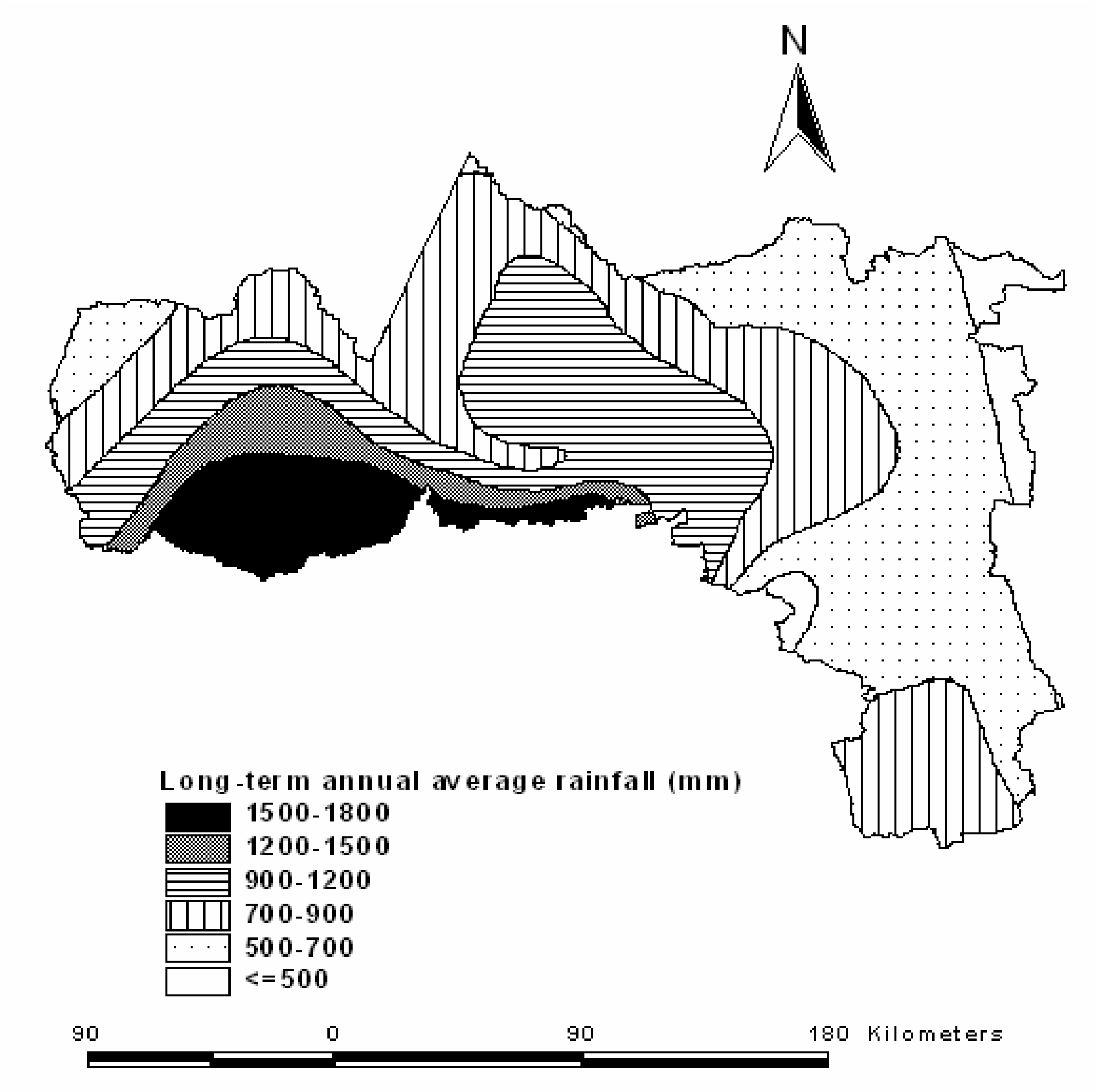


Figure 3. Spatial distribution of average annual rainfall in Tigray (WBISPPO, 2002)

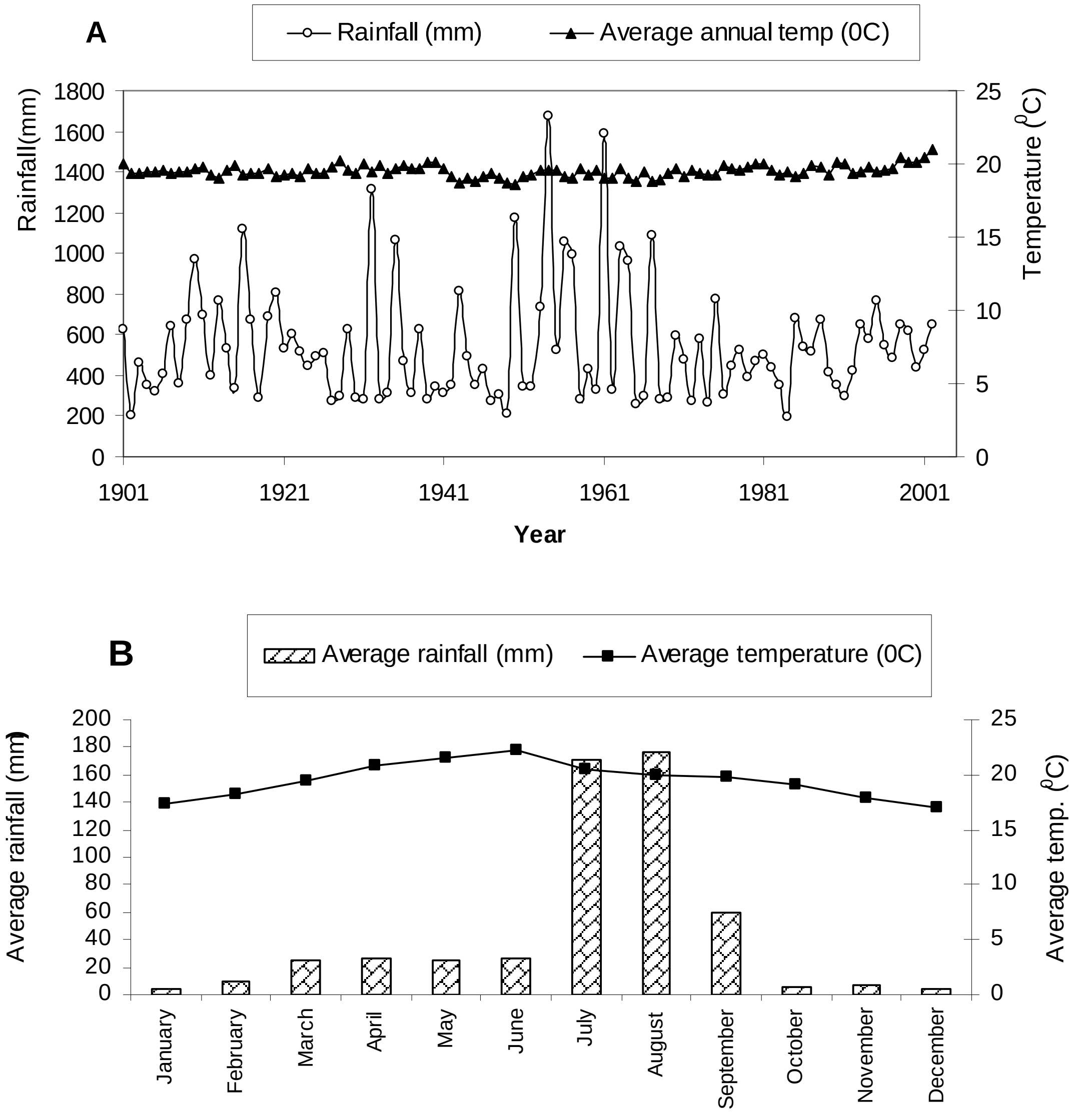


Figure 4. Annual rainfall and average annual temperature (A) and average monthly rainfall and temperature (B) for Teghane, 1901-2002 (Viner, 2003)

Temperature

Average annual temperature varies from <7.5 ^{0}C in locations >3500 m asl to > 27 ^{0}C in the eastern lowlands (Figure 5). Maximum monthly average temperature is in June, whereas the minimum is in December (see for example Figure 4B for Teghane).

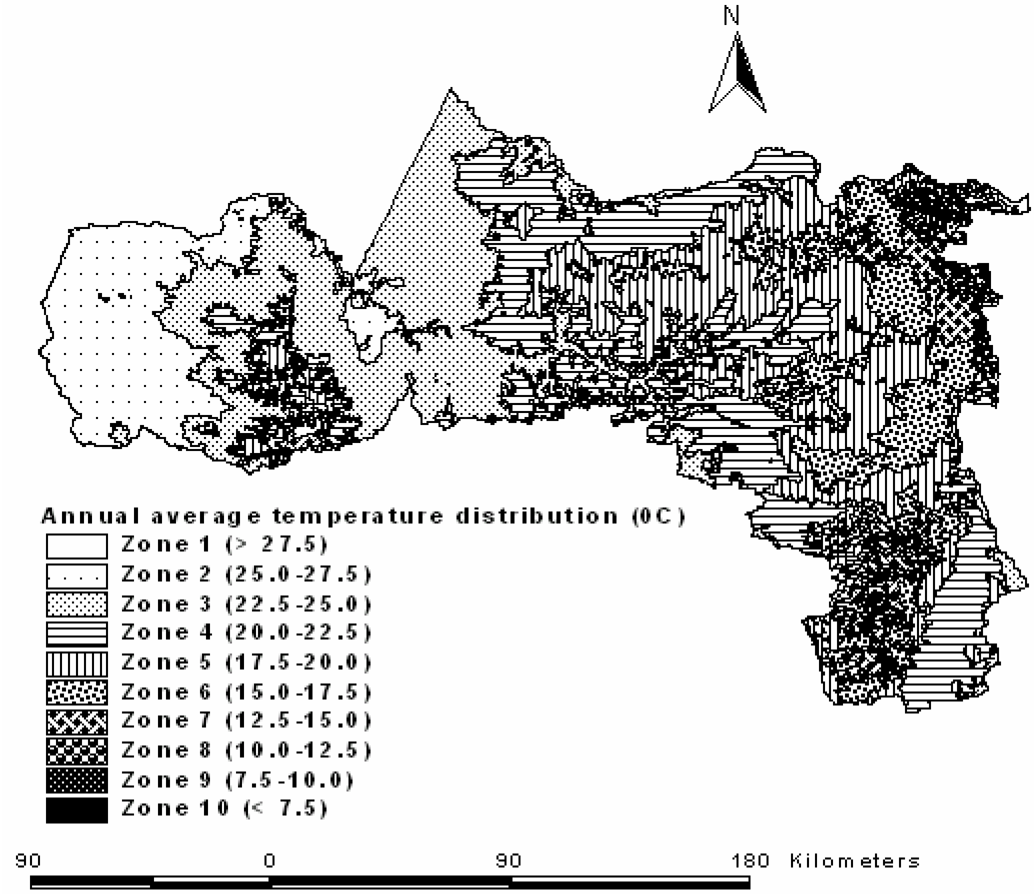


Figure 5. Spatial distribution of annual average temperature (^{0}C) in Tigray (WBISPPO, 2002)

Agro-ecological zonation

Marked variations in altitude (from < 500 m to over 4000 m asl, Figure 2), rainfall (from < 500 to over 1800 mm yr^{-1}, Figure 3) and temperature (from < 7.5 to > 27.5 ^{0}C, Figure 5) result in different agro-ecological zones within short distances (Figure 6). On the basis of elevation and temperature, we can identify four major agro-ecological zones: Wurch, Dega, Weyna Dega and Kolla (WBISPPO, 2002). By adding rainfall in the classification, 13 agro-ecological zones can be identified (Table 1 and Figure 6), and Teghane is located in “Deg” in the former and “Dega Dry” in the latter classification.

Table 1. Agro-ecological zonation on the bases of altitude and rainfall distribution for Tigray, Northern Highlands of Ethiopia (WBISPPO, 2002).

Agro-ecological zone	Altitude (masl)	Rainfall (mm yr^{-1})
Wurch dry	3500-4000	500-700
Upper Dega dry	3000-3500	500-700
Dega wet	2500-3000	1500-1800
Dega dry	2500-3000	500-700
Weyna Dega wet	2000-2500	1500-1800
Weyna Dega moist	2000 -2500	900-1200
Weyna Dega dry	2000-2500	500-900
Upper Kolla wet	1000-2000	1500-1800
Upper Kolla moist	1000-2000	900-1500
Upper Kolla dry	1000-2000	500-900
Lower Kolla wet	500-1000	1500-1800
Lower Kolla woist	500-1000	900-1500
Lower Kolla dry	500-1000	<500-700

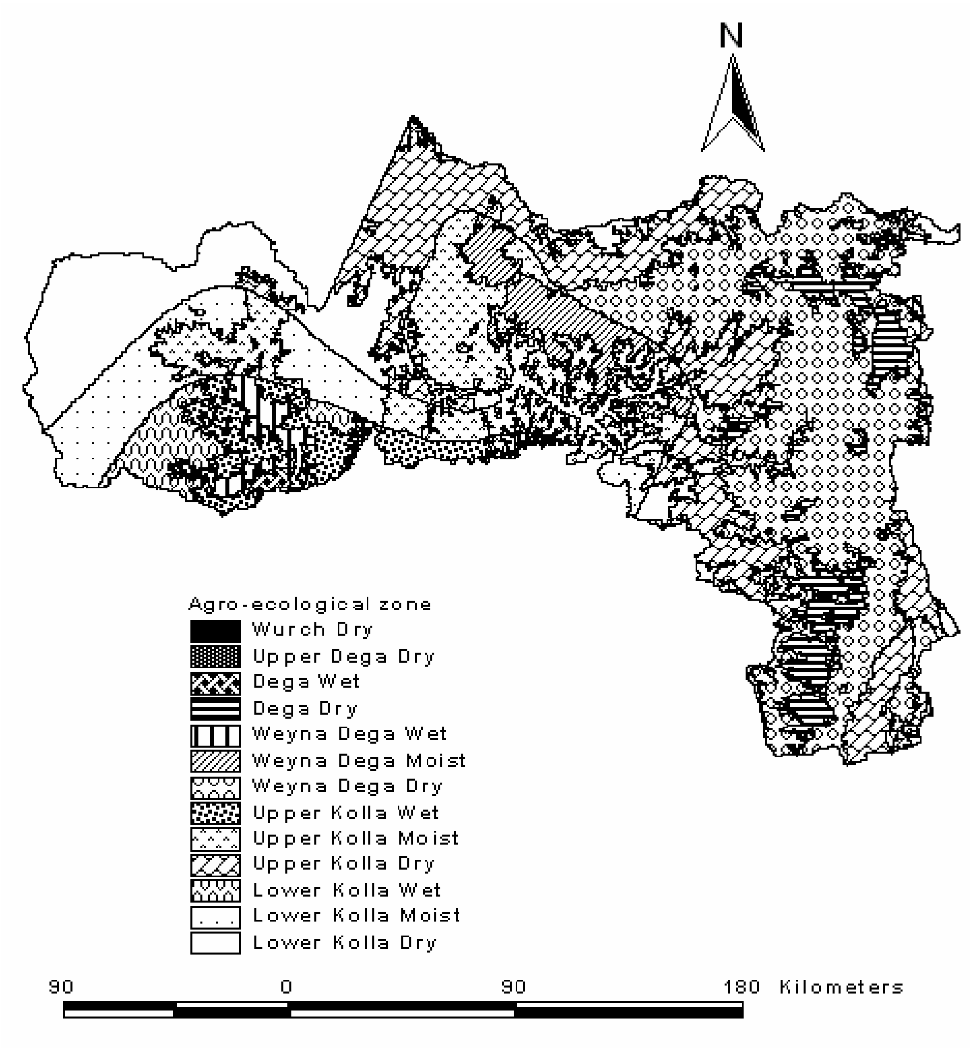


Figure 6. Agro-ecological zones of Tigray (WBISPPO, 2002)

Soils

Sofar, no systematic soil survey has been carried out for the whole of Tigray. However, on the basis of the world soil resources reference, the soil distribution of Tigray (Figure 7) has been mapped (WBISPPO, 2002). Two extensive surveys have been conducted in the central highlands of Tigray by Mitiku (1997) and Hunting (1975) and the major soils identified in these surveys include Cambisols, Luvisols, Rendizinas, Lithosols (Leptosols), Fluvisols, Nitosols, Arenosols, Vertisols, Xerosols and Andosols. Some of the main characteristics of these soils are presented in Table 2.

Table 2. Major soils in Tigray with their average properties[1] (Mitiku, 1997)

Soil Uni (FAO)	Series	Depth (cm)	Texture	OC (%)	CEC (cmol (+ kg^{-1})	Olsen-P (ppm)	BS (%)
Lithosols	Dindera	30	SCL	-	-	-	-
Vertisols	Humera	200	C	1.2	42	19.0	91
Vertisols	Gormedo	115	C	2.6	29	5.0	100
Fluvisols	Lahama	160	SL	2.4	20	1.4	100
Gleysols	Kesafi	120	L	-	27	-	95
Arenosols	Menchebu	180	SL	1.0	13	1.8	100
Rendzinas	Mosebu	45	C	3.3	41	2.3	76
Xerosols	Kalla	100	SL	2.0	22	4.0	82
Luvisols	Tabeldi	200	SCL	0.4	20	7.0	89
Luvisols	Romanat	130	CL	1.4	25	27.0	88
Cambisols	Yemad	144	SCL	1.1	12	8.6	60
Cambisols	Senda	125	SCL	1.0	16	2.0	91

[1]OC: organic carbon, CEC: cation exchange capacity, P: phosphorus, BS: base saturation Note: SCL = sandy clay loam, C= clay, SL = sandy loam, L = loam, CL = clay loam

In Teghane micro-catchment, a well-defined soil catena can be described in relation to relief**,** geology and soil characteristics. The major soil units include Leptosols, Luvisols and Cambisols covering 46, 26 and 26% of the study area, respectively (Figure 8A). Major characteristics of these soils are given in Table 3 (soil survey of 2003 in this study).

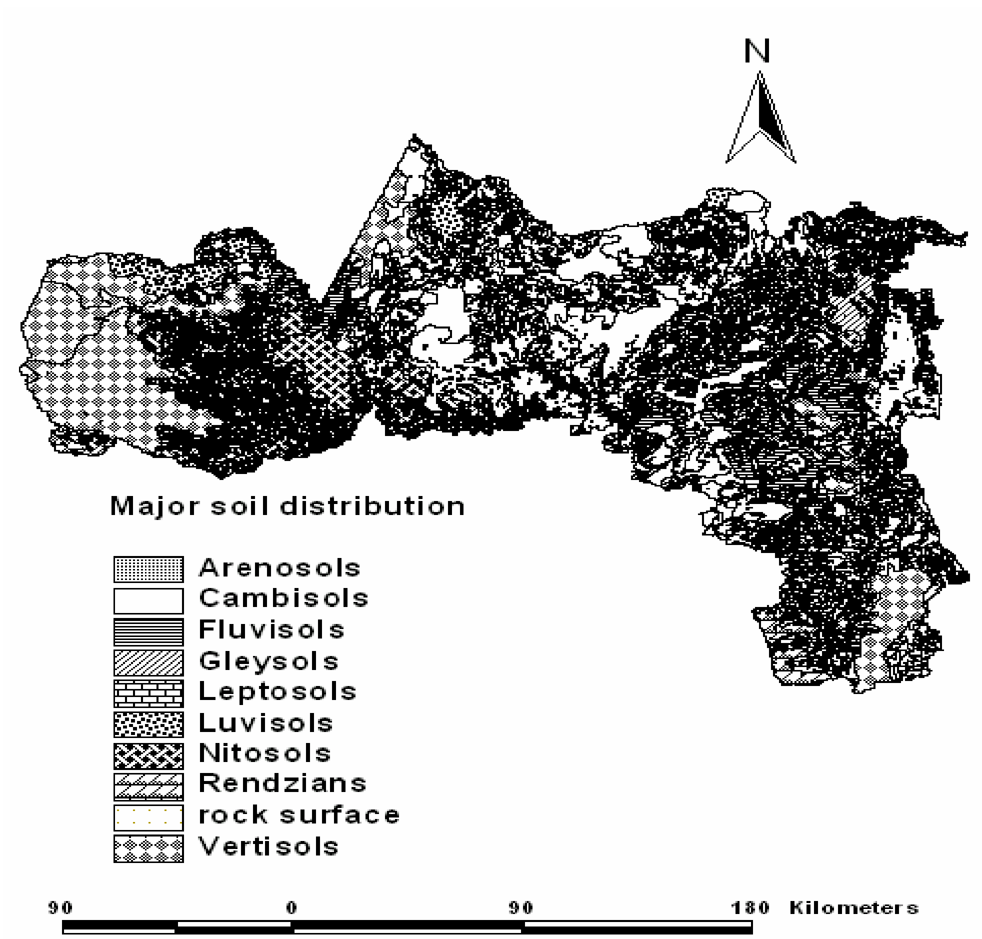


Figure 7. Spatial distribution of major soils in Tigray (WBISPPO, 2002)

Based on land units and morphology, four relief classes (physiographic regions) are identified (Figure 8B) and the associated soil units described. The first physiographic region comprises the elevated "messa" or plateau and the escarpment (scarp) in the eastern part of the area (covering 24% of the area), that separates the Tekeze and the Afar drainage systems. Its geology is sandstone sedimentary rock of the Mesozoic formation overlying Precambrian rock (Kazmin, 1975). Soils are mainly Leptosols (FAO-UNESCO, 1990), restricted in depth by continuous hard sedimentary rock, at a depth of 25 cm or having less than 20% of fine particles to a depth of 75 cm. These soils are generally degraded and eroded, characterized by very shallow depths, coarse texture, low nutrient content, and low moisture holding capacity. They are not suitable for cultivation. The escarpment slopes have rock outcrops, and, in patches of Leptosols, remains of open woodland of original Juniper trees are present.

Table 3. Some physical and chemical characteristics of representative soils in Teghane

Depth	PH H_2O	Sa	Sil	C		Na	K	Ca	Mg	Sum	CEC	BS[1]	TN[2]	OC[3]	Av. P[4]
Cm	1:2.5	%	%	%	Class	$\frac{Meq}{100g\ soil}$					$\frac{Meq}{100g\ soil}$	%	%	%	ppm
Leptosols*															
0-30	7.4	22	46	32	CL	0.20	0.13	8.48	3.78	12.6	13.40	94	0.104	0.978	7.44
Cambisols															
0-20	6.27	10	38	52	C	0.17	0.24	9.63	5.43	15.47	18.60	83	0.227	2.354	21.62
20-50	6.32	14	40	46	C	0.17	0.24	9.63	5.43	15.47	18.60	83	0.227	2.354	21.62
50-120	6.63	16	28	56	C	0.21	0.16	8.28	4.77	13.42	20.20	66	0.116	1.057	21.18
Luvisols*															
0-20	6.99	32	36	32	CL	0.20	0.39	7.78	3.46	11.83	14.60	81	0.122	1.397	10.28
20-80	7.88	16	32	52	C	0.11	0.18	13.47	7.74	21.50	23.60	91	0.040	0.399	10.84
80-190	7.90	8	50	42	SiL	0.10	0.17	18.26	9.63	28.16	20.00	141	0.020	0.200	13.82
Rock outcrop and water body*															

[1]Base saturation, [2]Total nitrogen, [3]Organic carbon, [4]Available phosphorus (Olsen), CL = clay loam, C= clay, SiL = silt loam, Sil = silt , Sa = sand

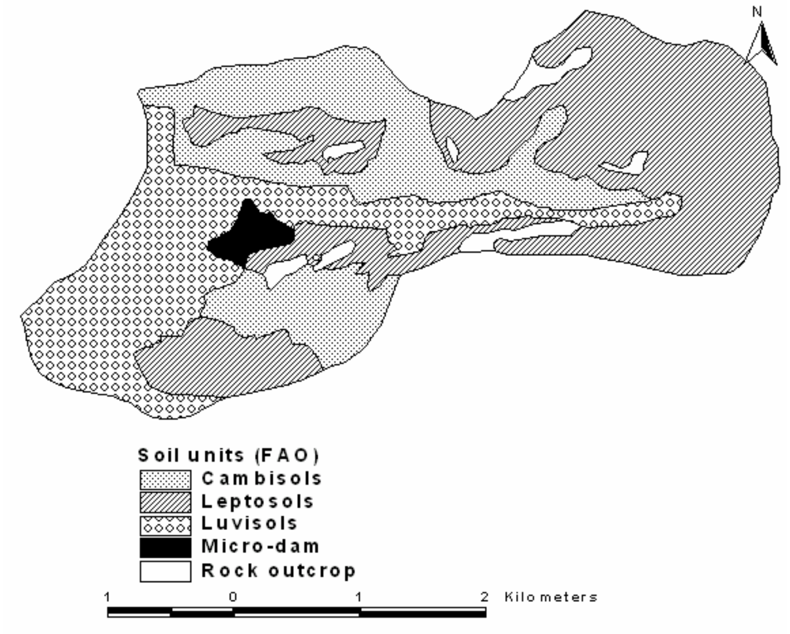
* Area coverage of the study area is 46, 26, 26 and 2% for Leptosols, Cambisols, Luvisols and rock outcrop and water body, respectively.

The second physiographic region consists of hills (11% of the area), including crests and ridges. Rock outcrops, Leptosols and patches of Luvisols cover this area. The rock outcrops and parent materials are meta-volcanic. This relief class occupies part of the eroded landform of the catchment, in which the original topsoil and subsoil have been completely removed as a result of long and continuous cultivation and inappropriate farm management practices. In much of this area, the plow layer (Ap horizon) is developed in the C horizon (parent material).

The third region consists of colluvial terrace slopes (37% of the area), where debris of pebbles, rock fragments and soils from upper slopes have accumulated through erosion and gravitational forces. Here, Cambisols, overlying on meta-volcanic parent material, dominate and these are intensively cultivated.

The last physiographic region is the valley bottom or flood plain (26% of the area). It occupies the depositional part of the micro-catchment. In this relief class, relatively deep Luvisols are dominant. Irrigated fields, some excellent rainfed fields, grazing lands and micro-dam (water reservoir) are found.

A



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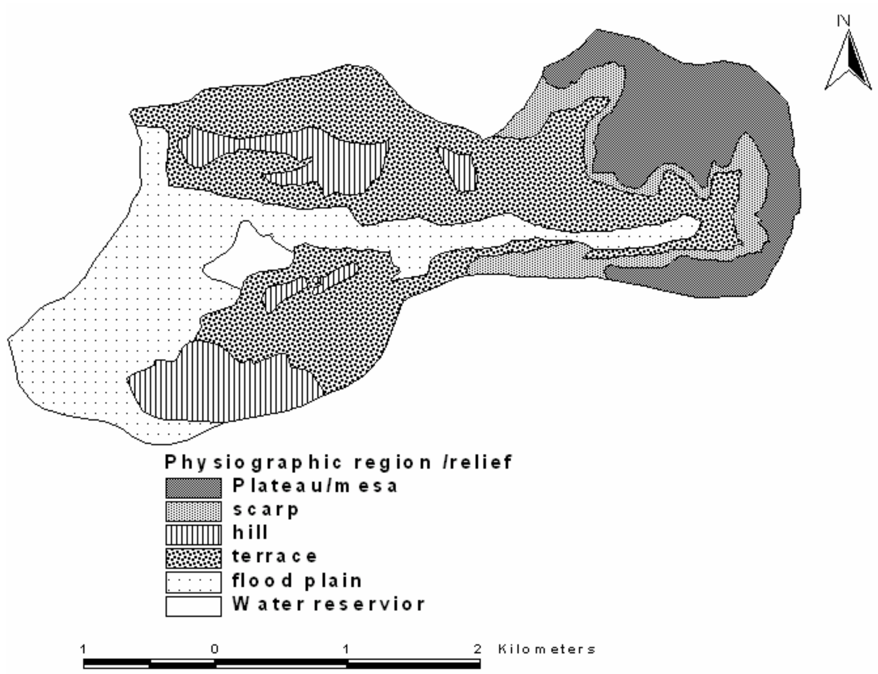

Figure 8. Soil units (A) and physiographic region/relief (B) in Teghane, Northern Highlands of Ethiopia (survey of this study, 2003)

3 Farming systems

In the history of Ethiopian civilization, agricultural development in the Northern Highlands of Ethiopia, particularly in Tigray has undergone a series of evolutionary developments in crop and livestock production. The early production systems and farm management practices in the region enabled surplus production over and above the regional requirements of that time and the people were engaged in arts and crafts on the basis of these production surpluses. The historical antiquities of Ethiopian wealth in Northern Ethiopia bear witness to this fact. At present, pastoral systems, mixed pastoral-cereal production systems and mixed crop-livestock systems are the main farming systems, of which the mixed crop-livestock farming system is dominant (Fitum et al., 1999).

Smallholder farmers manage crop and animal production in an integrated way, to maximize returns from their limited land and capital, minimize production risk, diversify sources of income, provide food security and increase productivity. The farm animals provide draught power for cropping, offspring to the household and fertilizer for crops and natural pasture lands in the form of manure. Dried animal manure is also used as fuel. Crop residues and grass are used as feed for livestock. Outputs from livestock, such as milk, meat and eggs are important sources of food for the farm household. Sales of animal products and live animals are important sources of cash and means of savings. External inputs to the livestock include purchased salt and veterinary services.

Crop cultivation involves the traditional “maresh”, plowing with a pair of oxen. Major crops grown in Tigray are barley (*Hordeum* spp.), wheat (*Triticum* spp.), and teff (*Eragrostis* spp.) which account for about 60% of the cultivated area, followed by sorghum, millet and maize, which together cover just over 10% and pulses, which include faba bean (*Vicia* spp.), field pea (*Pisum* spp.) and lentils, occupying slightly less than 10% (cf. Mintesinot, 2002) with only one harvest each year.

In Teghane, annual food crops, such as barley (*Hordeum* spp.) and wheat (*Triticum* spp.) are the major crops, grown on 66 and 14%, respectively of the cultivated land in 2002. Field pea (*Pisum* spp.) and faba bean (*Vicia* spp.) are the next important crops, occupying 10 and 9%, respectively. Most of the grazing lands are in the valley bottom, where water logging is a serious problem for growth of crops. Marginal fields are under open woodland and prickly pear (*Opunta* spp.).

Climatic factors, i.e. rainfall pattern and temperature, mainly control the crop calendars. The main period for cropping and grass growth is the rainy season between July and October, whereas from February to June barley and some vegetables are grown in small irrigated fields.

Cattle, sheep and donkey are the most important farm animals in Teghane. Average arable land holdings are reported at 1.2 hectares per household, varying from 0.5 ha in the highlands to 2.0 ha in the lowlands (Fitum et al., 1999). In Teghane, average total land holdings vary between 0.5 ha for the poor farm group to 1.6 ha for the rich group (survey of this study, 2002).

4 Dynamics of soil fertility management practices

Soil fertility management practices include shifting cultivation/fallowing, crop rotation, manuring and mineral fertilization. In the early stages of agricultural development, the agricultural system was supported by indigenous soil fertility. The prevailing farming system was that of shifting cultivation, whereby areas were cleared of trees for land preparation and the remaining materials burned to add ash to the soil. After some years of cultivation, the plots were abandoned for regeneration and new sites opened. With increasing population pressure, the farming system gradually developed into a sedentary system with continuous cropping.

In the sedentary farming system, characterized by continuous and intensive cropping, soil fertility rapidly declined. In response, land management was modified to a system in which a proportion of the land was fallowed, allowing the natural vegetation to return and regenerate natural soil fertility. However, accelerated population increase led to breakdown of this system, so that continuous cultivation became common practice and with it soil fertility decline.

Continuous cultivation, with crop rotation was introduced as a management system to maintain favorable soil conditions and satisfactory yields. Recently, rapid population increase, which has resulted in very small holdings, has changed the situation. All the land, including marginal lands, which are heavily degraded and eroded, is used for rainfed cultivation. Fallowing has almost completely been abandoned. About 50% of all cropland in Ethiopia is affected by soil degradation (Campbell, 1991; Stahl, 1990). Much of the animal manure is used for household fuel and all crop residues are collected from the field for livestock feed, so that returns of organic material to the crop land, for instance in the form of composted manure mixed with residues of animal feeds, are minimal. Grazing lands are excessively overstocked. Levels of external inputs in the form of inorganic fertilizer and/or animal feed are very low or zero. Recommended fertilizer use on grain crops in the area consists of urea in combination with diammonium phosphate (DAP) at the rate of 100 kg each ha^{-1} yr^{-1} (= 64 kg of N and 21 kg P); however, farmers apply inorganic fertilizer only in irrigated fields mainly due to economic constraints and risk aversion (Van Noordwijk et al., 1994). Thus, soil nutrients are rapidly depleted (Gebremedhin et al., 2003; Corbeels et al., 2000).

5 Rationale of the study and general objective

The mainstay of the Ethiopian economy is agriculture. No other countries in sub-Saharan African, and only two other countries in the world, derive a higher share of gross domestic products (GDP) from agriculture (Block, 1999). It accounts for 46% of its GDP and 90% of its export earnings and employs 85% of the country's labour force (UNDP, 2002). About 95% of the agricultural output is from subsistence smallholder farms of the highlands of Ethiopia (ADF, 2002). The country's long-term economic development strategy, "Agricultural Development-Led-Industrialization" (ADF, 2002), has been designed to target these smallholders' private agricultural economy to maintain food security and strong economic growth. It is also supposed to initiate development of home industries, stimulate the service sectors and create additional purchasing power. These broad indicators underline the importance attached to agriculture in the Ethiopian economy (Block, 1999). For attainment of the goals formulated for agriculture, sustainable agricultural development is a pre-requisite, which in turn requires development of appropriate farm management systems.

However, the agricultural systems in the highlands of Ethiopia in general, and in its northern highlands in particular are subject to continuous and widespread disequilibrium dynamics. Soil nutrient losses from agricultural systems of Ethiopia are among the highest in the Sub-Saharan African countries, i.e., - 41 kg N, -13 kg P and –31 kg K ha^{-1} of cultivated land in 1983 (Stoorvogel and Smaling, 1990).

Very low use of fertiliser--for example, only one-third of the Ethiopian rural households used fertiliser in 1995 at an average level of 11 kg per hectare, compared to 48 and 97 kg ha^{-1}, respectively in Kenya and world-wide (Pender et al., 1999). Agricultural practices with low external inputs carry the risk of depleting soil nutrient stocks, seriously threatening future agricultural production (Tellarini and Caporali, 2000; Elias et al., 1998; Harris, 1998; Bojo and Cassels, 1995, Stoorvogel and Smaling, 1990). Within the system, only small amounts of manure are applied to arable crops (dung cakes are used for fuel) and most crop residues are used for animal fodder and burned for household fuel. Fallowing, for natural soil fertility replenishment, has almost completely disappeared from agricultural practice, due to the small farm sizes associated with high population growth. In general, soil nutrient balances in the farming systems of the northern highland of Ethiopia are strongly negative. Thus, agricultural development in this region, one of the agro-ecologically and economically less-favoured areas of the world, is slow or stagnant and not sustainable.

Low and declining nutrient availability results in crop and livestock production decline and food insecurity. Cereal crop output is less than 1 Mg ha^{-1} of cultivated land (Fitum et al., 1999), and milk and beef production are 230 kg per cow and 109 kg carcass per animal, respectively (Gryseels, 1988). On the other hand, population is growing at a rate of 2.7% (IRIN, 2003) and land holdings are small. Consequently, for the last decade the people have been food-insecure and dependent on external food aid (USAID, 2004).

Increasing agricultural production is absolutely necessary to feed the increasing population, either by increasing the area of farming and grazing lands or by increasing land productivity. However, future expansion of the agricultural area seems undesirable in the highlands of Tigray, because all suitable cultivable and grazing lands are already in use. The feasible option therefore seems to increase the productivity of the land already in use, by improving soil fertility management for crop production and introducing optimum feed resource use strategies for higher livestock productivity as a core strategy. The most important soil characteristics to be considered are soil organic matter content, and availability of macro-nutrients, such as nitrogen, phosphorus and potassium and its effect on crop production. Study of the dynamics of soil nutrients and assessment of quantity and quality of the available feed resources and the consequences for livestock production, are therefore necessary for the highlands of Tigray.

The general objective of the study was to describe the interactions between farm management and soil nutrient dynamics and feed availability and quality as a basis for the design of more sustainable farming systems. As the time constants of change of soil nutrient qualities are large, long-term effects have been considered, which requires application of modelling approaches. Quantification of the relation between current farm management practices and natural resource qualities (soil nutrients and feed resources) form the basis for parameterization, calibration and validation of the models developed, which are then applied to explore long-term effects of both current and alternative farm management practices.

6 Specific objectives

The first objective of this study was to monitor inflows and outflows of N, P and K at plot and farm scales using the NUTMON-toolbox (Van den Bosch et al., 2001), as a basis for assessing the current rates of change in nutrient stocks under the prevailing farm management practices. Plot and farm scales studies of nutrient balances in relation to nutrient stocks are important tools to create awareness among farmers and other stakeholders, such as policy makers with respect to rates of soil nutrient depletion. Their results can also contribute to the ongoing debate on appropriate policies, strategies and interventions to stimulate adoption of sustainable agricultural system (Scoones and Toulmin, 1998).

To increase production of cereal crops, increased use of chemical fertilizers has been suggested (Amsal Tarekegne et al., 1997; Asnake Woldeab et al., 1991) of which expensive imported N and P are the two most widely used (Gezahegn Ayele and Tekalign Mamo, 1995). Inefficient use of these expensive nutrients contributes to the depletion of scarce financial resources, increased production costs and potential environmental risks (Amsal Tarekegne and Tanner, 2001). Thus, the second objective was to parameterize indigenous soil nutrient supply and nutrient requirements of barley and to calibrate a nutrient balance model, QUEFTS (**QU**antitative **E**valuation of the **F**ertility of **T**ropical **S**oils) (Janssen et al., 1990), for fertilizer management for the Northern Highlands of Ethiopia.

Farmers and agricultural development agents differed widely in their assessment of major constraints for livestock production and courses of action that need to be taken in the Highlands of Ethiopia (Kassa, 2003). Knowledge of on-farm available feed resources and their quality is fundamental in exploring opportunities to increase farm productivity by targeting the available resources. Therefore, the third objective of this study was to examine availability and quality of feed resources and their relationship with livestock performance in smallholder farms. Animal production is a function of both amount and quality of feed intake (Kamalzadeh et al., 1997; Ryan et al., 1993). Availability of high quality feed will lead to intake in accordance with the animal's energy requirements, so that potential liveweight and/or milk production can be achieved (Van de Ven et al., 2003). In situations where both low and high quality feeds are available, farmers have to select the best quality feeds, or a limited number of animals should be allowed to select, to achieve optimum production for a given production objective (Zemmelink, 1995). Thus, the fourth objective was to describe the relationships between feed availability (quantity and quality) and feed intake on the one hand and live weight and milk production and soil carbon (C) balance in relation to manure production on the other, to assess the best feed utilization pattern in view of various production objectives of farmers, i.e. liveweight production, milk production, draught power and maintenance of soil carbon stock.

The last objective was to explore long-term dynamics of soil C, N and P and the consequences for crop-available N and P under alternative farm management practices, using a summary simulation model that can support the design of appropriate farm management practices. Modelling long-term dynamics of soil organic matter, nitrogen and phosphorus can improve insight in future farm management scenarios and can serve as a framework for assessing options for alternatives for sustainable nutrient management.

7 Thesis outline

Following this general introduction, Chapter 2 gives a detailed account of partial balances of the macronutrients (nitrogen (N), phosphorus (P) and potassium (K)) to evaluate the sustainability of current farming systems in terms of nutrient elements. In Chapter 3, nutrient requirements of barley have been quantified based on soil chemical analyses and results of fertilizer experiments on three soils. For formulation of more accurate fertilizer recommendations, the QUEFTS model has been calibrated. In Chapter 4, results of an analysis of forage availability and livestock performance at farm scale are presented. Chapter 5 gives a detailed account of the relations between differential feed use (in terms of quality) and livestock productivity at village level. Chapter 6 presents the summary simulation model of soil N, OC and P and the simulation results of long-term nutrient dynamics at five farm management regimes. Finally, Chapter 7 presents the general discussion.

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Chapter 2

Nutrient dynamics on smallholder farms in Teghane, Northern Highlands of Ethiopia

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Nutrient dynamics on smallholder farms in Teghane, Northern Highlands of Ethiopia

Abstract

To evaluate the sustainability of agricultural systems, the dynamics of nitrogen (N), phosphorus (P) and potassium (K) were studied at field and farm scales in Teghane micro-catchment, Northern Highlands of Ethiopia. Three farm wealth groups (rich, medium and poor) were distinguished based on farm size, capital assets and grain stocks. The NUTMON questionnaire and software have been used for data collection and calculation of partial macronutrient balances. The study indicates that total input to farm fields of all three macronutrients does not balance nutrient removal in crop yield and animal feeds. Consequently, N, P and K stocks in the soil are rapidly declining, with annual depletion rates higher for the rich group (2.4% of total N, 1.3% of total P and 1.3% of total K) than for the poor group (1.0% of total N, 0.2% of total P and 0.4% of total K), and the medium group taking an intermediate position. For all three groups, current farm management is not sustainable. The study clearly identifies the need for the development of integrated nutrient management systems to reduce the high rates of nutrient depletion and to transfer to sustainable farm management systems. Three possible measures can be suggested: First, improvements in nutrient use efficiency from manure, which could be attained through judicious management, i.e. manure must be carefully stored to minimize physical loss of the manure/compost and nutrients, and that manure must be applied to the appropriate crop with the appropriate method at the proper time. Secondly, introduction of energy-saving stoves to reduce use of cattle dung for fuel and consequently increasing manure availability for field application. Thirdly, application of more external chemical fertilizer, together with improved rainwater harvesting for supplementary moisture supply.

Key Words: Mixed farming systems, nutrient balances, nutrient mining, NUTMON

1 Introduction

Agriculture is the basis of the Ethiopian economy, accounting for 46% of its GDP and 90% of its export earnings and employing 85% of the country's labor force (UNDP, 2002). About 95% of the agricultural output originates from subsistence smallholder farms in the highlands (ADF, 2002). The country's long-term economic development strategy, "Agricultural Development-Led-Industrialization" (ADF, 2002), has been designed to target these smallholders' private agricultural economy with the aim of maintaining food security and supporting economic growth. Moreover, it aims at initiating development of home industries, stimulating the service sectors and creating additional purchasing power. These objectives illustrate the important role envisaged for agriculture in the Ethiopian economy (Block, 1999). For attainment of the goals formulated for agriculture, sustainable agricultural development is a pre-requisite, for which development of appropriate soil fertility management systems is one of the tools (Terry, 1999). However, most of the environmental problems facing the country are associated with subsistence agriculture-related activities (UNEP, 2002), such as inappropriate land management practices associated with low external nutrient inputs and population pressure (UN, 2002). Agricultural practices based on low external input levels carry the risk of depleting soil nutrient stocks, seriously threatening the sustainability of agricultural production (Hengsdijk et al., 2005; Tellarini and Caporali, 2000; Elias et al., 1998; Harris, 1998; Bojo and Cassels, 1995; Stoorvogel and Smaling, 1990). Within the farming systems of the Ethiopian highlands, only small amounts of manure are applied to arable crops (cattle dung cakes are predominantly used for fuel) and most crop residues are used as animal feed. Fallowing, for natural soil fertility replenishment, has almost completely disappeared from agricultural practice, due to the small farm sizes associated with high population pressure.

Soil nutrient dynamics are important sustainability indicators for agricultural production systems (Smaling, 1998). Soil nutrient status in agricultural systems is, on the one hand, determined by physical, chemical and biological processes in the soil, which are affected by climate, soil type and topography (Janssen, 1999) and, on the other hand, by farm management practices. Inappropriate farm management practices play a role in the development of unsustainable agricultural systems (Stoorvogel and Smaling, 1990).

Many of the previous studies on land degradation in Ethiopia have focused on losses of nutrients through physical soil erosion caused by run-off (see for instance, Belay, 1992; FAO, 1986; Constable, 1984). Since the beginning of the 1990s, attention has also been paid to removal of economic yield and all crop residues from agricultural land as one of the major components of soil nutrient depletion (Tellarini and Caporali, 2000; Elias et al., 1998; Harris, 1998; Bojo and Cassels, 1995; Stoorvogel and Smaling, 1990). Rates of nutrient depletion in Africa have been quantified at various spatial scales and for different farming systems (for example Stoorvogel and Smaling (1990) for sub-Saharan Africa, Van der Pol (1992) for southern Mali, Smaling et al. (1993) for Kisii district of Kenya). Based on such studies, it has been concluded that analysis of inputs and outputs of the macronutrients, nitrogen (N), phosphorus (P) and potassium (K) is an important component of sustainability assessment of farming systems. Although doubts have been voiced about the usefulness of nutrient balance studies for sustainability evaluation (Scoones and Toulmin, 1998), careful analysis of the inflows and outflows of nutrients from farming systems may reveal imbalances, and may serve as a starting point for the design of modifications in the system, leading to more balanced nutrient flows. Moreover, the results may serve as awareness raisers for the local farming community and to alert policy makers (Janssen, 1999).

The sub-Saharan Africa study by Stoorvogel and Smaling (1990) indicated that Ethiopia is one of the countries with the highest rates of nutrient mining, with aggregated national values of -41 kg of N, -13 kg of P and -31 kg of K ha^{-1} of cultivated land in 1983. However, Ethiopia is characterized by diverse climatic conditions, soil types and topography, resulting in a wide variety of farming systems, each with its specific nutrient management system, and the associated rates of nutrient addition or depletion. For instance, Elias et al. (1998), in their nutrient balance analyses, recorded high rates of N depletion by well-endowed (annually -102 kg ha^{-1}) and medium-endowed farmers (-88 kg) in the highlands and -24 kg ha^{-1} by poor and -57 kg ha^{-1} by very poor farmers in the lowlands in Kindo Koisha district, southern Ethiopia. Such results can not be extrapolated to the Northern Highlands of Ethiopia, characterized by completely different relief, climate conditions, soil types, history of farming, and farm management systems. For example, a recent study at plot scale in cultivated fields in the Northern Highlands of Ethiopia (Hengsdijk et al., 2005) reported a negative balance of 27 kg N ha^{-1}. Hence, there is a need for assessment of nutrient dynamics at field and farm scales in different localities and under different socio-economic conditions, as a basis for the design of technically feasible, ecologically non-degrading, and economically viable nutrient management strategies. The study described in this paper responds to that need, reporting on assessment of partial macro-nutrient balances at field and farm scale in Teghane, in the Northern Highlands of Ethiopia.

2 Materials and methods

The study area

The study was conducted during 2002-2003 in Teghane, Atsbi Wonberta district, situated between 13^0 52' 53" and 13^0 53' 37" N and between 39^0 42' 05" and 39^0 43' 57" E, in Tigray Regional State in the Northern Highlands of

Ethiopia, covering an area of 13.56 km^2. Its altitude ranges from 2710 to 2899 m above mean sea level. The climate is "Dega" (WBISPPO, 2002), with average annual monomodal rainfall from July to September of 541 mm (coefficient of variation 53%, for the period 1901-2002, at a location near Teghane at 14^0 N and 40^0 E (Viner, 2003)) (Figure 1). For the period 2000-2004, average annual rainfall was 532 mm (Atsbi World Vision, 2004), comparable to the long term average. The year in which the data were collected represents an ‘average’ production situation for the area (local farming experts, pers. comm.).

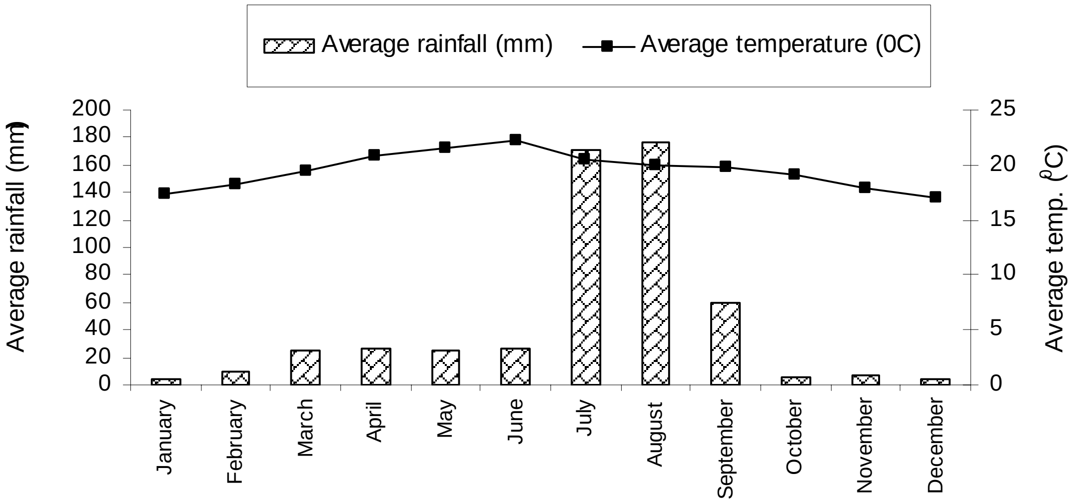

Figure 1. Average monthly rainfall and temperature for Teghane, 1901-2002 (Source: Viner, 2003)

Farming systems

The dominant farming system in Teghane is a subsistence mixed crop-livestock system. Smallholder farmers integrate crop and animal production to maximize returns from their limited land and capital resources, minimize production risk, diversify sources of income, provide food security and increase productivity (Paris, 2002).

Annual food crops, such as barley (*Hordeum* spp.) and wheat (*Triticum* spp.) are the major crops, grown on 66 and 14%, respectively of the cultivated land in 2002. Field pea (*Pisum* spp.) and Faba-bean (*Vicia* spp.) are the next important crops, occupying 10 and 9%, respectively. Most of the grazing lands are in the valley bottom, where water logging is a serious problem for growth of crops. Marginal fields are under open woodland and prickly pear (*Opunta* spp.). Climatic factors, i.e. rainfall pattern and temperature, mainly control the crop calendars. The main cropping period is the rainy season between July and October, whereas from March to June barley and some vegetables are grown in small irrigated fields.

The farm animals provide draft power and manure for crops. Dried animal manure is used extensively as a source of household energy. Crop residues are used as feed for livestock. Outputs from livestock, such as milk, meat and eggs are important sources of food for the family. Cash from the sales of crop products, animal products and animals is used to purchase farm inputs and cover expenditures for schooling, clothing and veterinary costs. Hence, livestock serves as a capital asset, in the form of a readily available source of cash and means of savings (Mohamed Saleem, 1998; Slingerland, 2000; Paris, 2002; Udo, 2002; Bebe, 2003).

Farm selection

Farmers were classified according to the community's viewpoint, during a village farmers' assembly, in three wealth groups (rich, medium and poor), on the basis of the socio-economic conditions in Teghane. The criteria used were land holding, herd size (HS) and the stock of seed/grain for planting and consumption, i.e., farmers in the 'rich' group possessed land > 1 ha, oxen ≥ 2, cows ≥ 2 and had enough seed/grain in stock to cover the requirements for planting and consumption, in the 'medium' group farmers possessed 0.75 – 1 ha, one ox and one cow and the 'poor' group possessed land holdings < 0.75 ha and owned one or no oxen, one or no cow and few other animals and had insufficient seed/grain in stock for planting and consumption. Through stratified random sampling, 5 households from the rich, 7 from the medium and 12 from the poor group were selected from the list of all households of the village. The community's classification has been validated with data collected during the first survey. Three experts in local farming practices were consulted on past farming practices in the area.

Framework for analysis of N, P and K flows

The NUTMON toolbox (Van den Bosch et al., 2001) was used to analyze nutrient flows. The NUTMON-methodology is based on systematic collection of information from the farm household on farm characteristics, farm practices and farm management. This information, both quantitative and qualitative, is used to quantify flows of material (with emphasis on nutrients) and cash through the farm system. Information collection starts with the *farm inventory*, that is, in principle, repeated before each crop cycle. In the farm inventory, information is collected on the farm household, i.e. its composition, and its assets (land, capital goods, i.e. machinery and animals). The farm household is characterised in terms of available labour and consumer units. Also the education level of the head of the household is recorded. The available land resources are specified in terms of both, *Farm Section Units (FSU)* (land units with more or less 'stable' soil characteristics) and *Primary Production Units (PPU)* (land units dedicated to production of a certain commodity in a given season). Capital goods are specified, such as hoe(s), plough(s), etc. Animals present at the farm (*Secondary Production Units (SPU)*), are defined in terms of Animal Management Groups, i.e. groups of animals (generally) of the same species that are managed by the farm household as homogenous units in terms of feeding, confinement, and grazing. The presence of *redistribution units (RU)*, such as stables (night corrals), manure heaps and compost pits is recorded. In addition, the *Household* (HH) is defined as the labour supply and consumption unit, *Stock*, as temporary store for staple crops (cereals and pulses), crop residues (for cattle feeding) and finally the 'external world' (EXT), consisting of markets, neighbours and/or other families, serving as a source of and/or destination for flows, that as externalities (not on-farm) are not monitored.

Quantifying nutrient flows

In the subsistence mixed crop-livestock farming system of Teghane, flows between the farm system and the external system/market (Figure 2, solid lines) and internal flows (Figure 2, broken lines) have been schematized to quantify N, P and K inflows and outflows at both, field and farm scale. The external system/market is the source of inputs into the farm, i.e. chemical fertilizer and grain/seeds to the soil sub-system, animal feed (grass, crop residues and salt) and veterinary input to the secondary production sub-system, and food grains (food aid) to the household. Flows out of the farm consist of sales of economic yield from the crop component and animal products and live animals from the livestock component.

Internal flows within the farm consist of nutrient supply from the soil sub-system to Primary Production Units (crop, woodlot and grass/roughage), crop residues, grass and prickly pear leaves from the Primary Production Units to the Secondary Production Unit and grains and prickly pear fruits to the Household. The Secondary Production Unit supplies manure to the soil and the stable, animal products as food to the Household and animal dung for household fuel. Manure is transferred from the stable (RU1) to the compost pit (RU2), from where compost is transported to the crop land. Woodlots supply wood to the Household for fuel. Household waste is swept into the compost pit.

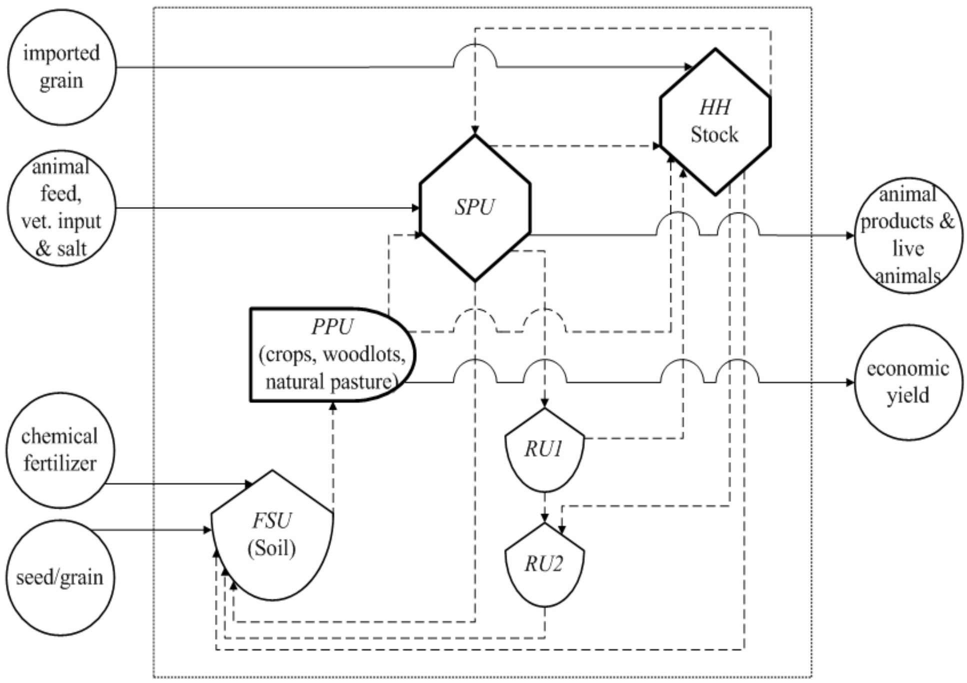

Figure 2. Inflows and outflows over the farm boundaries (‘farm gate flows’) (solid lines) and farm scale internal flows (broken lines)

Using the NUTMON-toolbox, the quantities of nutrients entering and leaving the system components have been estimated and the balances (= inputs – outputs) for N, P and K are calculated for: (i) the farm scale, (ii) the field scale (PPU) (aggregation of all PPUs and iii) individual PPUs. Five PPUs have been distinguished, i.e., barley, wheat, faba bean and pea and natural pasture. Economic yield and removed residues/weeds from each field were estimated by sampling two to three quadrats of 3x3 metres along a diagonal within each field. Economic yield and crop residues/weeds were separated and composite samples collected for laboratory analysis in the National Soil Research Center (NSRC), Addis Ababa to determine NPK contents. N removal from faba bean and pea fields was estimated at 50% of the total N content of harvested products (haulms and grain), assuming that the remaining N originates from biological fixation. ‘Hard-to-quantify’ nutrient inputs via atmospheric

deposition and sedimentation and outputs via leaching, denitrification and erosion were not considered in this study, (iv) the SPU scale.
The quantities of N, P and K in the manure deposited in the stable were calculated from the number, type and confinement period of the animals in the stable, and the composition of the manure. Manure used for household energy was estimated as the average value of monthly weightings for 8 months. Nutrients in manure added to the compost pit/heap were estimated from daily measurements of the quantities of manure transferred from stable to compost pit/heap. Nutrients in refused fodder and household waste were calculated in NUTMON. During the dry season, immediately after harvest, livestock freely graze crop residues. In the wet season and when arable fields are cropped, animals graze natural pastures. Nutrients ingested by the animals and deposited in manure in the same fields were calculated from the length of the grazing period, assuming *ad-libitum* feed intake. Nutrient flows from Primary Production Units to livestock were calculated from crop residue production, and other forms of feed/weeds for livestock and their NPK contents.

Nutrients transported from the woodlot for household energy were calculated from measured quantities of wood harvested and its nutrient content. Nutrient flows from Primary Production Units to stock/household were calculated from economic yields and their nutrient contents.

From each *FSU*, composite soil samples from the 0-20 cm surface layer were collected for laboratory determination of OC (Walkley and Black, 1947), available P (Olsen et al., 1954), total N (Bremner and Mulvaney, 1982) and total K (Knudsen et al., 1982) at the International Livestock Research Institute (ILRI), Addis Ababa and soil bulk density in the soils laboratory of Mekelle University.

Analysis of variance

Data on farm scale inflows, outflows and balances per farm group were subjected to analysis of variance using SPSS (SPSS, 2001).

3 Results

3.1 Agriculture in the Northern Highlands of Ethiopia

Agriculture in the Northern Highlands of Ethiopia has a very long history, in which schematically four stages can be distinguished in terms of farm management practices.

Stage I. In the early stage, the agricultural system was supported by indigenous soil fertility. The prevailing farming system was that of shifting cultivation, whereby areas were cleared of trees and the remaining materials burned to add ash to the soil. After some years of cultivation, the plots were abandoned for regeneration and new sites opened. As long as population densities were low, these systems were sustainable (Nye and Greenland, 1960). With increasing population pressure, the farming system gradually developed into a sedentary system with continuous cropping.

Stage II. In the sedentary farming system, characterized by continuous and intensive cropping, soil fertility rapidly declined, and so did crop yields (Bationo et al., 1998). In response, land management was modified to a system in which a proportion of the land was fallowed, allowing the natural vegetation to return and regenerate natural soil fertility. According to experts in local farming practices, use of long fallow periods greatly contributed to sustained agricultural production until about five decades ago. This was possible, because (i) sufficient arable land was available, and fallow periods of over 3 years could be maintained, (ii) demand for agricultural produce to feed a slowly growing population with low living costs was relatively low. However, accelerated population increase led to breakdown of this system, so that continuous cultivation became common practice and with it soil fertility decline.

Stage III. Continuous cultivation, with crop rotation was introduced as a management system to maintain favorable soil conditions and satisfactory yields. In these rotations, a grain crop (wheat or barley) was often grown the first year, followed by a legume crop (faba bean or field pea) in the second year and a grain crop (barley or wheat) in the third year, and 1-2 years of fallowing after 5-7 years of continuous cultivation.

Stage IV. Recently, rapid population increase, which has resulted in very small holdings, has changed the situation. All the land, including marginal lands, which are heavily degraded and eroded, is used for rainfed cultivation with a rotation of 4-5 years of cereal crops, followed by a leguminous crop. Fallowing has almost completely been abandoned, much of the animal manure is used for household energy, all crop residues are collected from the field for livestock, and grazing lands are excessively overstocked. Levels of external inputs in the form of inorganic fertilizer and/or animal feed are very low. Thus, soil nutrients are rapidly depleted.

3.2 Farm scale analysis

Stocks and soil nutrient flows

Soil nutrient stocks per farm were defined as the total quantities of the macro-nutrients present in the top 20 cm of the soil profile, from where crops usually take up the major part of the nutrients (Van den Bosch et al., 1998; De Jager et al., 1998). These stocks include dissolved ions, nutrients in organic matter, adsorbed to the solid phase or in stable inorganic components. To assess the size of these stocks per farm for the macro-nutrients NPK, between 10 and 25 samples per farm have been analysed, depending on farm size and heterogeneity of its soils (Table 1).

Table 1. Organic carbon (OC), total nitrogen (TN), total P, available P (P-Olsen) and total K contents of the surface soil (0-20 cm) per farm group

Farm group	*OC (%)*	*TN (%)*	*Total P (ppm)*	*P-Olsen (ppm)*	*Total K (ppm)*
Rich	2.89	0.26	567.5	26.0	5372
Medium	1.95	0.17	500.2	19.3	4036
Poor	1.17	0.12	544.9	9.1	4311

Total biomass production and nutrient removal (both in absolute and relative terms) were higher from soils with higher total nitrogen contents (Table 2). Relative depletion rates were highest for N for all farm groups (but with varying rates, i.e., 2.4% for the rich, and 1.0% for both the medium and poor groups), followed by K and lowest for P for the medium and poor groups, whereas for rich farms, rates for P and K were the same.

Farm gate balances

Farming in Teghane is characterized by subsistence farming systems with small land holdings, simple farm technology, and low yields. Farm scale NPK flow analysis (Figure 3A) indicates that although the quantities of both exported and imported nutrients are small, imported nutrients from external sources into the farm are higher than nutrients exported to external destinations. Hence, for all farm groups the balances for all three macro-nutrients are positive, with higher values for the rich farms than for the medium and the poor farms ($P<0.05$).

Table 2. Nutrient stocks to a depth of 20 cm, calculated with average soil bulk density of 1240 kg m^{-3}, and rates of change in Teghane, Northern Highlands of Ethiopia, 2002

	Rich	Medium	Poor
Total N stock (kg ha^{-1})	3998	2614	1845
N-flows (kg ha^{-1} yr^{-1})	-96.0	-24.9	-18.3
N-flows (% of stock yr^{-1})	-2.4	-1.0	-1.0
Total P-stock (kg ha^{-1})	869	769	836
P-flows (kg ha^{-1} yr^{-1})	-11.3	-4.9	-1.3
P-flows (% of stock yr^{-1})	-1.3	-0.6	-0.2
Total K-stock (kg ha^{-1})	8620	6206	6629
K-flows (kg ha^{-1} yr^{-1})	-110.5	-42.1	-25.6
K-flows (% of stock yr^{-1})	-1.3	-0.7	-0.4

Inflows

For all three farm groups, inflows into the farm (Figure 3B) include chemical fertilizer, veterinary products, animal feed and salt, purchased grain and other food items, plus external food aid in the form of food for work for medium and poor farmers. Inflows of the inorganic fertilizers urea and diammonium phosphate (DAP), restricted to irrigated fields, were very small, i.e. 12.5 kg N and 4.4 kg P ha^{-1} for the rich; 10 kg N and 3.5 kg P ha^{-1} for the medium; and 8.2 kg N and 2.9 kg P ha^{-1} for the poor farm group, respectively.

Medium and poor farmers depended on external food aid, because grain production from their own fields was insufficient to meet the food requirements of the household. In total, 3 kg N, 0.9 kg P and 1.2 kg K ha^{-1} for the medium group, and 4.4 kg N, 1.4 kg P and 1.8 kg K ha^{-1} for the poor group, were imported in the form of wheat and sorghum. Rich farmers purchased "teff" (*Eragrostis tef*) from the market, after selling barley or wheat from their stock and/or live animals.

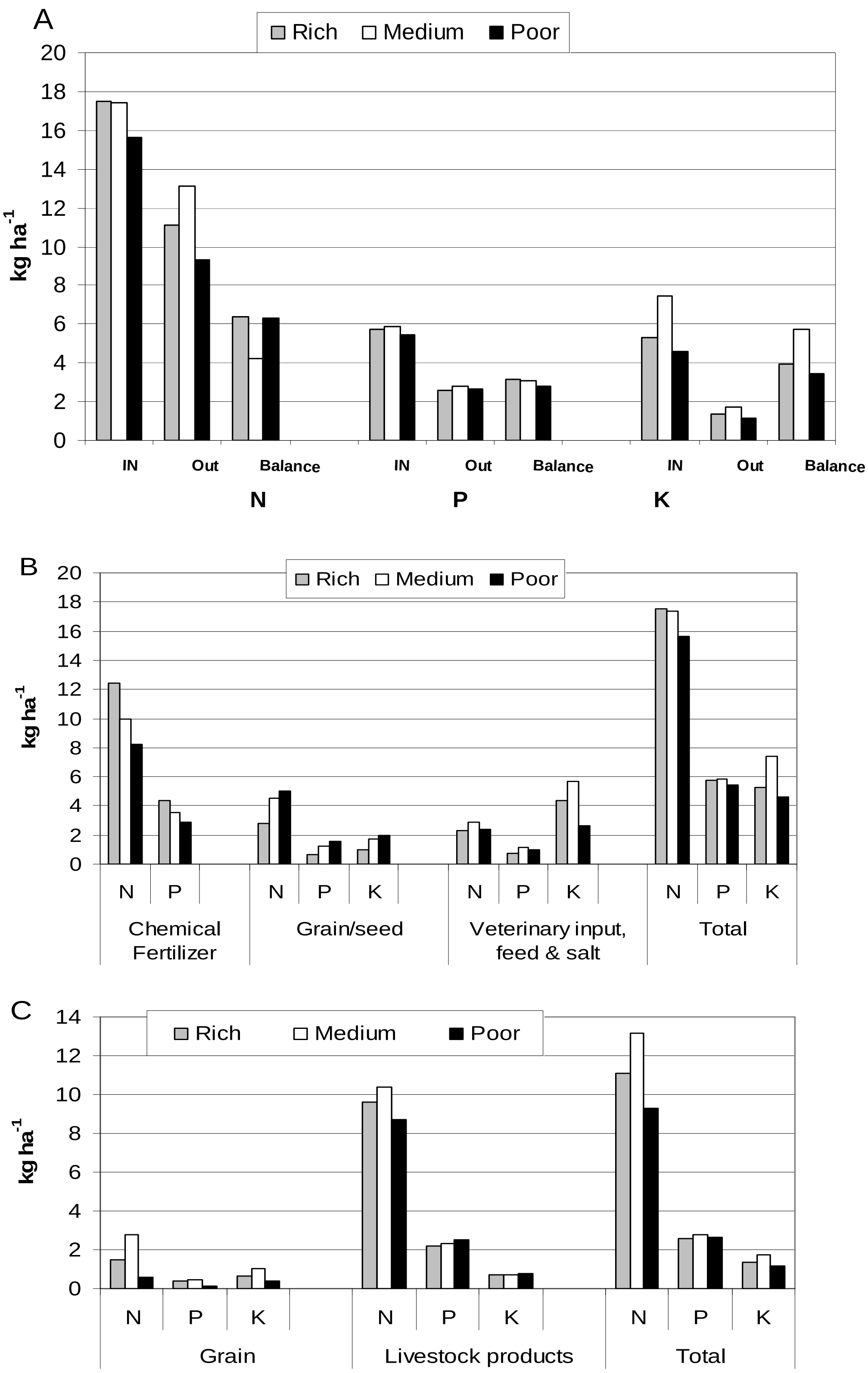

Figure 3. Farm gate NPK inflows, outflows and balances (A), inflows from external sources (B) and outflows to external destinations (C) (kg ha^{-1} yr^{-1}) per farm group

Outflows

Farm scale outflows consisted of grain from stock, live animals and livestock products, i.e. eggs, skins and hides (Figure 3C), sold as a source of cash to buy chemical fertilizer, food items and clothing, for school fees and materials, and for land tax. For all farm groups, the highest outflows are through live animals and animal products.

3.3 Farm field analysis

Farm field here is defined as the 'aggregated' arable and natural pasture fields. In the following Sub-sections (balances and flows) balances and flows are analyzed based on inputs "into" and outputs "from" cultivated fields and natural pastures, taking into account both external and internal transfers of NPK.

Balances

The balances of N, P and K showed negative values for all three farm groups (Figure 4), with higher values for the rich than for the medium and the poor farms ($p<0.05$). The major causes of these high rates of nutrient mining are very small land holdings, large families, large herds (with cattle dung mainly used for fuel) and very limited external inputs. Land is a very scarce resource with average holdings of 1.6, 0.9 and 0.6 ha per household, for the rich, the medium and the poor, respectively and household sizes of 8 members for the rich, 6 for the medium and 4 for the poor. Average herd sizes are large in relation to the available grazing resources (Chapter 4).

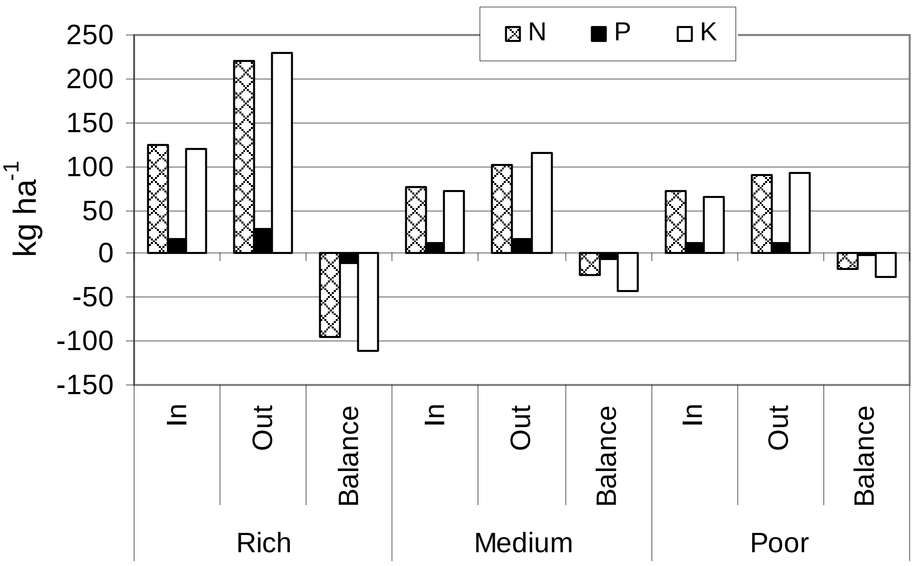

Figure 4. Partial NPK balances from farm fields per farm group (kg ha^{-1} yr^{-1})

Flows

Inflows of N, P and K were higher for the rich farms than for the medium and the poor ($P<0.05$). In all farm groups, inflows of nutrients into farm fields originated partly from internal transfers (IN2), comprising compost, animal excreta voided during grazing and grain/seeds from stock, and partly from external sources (IN1), i.e. purchased inorganic fertilizer and seeds. Internal transfers accounted for more than 90% of the total inflows for all wealth groups, however with vastly different absolute rates: 112.4, 14.7 and 119.8 kg ha^{-1} for N, P and K for the rich, 66.8, 10.1 and 69.9 kg ha^{-1} for the medium and 62.3, 9.4 and 64.8 kg ha^{-1} for the poor (Figure 5). Nutrient-saving techniques, such as soil and water conservation practices, were practiced more frequently by the rich group.

Animal excreta directly voided in the field provided the largest contribution for all farm groups (Figure 6): 93.6 kg N, 13.1 kg P and 107.2 kg K ha^{-1} for the rich, 51.5 kg N, 9.2 kg P and 60.6 kg K ha^{-1} for the medium and 48.7 kg N, 8.9 kg P and 54.9 kg K ha^{-1} for the poor group. Chemical fertilizer (urea and DAP) contributed only 5.6 - 12% to the total inputs.

Outflows of N, P and K were higher for the rich farms than for the medium and the poor farms ($P<0.05$). Removed crop products and animal feed (crop residues, grazed roughage/grass and removed weeds) comprised the main outflows of NPK from farm fields (Figure 7). In all fields of all farm groups, the largest outflow was through removal of grass/roughage and crop residues for animal feed.

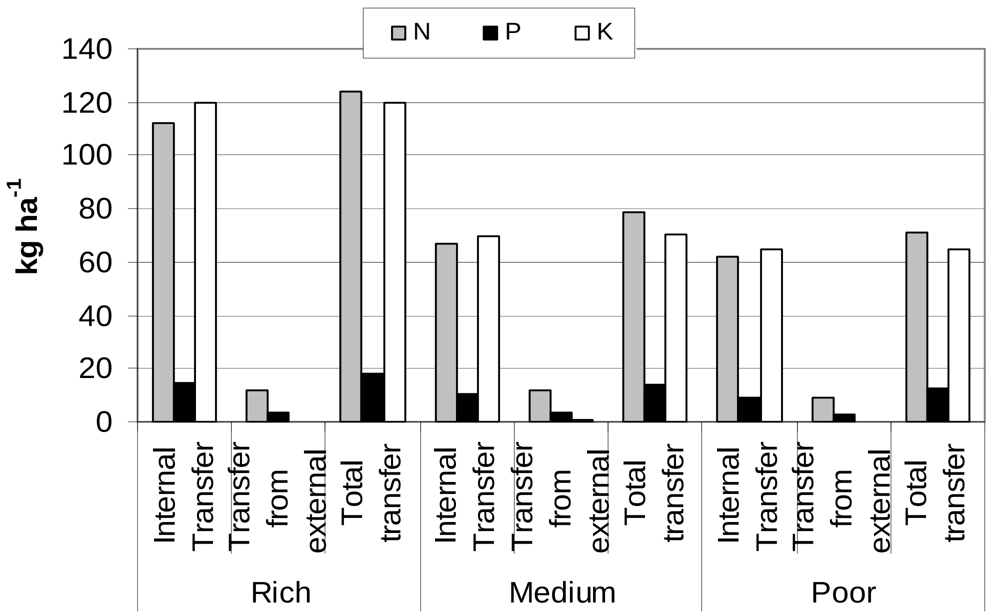

Figure 5. NPK transfers in farm fields per farm group (kg ha^{-1} yr^{-1})

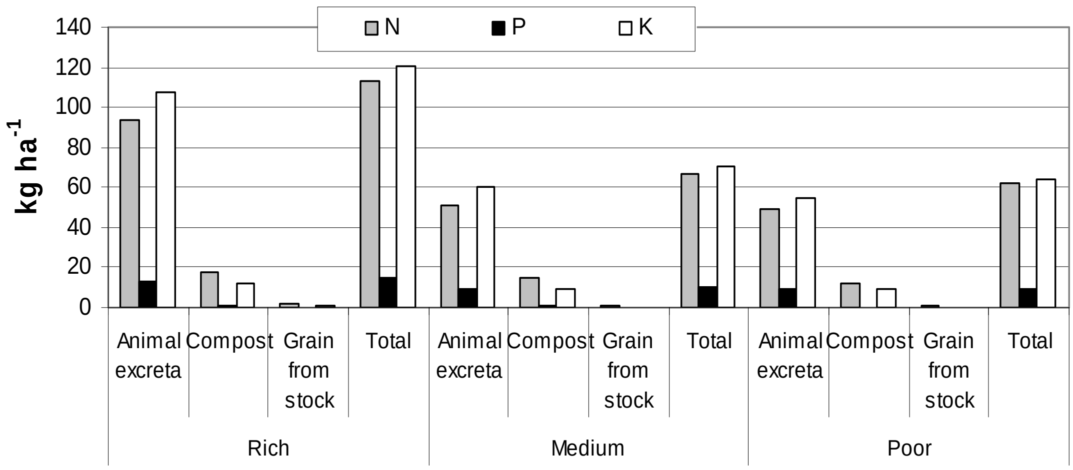

Figure 6. NPK internal transfers in farm fields per farm group (kg ha^{-1} yr^{-1})

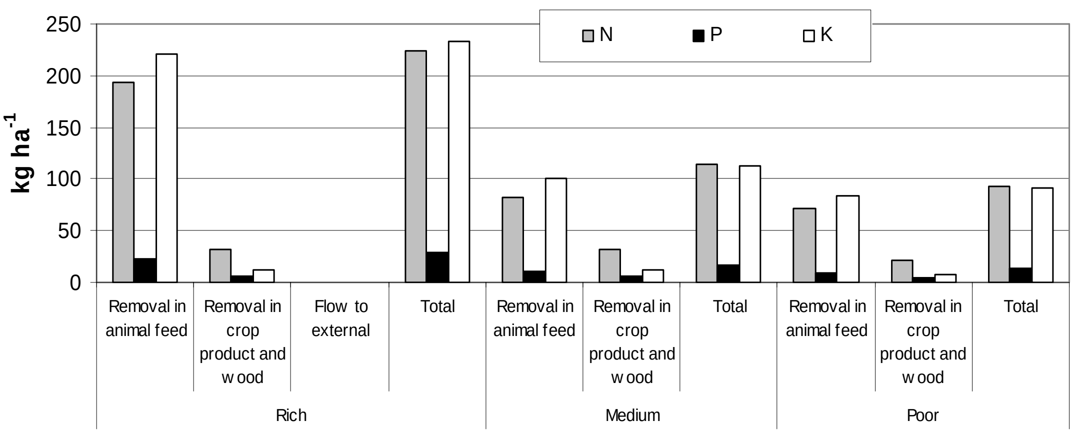

Figure 7. NPK removals from farm fields per farm group (kg ha^{-1} yr^{-1})

3.4 Field scale analysis/primary production units

Balances

The most important primary production units were barley, wheat, faba bean and pea and natural pasture. Grazing lands, including small pasture plots, borders of crop fields and areas around homesteads, are overgrazed and depletion rates were highest for all farm groups: -115 kg N, -5.8 kg P and -112 kg K ha^{-1} for the rich, -56.2 kg N, -42.5 kg K ha^{-1} for the medium and -56.5 kg N and -34.6 kg K ha^{-1} for the poor farms (Figure 8). For the latter two groups, P was almost in balance.

In barley fields, the highest negative balances were recorded for K: -112 kg ha^{-1} for the rich, -50.4 kg for the medium and -18.2 kg for the poor (Figure 8). The N balance was positive for the poor group (5.1 kg ha^{-1}) and negative for the rich (-81.9 kg ha^{-1}) and the medium groups (-8.7 kg ha^{-1}).

For wheat, all balances were negative for all farm groups (Figure 8). N balances for all fields were negative for the rich farm group with the lowest balance for faba bean and pea (-10.5 kg ha^{-1}). N balances for faba bean and pea were positive for the medium and poor farmers, with values of 4.0 and 20.3 kg ha^{-1}, respectively.

Flows

Stall-feeding is not practiced and nutrient outflows from grazing fields are through the removal of grass/roughage. During the dry season, March-July, a substantial proportion of the animals' ration consisted of prickly pear leaves. The only input to the grazing fields was animal excreta voided during grazing. Women and children collect part of the cattle excreta from the fields for household energy in the dry season (October-June), so that only during the wet season all animal excreta remain in the field.

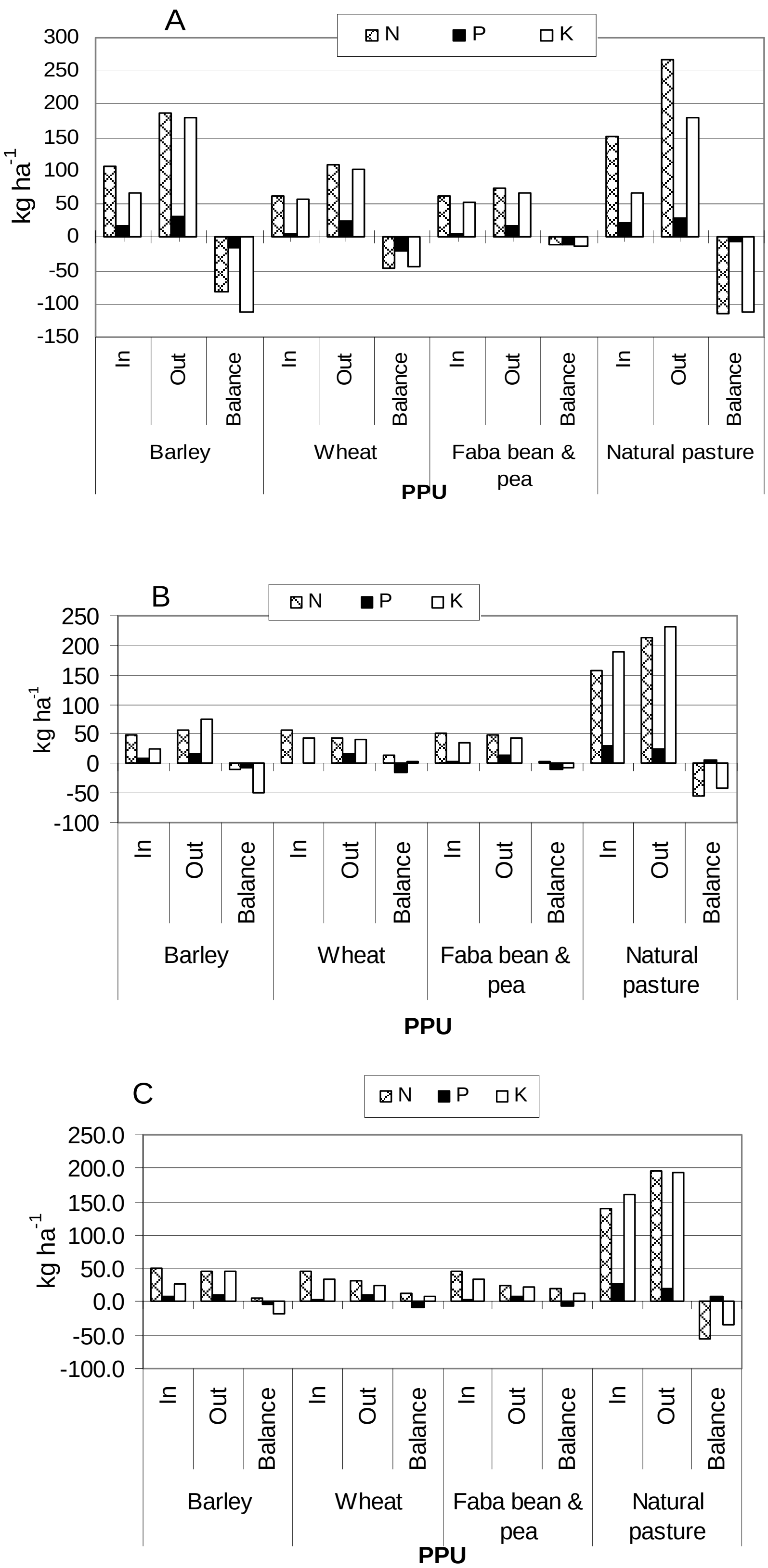

Figure 8. Average field scale NPK flows for rich farms (A), medium farms (B) and poor farms (C) kg ha^{-1} yr^{-1}

For barley fields, inputs consisted of compost, animal excreta, chemical fertilizer (in irrigated fields), and seed. For wheat, inputs included compost, animal excreta and seed. For faba bean and field pea, inputs consisted of compost, animal excreta, biological N fixation from the atmosphere, and seed. Removed grain, residues and weeds were sources of nutrient outflows from fields.

Significant quantities of the manure collected in the stable were used for household energy (Figure 9). The physical state of the stables and manure management in the stable led to some losses, i.e. 25.3 kg N, 5.8 kg P and 23.8 kg K ha^{-1} for the rich group, 25 kg N, 5.5 kg P and 33 kg K ha^{-1} for the medium group and 8.8 kg N, 2.4 kg P and 8 kg K ha^{-1} for the poor group. Compost is applied by spreading to the cultivated fields in the period from just after harvest (January) till sowing (end of June). The compost is not immediately incorporated in the soil, and, therefore, some of the N will be lost through volatilization. Compost is applied to cultivated land, irrespective of crop type, although, it was observed that fields with compost were mostly planted to barley and faba bean. As insufficient compost is available for all fields, some fields may not receive compost for 3 to 5 years.

All cattle, sheep, donkeys and chickens share the same stable at night. Stable floors consist of compacted soil, run under slope angles exceeding 10%, and have 2 to 5 urine drainage lines. Consequently, urine and manure do not mix, so that all nutrients in the urine are lost. Moreover, the stable is only partly covered, so that during the rainy season water flows through the accumulated manure and drains through the urine lines. Compost is stored in pits/heaps for long periods in the open, and after application to the field may again be exposed for extended periods before being worked in. This management leads to losses of the major part of the (inorganic) nitrogen from this material through volatilization and/or leaching.

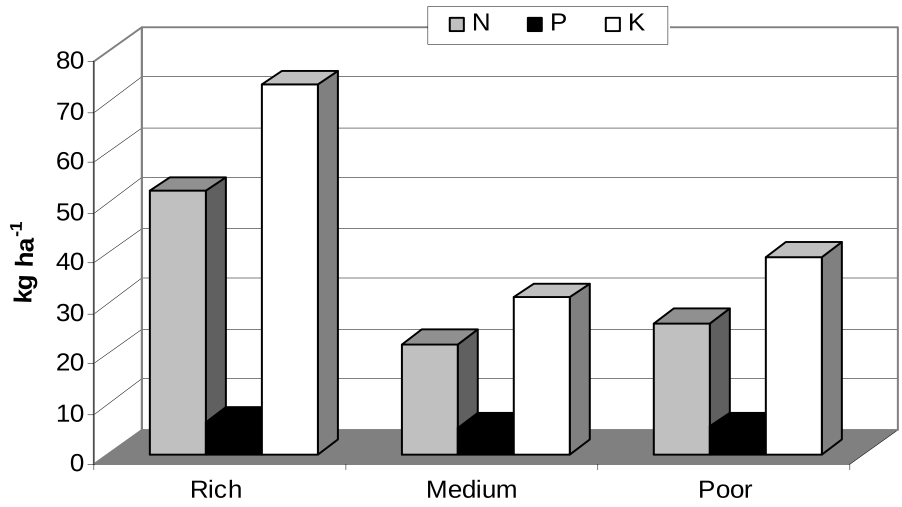

Figure 9. NPK contents of manure used for household energy per farm group (kg ha^{-1} yr^{-1})

4 Discussion and conclusions

In this study, the NUTMON software was applied to quantify and analyze nutrient flows and management at field and farm scale. Although the method performed satisfactorily for use at farm scale in Ethiopia, it needed some modification. First, in Ethiopia most of the manure from the livestock sub-system (stable and grazing fields) is transferred to the household subsystem of the farm as a source of household energy. This process was not captured in the NUTMON methodology. Second, NUTMON underestimates farm scale nutrient outflows in two ways: a) all nutrients transferred to household/stock and livestock from cultivated and grazed fields in the form of grain and residues/roughage are retained in the system without loss. In reality, almost all nutrients transferred to the household and part of the nutrients transferred to livestock are not recycled, as they are used for growth of animals and the household members and eventually will be exported out of the farm, b) flows of nutrients out of the livestock sub-system through sales or when they die or are consumed by the household are not considered. Modifications in the size of the livestock sub-system (birth, death, sales, transferred and consumed) are only considered in the financial analysis.

Analyses at PPU and farming field scale of partial macro-nutrient (NPK) balances in Teghane, in the Northern Highlands of Ethiopia indicate that soil nutrient depletion proceeds at an alarming rate at both ‘farm field’ and plot scales. This soil mining is associated with increasing population pressure, which has led to very small land holdings. Thus, the only option for farmers is to exploit their farmland to the maximum to feed the family and the livestock, and satisfy household energy requirements as much as possible. Animal feed is extremely scarce and hence, every piece of crop organic matter, including roots and weeds, are collected from the farm fields at harvesting time (de Ridder et al., 2004). Moreover, from immediately after harvest till first ploughing, animals graze the cultivated land, so that hardly any plant remains are recycled in cultivated fields.

Nutrient depletion rates differ significantly among different farmer wealth groups. The highest rates were recorded for the rich farm group, followed by the medium and poor farm groups. These differences are associated with the differences in crop production, i.e., higher crop production by rich farm group, followed by the medium as the result of two causes. First, chemical and physical soil fertility of the cultivated fields of the rich is generally higher. Secondly, they implement more frequently nutrient-saving techniques, such as soil and water conservation practices and apply more external and internal inputs. These farmers better prepare their land, seed on time, practice timely weeding, all of which require higher labor inputs. On the other hand, the low rates of depletion in the poor farm group are partly associated with low crop production, due to low indigenous soil fertility, low inputs and poor crop management.

The results indicate that significant quantities of manure are used for household energy supply, equivalent to 52.3, 21.9 and 26 kg N ha^{-1} yr^{-1}, respectively by rich, medium and poor farmers. In addition, due to inappropriate management of manure in the stable and the compost heap, significant losses take place, averaging 25.3 kg N, 5.8 kg P and 23.8 kg K ha^{-1} $year^{-1}$ for the rich group, 25 kg N, 5.5 kg P and 33 kg K ha^{-1} for the medium group, and 8.8 kg N, 2.4 kg P and 8 kg K ha^{-1} for the poor group.

It may be concluded thus, that there is a need for development of integrated nutrient management systems. Two major processes restrict the efficiency of nutrient recycling through manure. First, a substantial proportion of the manure, both from the stable and from the grazing land is used for household energy. Although during burning, the major part of the nitrogen is lost, phosphorus and potassium are to a large extent retained in the ashes. However, for cultural reasons, only a small proportion of the ashes is recycled. Second, manure/compost management is far from optimal. Hence, improvements in nutrient use efficiency from manure could be attained through judicious manure management. First, it must be carefully stored to minimize physical loss of manure/compost, and its nutrients and it must be applied to the appropriate crop with the appropriate method at the proper time. Second, introduction of energy-saving stoves so that more manure, now used for household energy, can be applied to farming fields. On top of these, conditions should be created to make application of external inorganic fertilizer more attractive (Breman et al., 2001; Breman and Debrah, 2003). This could lead to application of more external chemical fertilizer in both irrigated and rainfed fields, combined with expansion of moisture harvesting for supplementary moisture supply.

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Chapter 3

QUEFTS for fertilizer management for barley in three soils of the Northern Highlands of Ethiopia

To be submitted

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QUEFTS for fertilizer management for barley in three soils of the Northern Highlands of Ethiopia

Abstract

So far, application of fertilizer to mitigate problems of nutrient-limited yields in farmers' fields in the Highlands of Ethiopia has been based on conventional blanket fertilizer recommendations, without taking into account indigenous soil nutrient supply. Moreover, though in some soil fertility studies, indigenous nutrient availability is considered, different nutrients are treated separately and fertilizer recommendations are usually based on the most limiting nutrient, ignoring the interactive effects among nutrients. In this study, the QUEFTS (**QU**antitative **E**valuation of the **F**ertility of **T**ropical **S**oils) model, that takes into account indigenous soil nutrient supply, internal nutrient use efficiency at maximum nutrient accumulation and dilution, actual uptake and recovery fractions of applied fertilizers, has been parameterized and calibrated for barley in the Northern Highlands of Ethiopia. For parameterization and calibration, we carried out factorial field experiments with application rates of N (0, 25 and 50 kg ha^{-1}), P (0, 25, 50 and 75 kg ha^{-1}) and K (0, 25 and 50 kg ha^{-1}) in three replicates in four fields. The constants for maximum accumulation and dilution, kg grain kg^{-1} N (34 and 52), P (182 and 365), and K (44 and 127), coefficients for estimation of potential supply of N, P and K, respectively, q = 6.0, r = 0.55, and s = 166, and maximum recovery fractions 0.5, 0.2 and 1.0, respectively for N, P and K were estimated as standard parameters for the QUEFTS model and then applied to calculate balanced rates of fertilizer for barley in the Northern Highlands of Ethiopia on the basis of soil OC content, exchangeable K, and P-Olsen.

Additional key words: Nutrient-limited yield; indigenous soil nutrient supply; internal nutrient use efficiency; agronomic efficiency

1 Introduction

Barley is one of the most important food crops in the Highlands of Ethiopia, occupying about 12% of the total area of major cereal crops and accounting for 10% of the total annual cereal production in 1999 (ICARDA, 2003). In the Northern Highlands, barley grain is used for the preparation of various traditional dishes, such as "injera", "kita", "kolo" and "besso" and local drinks, such as "tela" and beer. The straw is used as animal feed, especially during the dry season. Barley yields are stagnant or declining in many parts of the highlands of Ethiopia (ICARDA, 2003), which could be the result of a decline in the natural supply of one or more crop nutrients. On the other hand, population is growing at an annual rate of 2.7% (IRIN, 2003) and land holdings in the area are less than 2 ha per household (Assefa et al., Chapter 5). Consequently, for much of the last decade the people were food-insecure and dependent on external food aid (USAID, 2004). To increase production of cereal crops, increased use of chemical fertilizers has been suggested (Asnake Woldeab et al., 1991, Amsal Tarekegne et al., 1997), of which expensive imported N and P are the two most widely used (Gezahegn Ayele and Tekalign Mamo, 1995). Inefficient use of these expensive nutrients contributes to the depletion of scarce financial resources, increased production costs and potential environmental risks (Amsal Tarekegne and Tanner, 2001).

Currently, 100 kg DAP (21 kg P and 18 kg N) and 100 kg urea (46 kg N) ha^{-1} are being used for barley and other cereal crops in the Northern Highlands of Ethiopia (Mulat Demeke et al., 1997). Such a blanket recommendation does not do justice to the differences in agro-ecological environments, indigenous soil nutrient supplies and crop specifications. Refinement of fertilizer recommendations is required in Ethiopia. Farmers' practice is heavily biased towards one type of fertilizer, mainly DAP, and this may cause unbalanced nutrient supply and jeopardize the efficiency of utilization of fertilizers (Mulat Demeke et al., 1997). Moreover, most site-specific methods for evaluation of soil fertility and nutrient requirements address a single nutrient, without taking into account that uptake of one nutrient partly depends on the availability of other nutrients (Smaling, 1993). For example, uptake of N appears to be strongly affected by application of P fertilizer, especially in soils with low P-Olsen values (Penning de Vries and van Keulen, 1982; Janssen et al., 1990). At low P-availability, only a fraction of the potentially available N is taken up by the crop (Smaling, 1993). In soils low in available N, uptake of P was stimulated by N-fertilizer application (Kamprath, 1987) through decreasing rhizosphere pH and increasing solubility of soil phosphates, stimulating root growth and root physiological capacity. Moreover, water use efficiency, i.e., the amount of dry matter produced per unit of water consumed increases with increasing nitrogen availability (van Keulen and Seligman, 1987). In general the N:P-ratio in plant tissue varies within a relatively narrow range, so that deficiency of one element may restrict uptake of the other (Penning de Vries and van Keulen, 1982). K application may increase yields considerably, particularly in fields where crop residues are removed under continuous cropping (Smaling, 1993). Conversely, optimal supply of moisture, N and P leads to increased yield responses to K fertilizer. Smaling (1993) criticized the attempts to link crop yields to the supply and uptake of a single nutrient, thus ignoring the evident interactions among nutrients.

Hence, for formulation of more accurate fertilizer recommendations, a more generic nutrient balance method is required that considers both, site-specific indigenous soil nutrient supply and interactions of nutrients. For that purpose, the QUEFTS (**QU**antitative **E**valuation of the **F**ertility of **T**ropical **S**oils) model, developed by Janssen et al. (1990), has been calibrated for barley in the Northern Highlands of Ethiopia. The sensitivity of the calibrated model coefficients and effects of variations in input variables have been tested.

2 Materials and methods

2.1 Background to the QUEFTS model

QUEFTS was developed on the basis of theoretical considerations and empirical relationships between soil fertility and yield (Janssen et al., 1990). The model was originally developed for estimation of fertilizer requirements and grain yields for tropical maize (Smaling and Janssen, 1993), and has been applied to other crops by calibrating basic parameters of the model related to specific crop nutrient requirements and indigenous soil nutrient supply (wheat in India: Pathak et al., 2003; rice in tropical Asia: Dobermann and White, 1999; Witt et al., 1999).

The central assumption of the model is that crop yield is a function of indigenous N, P and K supply and the rate of applied fertilizer, taking into account the site- and variety-specific potential yield of a crop. The model comprises four steps: (i) quantification of the potential supply of indigenous soil N (SN), P (SP) and K (SK), derived from soil chemical data or from grain yield measured in on-farm nutrient omission plots (Dobermann and White, 1999; Janssen et al., 1990); (ii) estimation of the actual uptake of the nutrients by the crop ((UN), (UP) and (UK)), as a function of indigenous supply plus the effective supply of a nutrient from applied fertilizer, derived from the fertilizer recovery; (iii) estimation of three possible yield ranges, one each for N, P and K, as a function of actual uptake of the nutrient and the cultivar-specific potential yield (Ymax) at a given site. The lower value refers to maximum accumulation (in the situation where the nutrient is abundantly available and one of the other two nutrients is yield-limiting: YNA, YPA, YKA), the upper value to maximum dilution (in the situation where the nutrient is yield-limiting and the other two nutrients are abundantly available: YND, YPD, YKD). The yield potentials can be derived from representative data sets from on-farm experiments (Dobermann and White, 1999; Janssen et al., 1990); (iv) combining of pairs of yield ranges and estimation of the final yield as the average of the yields for paired nutrients (Janssen et al., 1990; Smaling and Janssen, 1993). The four steps are described in detail in Janssen et al. (1990).

2.2 The study area

Location

Teghane is located in Atsbi-Wonberta district, Tigray Regional State, Northern Highlands of Ethiopia, about 850 km north of Addis Ababa, the capital. It is situated between 13^0 52' 53" and 13^0 53' 37" N and between 39^0 42' 05" and 39^0 43' 57" E. The study area covers about 13.56 km^2 and its altitude ranges from 2710 to 2899 meter above mean sea level.

Soil data

In February 2003, soils of Teghane were surveyed to determine their characteristics for biophysical modelling work. Following the toposequence survey method, nine representative soil pits have been opened and described following the FAO-UNESCO (1990) guidelines. From each profile, samples were taken for laboratory determination of physico-chemical properties. The samples were bulked for each soil type and analysed either at the National Soil Research Center (NSRC), Addis Ababa or the International Livestock Research Institute (ILRI), Addis Ababa.

Soils of the study area were identified as Cambisols, Luvisols and Leptosols (FAO-UNESCO, 1990). Cambisols, covering 26% of the area, are intensively cultivated. They are located on the colluvial terrace slopes. Luvisols, also covering 26% of the area, are located in the valley bottom or flood plain. They are relatively deep, with favourable physical and chemical characteristics. Traditionally, these soils were under grassland, but in recent years a significant proportion has been transformed to arable land in response to the shortage of land for food crop production. Leptosols, covering 46% of the area, are located on the elevated plateau and on hill slopes, crests and ridges, interspersed with rock outcrops and patches of Luvisols. They are formed from sandstone sedimentary rock of the Mesozoic formation, which overlies Precambrian rocks on plateau and meta-volcanic material on hills, crests and ridges (Kazmin, 1975). They are limited in depth to about 25 cm by underlying continuous hard sedimentary rock, or contain less than 20 percent fine particles to a depth of 75 cm (FAO-UNESCO, 1990). These soils are degraded and eroded and characterized by coarse textures, low nutrient contents and low moisture holding capacity and therefore hardly used for crop production.

Farming systems

Mixed crop-livestock farming is the dominant agricultural system in Teghane. In the 2002-2003 cropping season, barley (*Hordeum* spp.) and wheat (*Triticum* spp.) were the two major crops, grown respectively on about 69% and 16% of the cultivated fields (Assefa et al., Chapter 5). "Gunaza" (six row barley), "Sasa" and "Brguda" are the most common varieties of barley. Field pea (*Pisum* spp.) and faba bean (*Vicia* spp.) are the next important crops. Most of the grazing lands are on Luvisols in the valley bottom, where temporary water logging is a serious problem for cultivation of food crops in the rainy cropping season. Marginal fields on rock outcrops with patches of Leptosols are either under open woodland or in use as homestead.

2.3 Crop management and data

Four fields, two each on Luvisols and Cambisols, designated Cambisol-1, Cambisol-2, Luvisol-1 and Luvisol-2, have been selected for field experimentation in the 2003 cropping season. Leptosols were excluded because QUEFTS is applicable to deep and well-drained soils (Janssen et al., 2001). The two Cambisol fields and Luvisol-1 had been under continuous cultivation for over 50 years, while the Luvisol-2 field had been under grazing until seven years ago. In early July 2003 just before sowing, from each field, composite soil samples from the 0-20 cm surface layer were collected, as well as from 22 farm fields, for laboratory analyses: Organic Carbon (Walkley and Black, 1947), available P (Olsen et al., 1954), exchangeable K (Thomas, 1982), and soil pH-H_2O (1:2 soil:water ratio). Soil chemical characteristics of the experimental fields are presented in Table 1.

Table 1. Chemical characteristics of experiment fields (2003) in Teghane, Northern Highlands of Ethiopia

Soil unit	OC (g kg^{-1})	P-Olsen (mg kg^{-1})	Exch. K (mmol kg^{-1})	pH (H_20)
Cambisol	11.0	7.0	15.0	6.4
Luvisol-1	19.0	5.0	2.0	6.5
Luvisol-2	37.0	6.0	15.4	6.4

The trials were planted on a gross plot size of 2.75 x 2.75 m. Host farmers prepared the trial plots using the traditional ox-plowing practice. The treatments were laid out in a complete randomized design, replicated three times with three nutrients (three rates for N and K (0, 25, 50 kg ha^{-1}) and four rates for P (0, 25, 50 and 75 kg ha^{-1})). All P (triple superphosphate) and K (potassium chloride) were applied as basal dressing at sowing, while the N (urea) was split: one-half applied at sowing and the other half at early booting. Topdressing of N was combined with supplementary irrigation. In all fields, the local barley variety "Gunaza" was sown at a rate of 120 kg ha^{-1} on July 18 and harvested on November 17.

Hand weeding was used to control weeds. At physiological maturity, a net area of 2.5 x 2.5 m was harvested at ground level with a sickle. The harvested plants were air-dried and weighed to determine aboveground dry matter. Grain was separated from straw manually and weighed to determine grain yield. Harvest index was calculated by dividing grain yield by total aboveground biomass. Cambisol-2 was excluded from the analysis, because it was affected by erosion. From the 22 farmers' fields, yields were estimated in the same way and included in the analysis. Samples (both grain and straw) were analyzed for N, P and K.

From the experiment, N, P and K mass fractions were determined in 216 (3 x 72) grain samples (GN, GP and GK, respectively) and 108 (36 x 3) composite (from identical treatments) straw samples (NSt, PSt and KSt, respectively). Nutrient contents in grain (NGU, PGU and KGU) and straw (NStU, PStU and KStU) were calculated by multiplying grain and straw yields by their respective N, P and K concentrations and total uptake (TNU, TPU and TKU) calculated. N (NHI), P (PHI) and K (KHI) harvest indices were calculated as the ratios NGU/TNU, PGU/TPU and KGU/TKU, respectively, and expressed as percentages. Grain yields and total nutrient uptake were subjected to analysis of variance (ANOVA).

2.4 Model calibration

For model calibration, we: i) carried out soil chemical analyses (OC, total nitrogen, P-Olsen and exchangeable K) for estimation of indigenous soil nutrient supply (kg ha^{-1}), ii) carried out factorial experiments by considering the range of current fertilizer application practices in the Northern Highlands of Ethiopia, iii) estimated maximum recovery fraction of applied fertilizer, iv) estimated grain yield per kg N, P and K at maximum accumulation (YNA, YPA, YKA) and maximum dilution (YND, YPD, YKD) for the fertilizer rates under consideration, and v) estimated potential yield of barley.

Next, soil chemical data were related to total nutrient uptake in the aboveground plant dry matter to calculate the coefficients[1] of eqns. 9a-9c of q, r and s for estimation of SN, SP and SK, respectively.

$$q = \frac{1}{m}\sum_{y=1}^{m}\frac{1}{OC_m}\left(\frac{1}{n}\sum_{x=1}^{n}TNU_{yx}\right) \qquad (1)$$

where,

TNU : total N uptake (kg ha^{-1}) in aboveground plant DM at maturity in treatments $P_{50}K_{25}$, $P_{50}K_{50}$, $P_{75}K_{25}$, $P_{75}K_{50}$ without N fertilizer.

OC : organic carbon contents of the soil (g kg^{-1})

y : soil type 1, …, m

x : treatment 1, …, n

$$r = \frac{1}{m}\sum_{y=1}^{m}\frac{1}{P - Olsen_m}\left(\frac{1}{n}\sum_{x=1}^{n}(TPU - PSOC)_{yx}\right) \qquad (2)$$

where,

PSOC : potential supply of P from organic carbon and defined as O.35*OC (Janssen et al., 1990)

TPU : total P uptake (kg ha^{-1}) in aboveground plant DM at maturity in treatments $N_{25}K_{25}$, $N_{25}K_{50}$, $N_{50}K_{25}$, $N_{50}K_{50}$ without P fertilizer. In this analysis data of Luvisol-1 and Luvisol-2 were used because in these soils P-Olsen is relatively lower than that of Cambisol, so that P is supposed to be maximally diluted in these soils with the application of the other nutrients. $N_{50}K_{25}$ of Luvisol-2 is excluded because its value was higher compared to the other treatments under consideration, may be due to micro-heterogeneity of treatments.

$$s = \frac{1}{m}\sum_{y=1}^{m}\frac{1}{v_m}\left(\frac{1}{n}\sum_{x=1}^{n}TKU_{yx}\right) \qquad (3)$$

[1] Calculation of the coefficients of q, r and s is presented in Appendix A

where,

v : exch.K/(2+0.9*OC) (Janssen et al., 1990).

TKU : total K uptake (kg ha^{-1}) in aboveground plant DM at maturity in treatments $N_{25}P_{25}$, $N_{25}P_{50}$, $N_{25}P_{75}$, $N_{50}P_{25}$, $N_{50}P_{50}$, $N_{50}P_{75}$ without K fertilizer.

Exch.K : soil exchangeable K (mmol kg^{-1})

The recovery fraction of applied nutrient ($Nre_{(x)}$) was calculated as:

$$Nre_{(x)} = (TU_{(xf)} - TU_{(x0)})/ Fr_{(x)} \qquad (4)$$

where,

$TU_{(xf)}$: average total nutrient uptake (kg ha^{-1}) from treatments receiving a dose $Fr_{(x)}$

$TU_{(x0)}$: average total nutrient uptake (kg ha^{-1}) from the control (zero-fertilizer) treatments

$Fr_{(x)}$: rate of fertilizer application (kg ha^{-1})

$_{(x)}$: nutrient under consideration (N, P or K)

Grain yield per unit nutrient (x) uptake at maximum accumulation of that nutrient ($Y_{(x)}A$, kg kg^{-1}(x)) was calculated as:

$$Y_{(x)}A = GY_{(x)}A/TU_{(x)}a \qquad (5)$$

where,

$GY_{(x)}A$: grain yield (kg ha^{-1}) at maximum application rate of nutrient (x) and omission of the other two nutrients

$TU_{(x)}a$: total nutrient uptake in aboveground plant DM (kg ha^{-1}) at maximum application rate of nutrient (x) and omission of the other two nutrients

Grain yield per unit nutrient (x) uptake at maximum dilution of that nutrient ($Y_{(x)}D$, kg kg^{-1} (x)) was calculated as:

$$Y_{(x)}D = GY_{(x)}D/TU_{(x)}d \qquad (6)$$

where,

$GY_{(x)}D$: grain yield (kg ha^{-1}) from treatments receiving no nutrient (x) (and the maximum rates of the other two nutrients)

$TU_{(x)}d$: total nutrient uptake in aboveground plant DM (kg ha^{-1}) from treatments receiving no nutrient (x) (and the maximum rates of the other two nutrients).

Internal nutrient use efficiencies (INue, kg grain kg^{-1} nutrient) were calculated as:

$$INue = GY/TU \qquad (7)$$

where,

GY : grain yield (kg ha^{-1})

TU : total nutrient uptake (kg ha^{-1}) in aboveground plant DM at maturity

Agronomic efficiency (AE, kg grain kg^{-1} applied fertilizer) was calculated as:

$$AE = (GY_{(xr)} - GY_{(c)})/R_{(xr)} \qquad (8)$$

where,

$GY_{(xr)}$: grain yield (kg ha^{-1}) of treatment receiving fertilizer nutrient x at rate r

$GY_{(c)}$: grain yield (kg ha^{-1}) of the control treatment

$R_{(xr)}$: rate of fertilizer (x) application (kg ha^{-1})

Potential yield (Ymax) of barley (8.5 Mg ha^{-1}) for the area was estimated with the **S**imple and **U**niversal **CRO**p growth **S**imulator (SUCROS) model (van Laar et al., 1997), on the basis of average long-term temperature and solar radiation and appropriate crop parameters (van Heemst, 1988).

3 Parameterization, calibration and evaluation of the model

3.1 Potential indigenous soil N, P and K supply

Equations in the calibrated QUEFTS model for estimation of potential indigenous soil N, P and K supply are:

$$SN = q * \text{organic carbon (g kg}^{-1}) \qquad (9a)$$

$$SP = 0.35 * OC\ (g\ kg^{-1}) + r * \text{P-Olsen (mg kg}^{-1}) \qquad (9b)$$

$$SK = (s * \text{exch. K (mmol kg}^{-1}) / (2 + 0.9 * OC\ (g\ kg^{-1})) \qquad (9c)$$

Where q, r and s are 6.0, 0.55 and 166, respectively, computed by eqns. 1-3 and Appendix A.

3.2 Grain yield and actual uptake of N, P and K

3.2.1Grain yield

Cambisol

In the Cambisol, GY varied between 2.61 ($N_0P_0K_{25}$) (Figure 1) and 4.87 ($N_{50}P_{75}K_{50}$) Mg ha^{-1}. Yields for all treatments differ from that of the control ($P<0.05$), except for $N_0P_0K_{25}$, $N_0P_0K_{50}$ and $N_{25}P_0K_{25}$. Moreover, yields at K_{25} and K_{50} were not significantly different at N_{25} and N_{50} and at P_{25}, P_{50} and P_{75} ($P<0.05$) (Figure 3). This implies that in the unfertilized situation, barley yield is not limited by indigenous K-supply. Mean yield of treatment $N_0P_{50}K_0$ (4.1 Mg ha^{-1}) is higher than that of treatment $N_{50}P_0K_0$ (3.3 Mg ha^{-1}) ($P < 0.05$) (Figure 1), suggesting that for Cambisol P is the most limiting nutrient, followed by N. The 'best' (in terms of grain yield) combinations in the experimental treatments were (not significantly different at $P<0.05$) $N_{50}P_{75}K_{25}$ (4.78 Mg ha^{-1}) and $N_{50}P_{75}K_{50}$ (4.87 Mg ha^{-1}).

Luvisol-1

In Luvisol-1, GY varied between 1.82 (control) and 4.52 ($N_{50}P_{75}K_{50}$) Mg ha^{-1}. Yields for all treatments are different from that of the control ($P < 0.05$), except for $N_{25}P_0K_{0,}$ $N_0P_{25}K_0$ and $N_{50}P_0K_0$ (Figure 1). Yield response is increasing with increasing rates of K fertilizer. Yields do respond to N and P fertilizers, though less than to K fertilizer (Figures 1 - 3). The response to P fertilization is stronger than to N fertilization. Thus, in this soil the most limiting nutrient is K, followed by P. The 'best' combinations for this soil were (not significantly different at $P<0.05$) $N_{25}P_{50}K_{50}$ (4.42 Mg ha^{-1}) and $N_{50}P_{75}K_{50}$ (4.52 Mg ha^{-1}).

Luvisol-2

In Luvisol-2, GY varied between 5.22 (at $N_{25}P_0K_0$) (Figure 1) and 8.00 (at $N_{50}P_{50}K_0$) Mg ha^{-1} (Figure 2). Because of lodging, the yield at $N_{25}P_0K_0$ was lower than that of the control. Only yields of the P_{50} and P_{75} treatments are higher than the control yield ($P<0.05$). This implies that in this soil, barley yield in the unfertilized situation is not limited by indigenous N and K supplies.

3.2.2 Recovery fraction

The N-recovery fraction varied between 0.39 in Luvisol-2 and 0.49 in Cambisol. The recovery fraction of P was between 0.08 in Luvisol-1 and 0.20 in Luvisol-2.

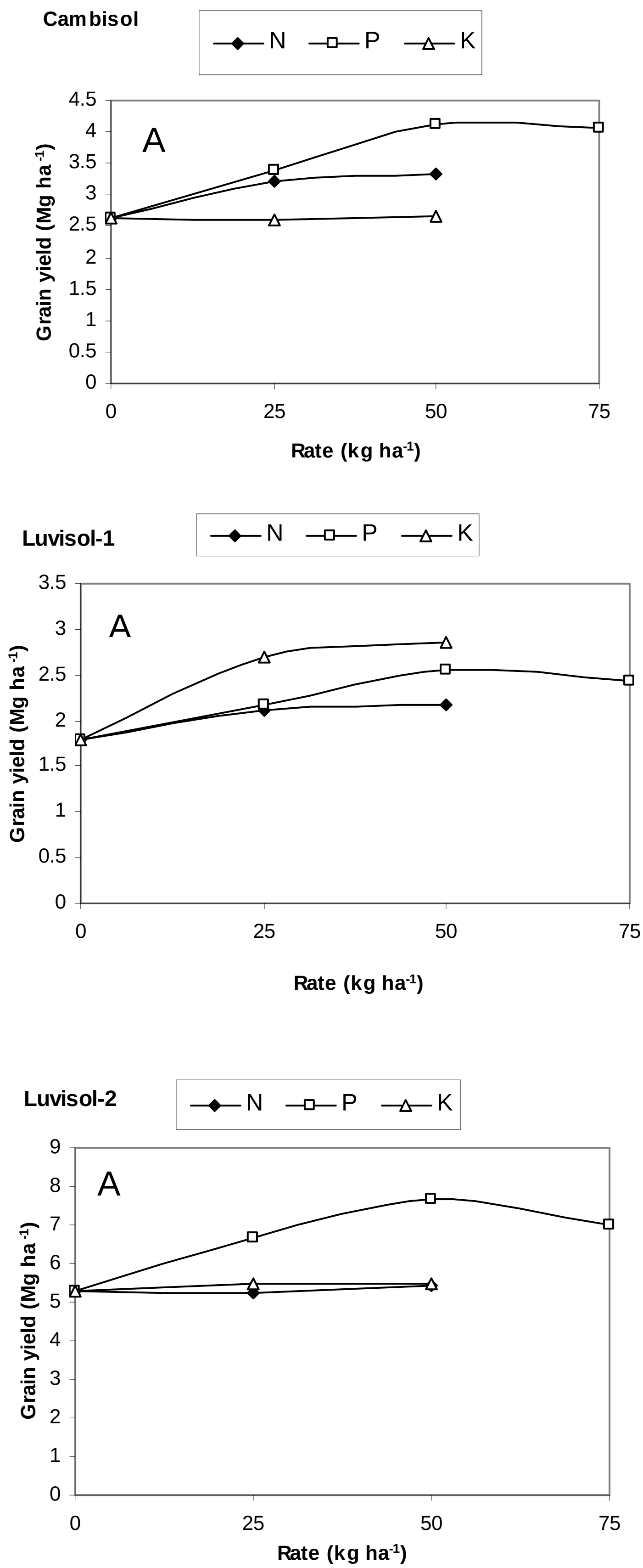

Figure 1. Grain yield in relation to fertilization rate of N, P and K.

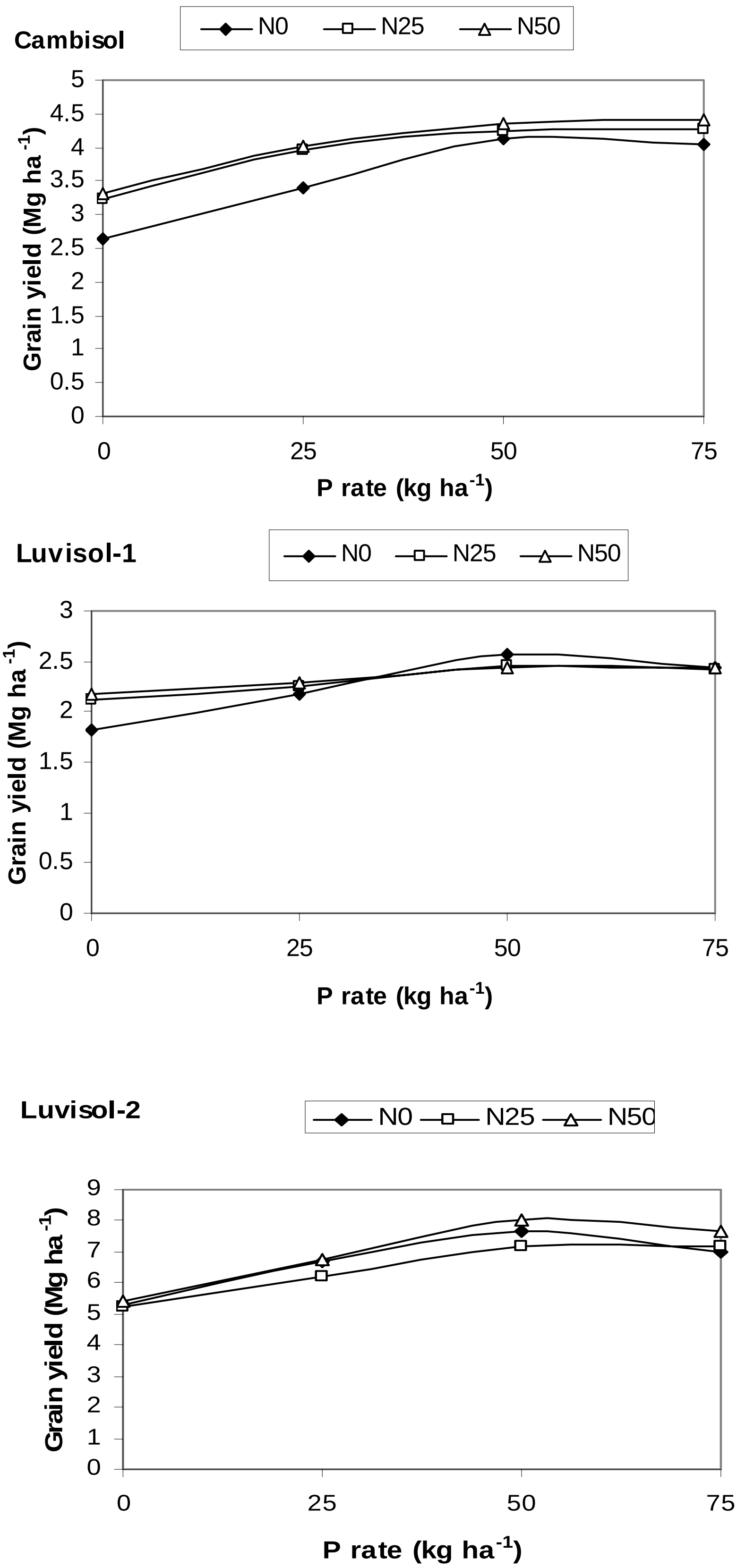

Figure 2. Grain yield in relation to fertilizer P for three levels of N fertilizer

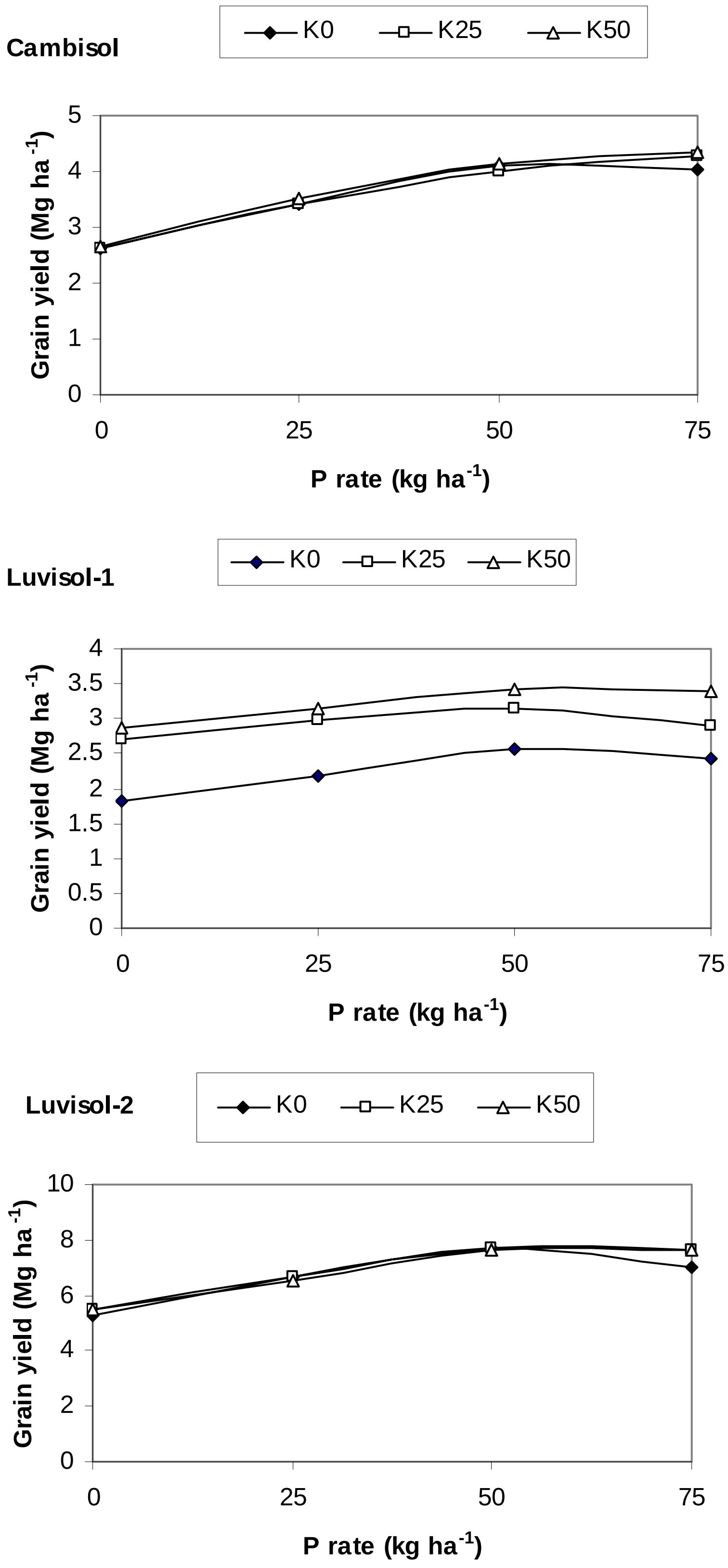

Figure 3. Grain yield in relation to fertilizer P for three levels of K fertilizer

The recovery fraction of K was between 0.57 in Luvisol-1 and 1.0 in Luvisol-2. Therefore, in the model for barley in the Northern Highlands of Ethiopia, maximum recovery fractions of 0.5, 0.2 and 1.0 have been selected for N, P and K, respectively.

3.2.3 Internal efficiency, agronomic efficiency and grain yield at maximum accumulation and maximum dilution

Internal efficiency

Average internal nitrogen use efficiency (Table 2) was higher in the Cambisol (43) than in Luvisol-1 (41) and Luvisol-2 (40) ($P<0.05$). Average internal phosphorus use efficiency was higher in Luvisol-1 (268) than in Luvisol-2 (254) and in the Cambisol (243) ($P<0.05$). Average internal potassium use efficiency was much higher in Luvisol-1 (89) than in Cambisol and Luvisol-2 (each 63) ($P<0.05$).

Agronomic efficiency

Average agronomic nitrogen efficiency (Table 3) was higher in the Cambisol (57) than in Luvisol-2 (44) and Luvisol-1 (35) ($P<0.05$). Average phosphorous agronomic efficiency was higher in Luvisol-2 (43) than in the Cambisol (35) and in Luvisol-1 (28) ($P<0.05$). Average agronomic potassium efficiency was higher in Luvisol-1 (58) than in the Cambisol (39) and in Luvisol-2 (40) ($P<0.05$).

Grain yield at maximum accumulation and maximum dilution

Average YNA (on Cambisol and Luvisol-1) in the 50 kg N treatments, without P and K fertilizers (Table 2), was 34 (‘a’), whereas average YND (on Cambisol and Luvisol-1) was 52 (‘d’) both in kg kg^{-1} total N uptake in the aboveground plant DM in the treatments receiving 75 kg P and 50 kg K ha^{-1} without N fertilizer. Therefore, in the model, equations for YNA and YND (Figure 4A) for barley were defined as:

$$YNA = 34 \quad (10a)$$

$$YND = 52 \quad (10b)$$

Table 2. Internal nutrient use efficiency in three soils of Teghane, Northern Highlands of Ethiopia

	Internal N use efficiency			Internal P use efficiency			Internal K use efficiency		
Application rate	Cambisol	Luvisol-1	Luvisol-2	Cambisol	Luvisol-1	Luvisol-2	Cambisol	Luvisol-1	Luvisol-2
N0,P0,K0	39	40	41	250	246	265	57	83	78
N0,P0,k25	38	38	40	278	277	243	71	77	65
N0,P0,K50	41	44	42	282	265	261	53	66	59
N0,P25,K0	45	36	42	262	198	272	69	81	58
N0,P25,K25	43	41	41	267	284	253	56	93	50
N0,P25,K50	43	43	39	217	321	305	68	86	ND
N0,P50,K0	47	46	44	206	208	283	67	144	92
N0,P50,K25	44	41	43	233	232	225	54	72	**44**
N0,P50,K50	48	44	44	257	289	265	62	98	51
N0,P75,K0	50	38	39	**175**	197	**190**	76	78	67
N0,P75,K25	46	44	44	221	275	245	59	84	72
N0,P75,K50	**52**	**51**	50	201	309	271	56	81	68
N25,P0,K0	41	39	37	304	274	265	69	78	81
N25,P0,K25	43	36	40	257	324	323	73	96	58
N25,P0,K50	38	46	35	294	**393**	**336**	60	101	86
N25,P25,K0	44	40	38	218	247	242	68	83	57
N25,P25, K25	44	40	39	189	250	246	63	71	45
N25,P25, K50	43	42	38	271	288	272	68	100	58
N25,P50,K0	41	37	40	214	247	257	70	103	60
N25,P50, K25	46	41	40	216	248	228	77	75	58
N25,P50,K50	48	40	41	205	223	246	57	65	76
N25,P75,K0	48	44	44	217	275	246	59	103	57
N25,P75, K25	45	41	37	211	270	259	55	92	75
N25,P75, K50	42	40	42	184	247	225	51	81	61
N50,P0,K0	**33**	**34**	35	274	299	323	76	118	39
N50,P0,K25	41	39	36	303	317	215	57	98	46
N50,P0,K50	36	37	38	299	330	310	63	91	54
N50,P25,K0	39	43	39	253	283	240	73	93	85
N50, P25, K25	44	37	44	257	258	225	76	64	48
N50, P25, K50	40	38	43	273	318	244	61	64	49
N50,P50,K0	42	39	42	295	248	245	66	104	86
N50, P50, K25	41	37	44	241	249	247	59	82	58
N50, P50, K50	40	44	40	243	222	221	38	79	51
N50,P75,K0	39	43	37	267	262	225	85	**150**	**104**
N50, P75, K25	41	39	38	209	255	245	48	77	68
N50, P75, K50	42	39	39	201	235	190	57	77	53
Average	43	41	40	243	268	254	63	89	63

Note: Bold figures are values used for grain yields at maximum accumulation and dilution

Table 3. Agronomic efficiency (AE) of applied fertilizer in three soils of Teghane, Northern Highlands of Ethiopia

AE of N				AE of P				AE of K			
Rates	Cambisol	Luvisol-1	Luvisol-2	Rates	Cambisol	Luvisol-1	Luvisol 2	Rates	Cambisol	Luvisol-1	Luvisol-2
N25,P0,K0	24	19	15	N0,P25,K0	31	14	56	N0,P0,k25	1	35	8
N25,P0,K25	22	28	19	N0,P25,K25	32	46	55	N0,P0,K50	0	39	4
N25,P0,K50	34	77	16	N0,P25,K50	35	53	50	N0,P25,K25	32	46	55
N25,P25,K0	53	23	35	N0,P50,K0	30	15	48	N0,P25,K50	18	63	Nd
N25,P25, K25	69	61	50	N0,P50,K25	28	27	49	N0,P50,K25	55	53	73
N25,P25, K50	54	34	61	N0,P50,K50	30	32	47	N0,P50,K50	30	68	47
N25,P50,K0	60	48	75	N0,P75,K0	19	8	28	N0,P75,K25	66	43	34
N25,P50, K25	69	46	78	N0,P75,K25	22	14	31	N0,P75,K50	34	64	47
N25,P50,K50	61	63	70	N0,P75,K50	23	18	31	N25,P0,K25	22	36	13
N25,P75,K0	65	35	76	N25,P25,K0	53	17	35	N25,P0,K50	17	63	3
N25,P75, K25	67	52	78	N25,P25, K25	69	38	50	N25,P25, K25	69	38	50
N25,P75, K50	69	63	67	N25,P25, K50	54	53	61	N25,P25, K50	27	63	30
N50,P0,K0	28	12	7	N25,P50,K0	30	13	37	N25,P50, K25	69	62	78
N50,P0,K25	35	19	20	N25,P50, K25	35	31	47	N25,P50,K50	30	88	47
N50,P0,K50	41	32	4	N25,P50,K50	30	52	47	N25,P75, K25	67	43	39
N50,P25,K0	56	26	29	N25,P75,K0	22	8	25	N25,P75, K50	35	73	47
N50, P25, K25	46	20	27	N25,P75, K25	22	14	31	N50,P0,K25	35	46	17
N50, P25, K50	64	37	25	N25,P75, K50	23	25	31	N50,P0,K50	20	60	4
N50,P50,K0	69	8	54	N50,P25,K0	56	19	58	N50, P25, K25	46	37	54
N50, P50, K25	74	26	47	N50, P25, K25	46	37	54	N50, P25, K50	32	71	25
N50, P50, K50	72	25	47	N50, P25, K50	64	68	49	N50, P50, K25	74	76	69
N50,P75,K0	71	18	47	N50,P50,K0	35	12	54	N50, P50, K50	36	60	47
N50, P75, K25	86	26	53	N50, P50, K25	37	38	47	N50, P75, K25	86	79	89
N50, P75, K50	90	38	47	N50, P50, K50	36	24	47	N50, P75, K50	45	90	47
				N50,P75,K0	16	8	31				
				N50, P75, K25	29	26	35				
				N50, P75, K50	30	36	31				
Average	57	35	44		35	28	43		39	58	40

Nd = no data

Average YPA (on Cambisol and Luvisol-2) in the 75 kg P treatments without N and K fertilizers was 182 (‘a’), whereas average YPD (on Luvisol-1 and Luvisol-2) was 365 (‘d’),both in kg kg^{-1} total P uptake in the aboveground plant DM in the treatments receiving N25 and K50 kg ha^{-1}. The equations in the model for YPA and YPD (Figure 4B) were defined as:

$$YPA = 182 \qquad (10c)$$

$$YPD = 365 \qquad (10d)$$

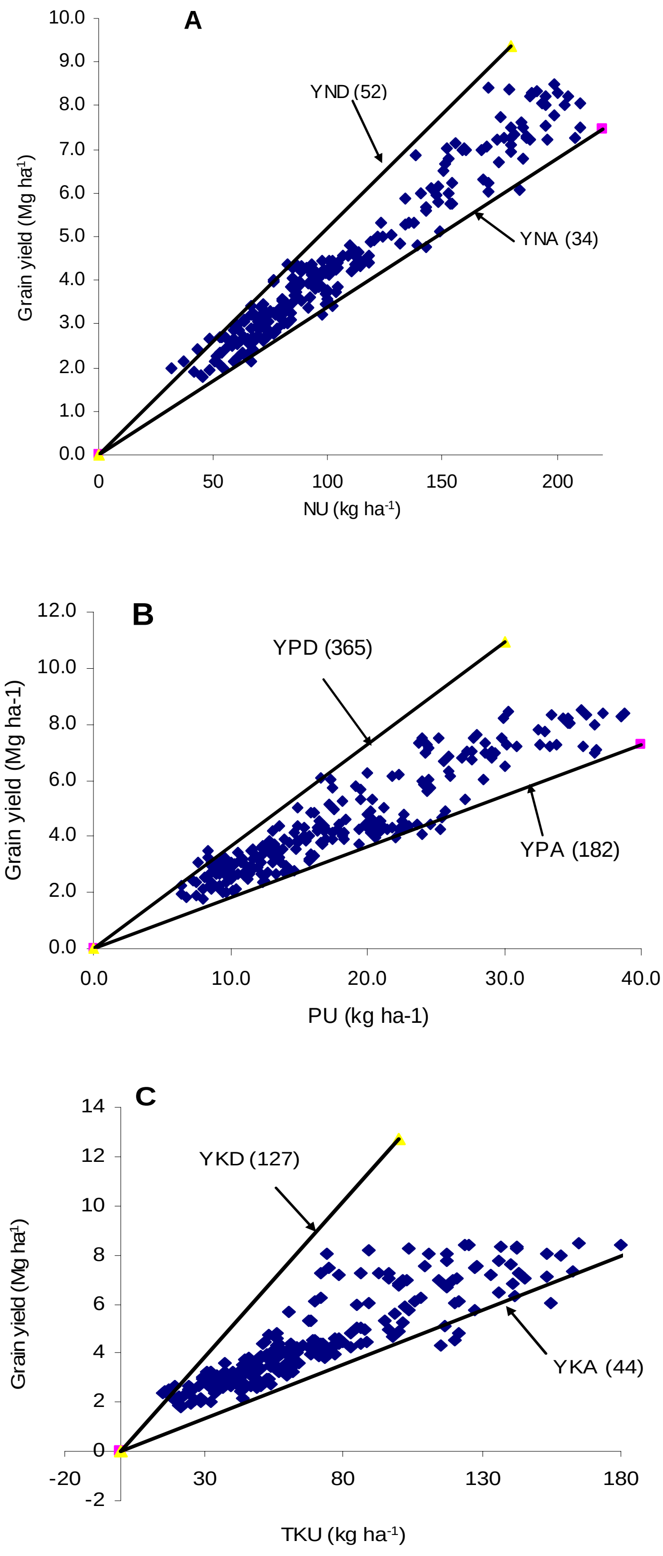

Figure 4. Relationship between grain yield (GY) of barley and total uptake of nitrogen (A), phosphorus (B) and potassium (C) in aboveground DM. YND, YPD and YKD = slope of the relation at maximum N, P and K dilution, respectively and YNA, YPA and YKA = slope of the relation at maximum N, P and K accumulation, respectively.

Average YKA (on Luvisol-2) in the 25 kg K and 50 kg P treatments without N fertilizers was 44 (‘a’), whereas average YKD (on Luvisol-1 and Luvisol-2) was 127 (‘d’), both in kg kg^{-1} total K uptake in the above ground plant DM in the treatments receiving 75 kg P and 50 kg N ha^{-1}. Thus, in the model the equations for YKA and YKD (Figure 4C) were defined as:

$$YKA = 44 \quad (10e)$$

$$YKD = 127 \quad (10f)$$

The ranges for barley in this study between maximum accumulation and maximum dilution are relatively narrow compared to reported values for other cereals, for example maize (YNA-YND, YPA-YPD and YKA-YKD, respectively 30-70, 200-600 and 30-120 (Janssen et al., 1990)) and wheat (YNA-YND and YPA-YPD, respectively 26.8-59.8 and 161.7-390.5 (Pathak et al., 2003)), possibly because the genetic potential of the local land races is too low (Mulat Demeke et al., 1997) to respond well to the two extremes.

3.2.4 Grain yield and actual uptake (experiment)

Average grain yields (Mg ha^{-1}) varied from 2.93 on Luvisol-1 via 3.91 on the Cambisol to 6.82 on Luvisol-2 ($P<0.05$). TNU (kg ha^{-1}) in aboveground plant DM varied between 67.0 (control) and 115.4 ($N_{50}P_{75}K_{25}$) on the Cambisol, 45.0 (control) and 114.7 ($N_{50}P_{75}K_{50}$) on the Luvisol-1 and 129.1 (control) and 208.9 ($N_{50}P_{75}K_{25}$ and $N_{25}P_{75}K_{25}$) on Luvisol-2. Mean TNU (kg ha^{-1}) was much higher on Luvisol-2 (169.0) than on the Cambisol (92.0) and Luvisol-1 (72.5) ($P<0.05$).

TPU (kg ha^{-1}) varied between 9.4 ($N_0P_0K_{25\&50}$) and 24.2 ($N_{50}P_{75}K_{50}$) on the Cambisol, 7.4 (control) and 19.8 ($N_{25}P_{50}K_{50}$) on Luvisol-1 and 16.2 ($N_{25}P_0K_{50}$) and 40.3 ($N_{50}P_{75}K_{50}$) on Luvisol-2. Average TPU varied from 11.1 on Luvisol-1 via 16.7 on the Cambisol to 27.4 on Luvisol-2 ($P<0.05$).

TKU (kg ha^{-1}) varied between 36.7 ($N_0P_0K_{25}$) and 117.8 ($N_{50}P_{50}K_{50}$) on the Cambisol, 17.8 ($N_0P_{50}K_0$) and 67.9 ($N_{25}P_{50}K_{50}$) on Luvisol-1 and 68.2 (control) and 174.2 ($N_0P_{50}K_{25}$) on Luvisol-2. Average TKU varied from 35.0 on Luvisol-1, via 63.2 on the Cambisol to 112.9 on Luvisol-2 ($P<0.05$).

3.2.5 Estimation of grain yield and actual uptake by QUEFTS

In the QUEFTS model, two estimates are made for actual uptake of each nutrient (UN, UP or UK), on the basis of the potential supply of each of the other two nutrients, after which it is set to the lower of the two values in accordance with the law of the minimum (Janssen et al., 1990). Figure 5 illustrates the relationship between potential supply and actual uptake of nitrogen, based on the potential supply of P. Potential supply of P is assumed to be 16 kg ha^{-1} (Luvisol-2 of Teghane). In situation "A" in the graph, potential supply of N is very low, in situation "C" very high and in situation "B" it is intermediate. In situation "A", all available N is taken up, i.e. UN = SN (UNI, eqn. 10b); on the other hand, in situation "C", all available P is taken up, i.e. UP = SP and a higher supply of N does not result in additional nitrogen uptake. In situation "A", maximum attainable yield is YND (Eqn.10b) = 52*(SN) (SN = (YPA*P)/YND = (182*16)/52 = 56 kg ha^{-1}), which is below the attainable yield on the basis of P-availability, thus P is maximally accumulated, YPA (Eqn.10c) = 182*(P) = 2912 kg ha^{-1}.

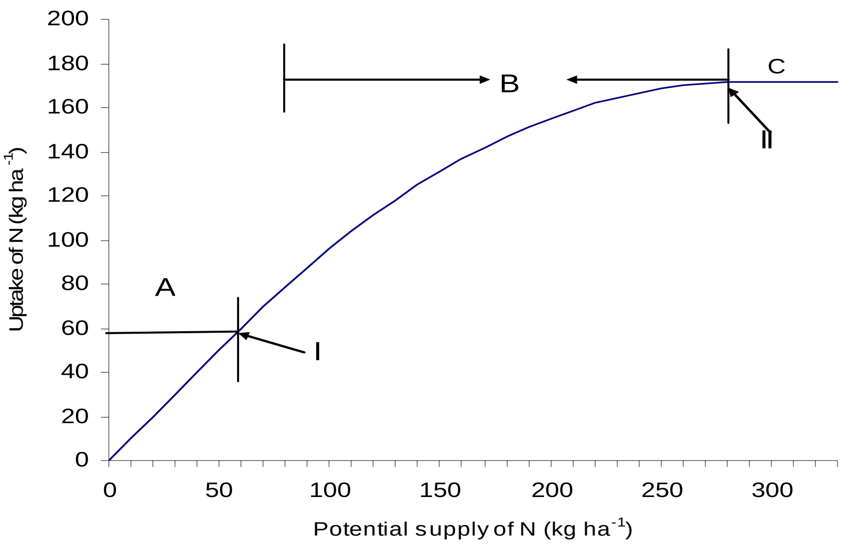

Figure 5. Actual uptake of N at varying rates of potential supply of N and at a fixed potential supply of P (16 kg ha^{-1}) (For explanation of situations A, B and C see text)

On the other hand, in situation "C", the supply of N is high and this element is maximally accumulated, whereas P is maximally diluted, resulting in an attainable yield YPD (Eqn.10d) of 365*(P) = 5840 kg. Beyond point II, actual uptake of N will not increase and at this point uptake of N (UNII; Eqn.10a) equals: (SP)* (365/34) = 171.8 kg ha^{-1}.

In general terms (Janssen et al., 1990), actual uptake of nutrient 1 in dependence of the potential supply of nutrient 2 (U1(2)) is calculated as:

U1(2) = S1 (situation “A”)

U1(2) = (S2) (d2/a1) (situation “C”)

U1(2) = S1 - {0.25 [S1-S2) (a2/d1)] ^{2}}/ [(S2) (d2/a1-a2/d1)] (situation “B”)

S1 and S2 represent the potential supplies of nutrient 1 and 2, as defined by Eqns. 9a-9c, ‘a’ and ‘d’ are constants representing attainable yield under maximum accumulation and dilution, respectively for the nutrients under consideration. Thus, uptake of N for barley can be calculated as:

if SN < (SP) (182/52) then UN(P) = SN

if SN > (SP) (365/34) then UN(P) = SP*(365/34)

else: UN = SN - {0.25 [S1-S2) (182/52)] ^{2}}/ [(S2) (365/34-182/52)] (12)

UN(K), UP(N), UP(K) UK(N) and UK(P) are calculated similarly, substituting 182 and 365, respectively for YPA (a) and YPD (d) for phosphorus and 44 and 127 respectively for YKA (a) and YKD (d) for potassium.

Final uptake of each nutrient (UN, UP, UK) is derived from the two estimates as:

UN = min [UN(P), UN(K)] (13)

UP and UK are calculated in a similar way.

3.3 Yield ranges

Yield ranges refer to the differences in yield estimates for the situations that nutrients are maximally accumulated and diluted, derived from Eqns. 10a and 10b, 10c and 10d, and 10e and 10f, for nitrogen, phosphorus and potassium, respectively.

3.4 Final yield calculation

Final yield is calculated by combining the yield ranges in two steps: first combining the yield ranges for two nutrients and subsequently combining the ranges for all three nutrients.

3.4.1 Combining yield ranges of two nutrients

Yield ranges of two nutrients are combined to obtain one yield estimate that would result from two interacting nutrients, illustrated in Figure 6 for N and P. In the example, P-supply is 16 kg ha^{-1}, YPD and YPA are 5840 and 2912 kg ha^{-1}, respectively. YND would be lower than YPA when N-uptake would be below YPA/52 = 56 kg (UNIII). On the other hand, maximum uptake of N is YPD/34 = 171.8 kg (UNIV). The combined yield must lie below the lines YPD, YND and Ymax and above the lines YPA and YNA, and YNP follows a parabolic curve between points III and IV (Janssen et al., 1990) calculated by:

If YND > YPA and YNA < min[YND, YPD, YKD, Ymax] and YPA > min then YNP = min:
If YND > YPA and YNA < min [YND, YPD, YKD, Ymax] and YPA < min then:

$$YNP = YPA + \{[(2(YPD-YPA)(UN-YPA/52)]/(YPD/34-YPA/52)\} - \{[(YPD-YPA)(UN-YPA/52)^2]/(YPD/34-YPA/52)^2\}$$

Else: YNP = min [YND, YPD, YKD, Ymax] (14)

YNK, YPN, YPK, YKN and YKP are calculated in a similar way.

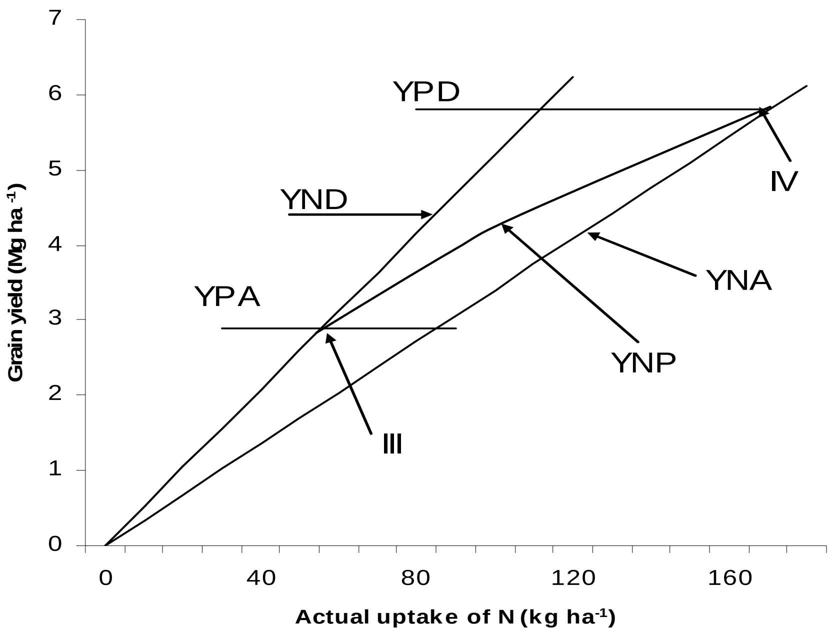

Figure 6. Estimation of grain yield of barley for a pair of nutrients (nitrogen and phosphorus) (see text for explanation)

3.4.2 Combining yield ranges of the three nutrients for final yield estimate

Using Eqn. 14, six average yields, i.e. YNP, YNK, YPN, YPK, YKN and YKP are calculated and the average of these yields is the final yield estimate.

3.5 Evaluation of the model

3.5.1 Sensitivity to 'a' and 'd'

The sensitivity to 'a' and 'd' has been tested for three sets of constants, one comprising the standard parameters for barley and two alternatives, generated by narrowing the range of 'a' and 'd' by 10 and 20% (Figure 7). For each test, the value of one variable was changed and the supply of the other two nutrients set to non-limiting. Potential yield of barley was set to 8.5 Mg ha^{-1}. The results show that the estimated yields for the three sets never overlap, contrary to the result reported by Pathak et al. (2003); and, the model is sensitive to "a" and "d" variation, thus the proposed coefficients can be used in the calibrated QUEFTS as these include the maximum range of variability. For all three nutrients, at the lower uptake levels, estimated yields are close to the lines of maximum dilution (upper yield limits), as the other two nutrients are set non-limiting.

3.5.2 Sensitivity to OC, P-Olsen and exchangeable K

It is important to test the sensitivity of the model to variations in indigenous soil nutrient supply, i.e. to values of OC, P-Olsen and exchangeable K (Figure 8). For each test, the value of one soil characteristic was varied in the range of possible nutrient contents in the soils, while the other two characteristics were fixed for each of the three soils at the level indicated in Table 1.

Yield does not change with increasing exchangeable K in the Cambisol, not even with a reduction of 11 mmol kg^{-1} in the current level. Similarly, in Luvisol-2, with high OC content and higher exchangeable K, increasing the latter does not lead to higher yield. In Luvisol-1, exchangeable K is very low (2 mmol kg^{-1}) and doubling this value result in a yield increase of 0.7 Mg ha^{-1}, which does not increase at higher values. Barley yield response to K fertilizer is relatively low (AFRD, 2005). The model is only sensitive to variations in exchangeable K at low levels of indigenous soil K supply. Barley yield responses to K fertilizer on soils with high K content are weak (AFRD, 2005).

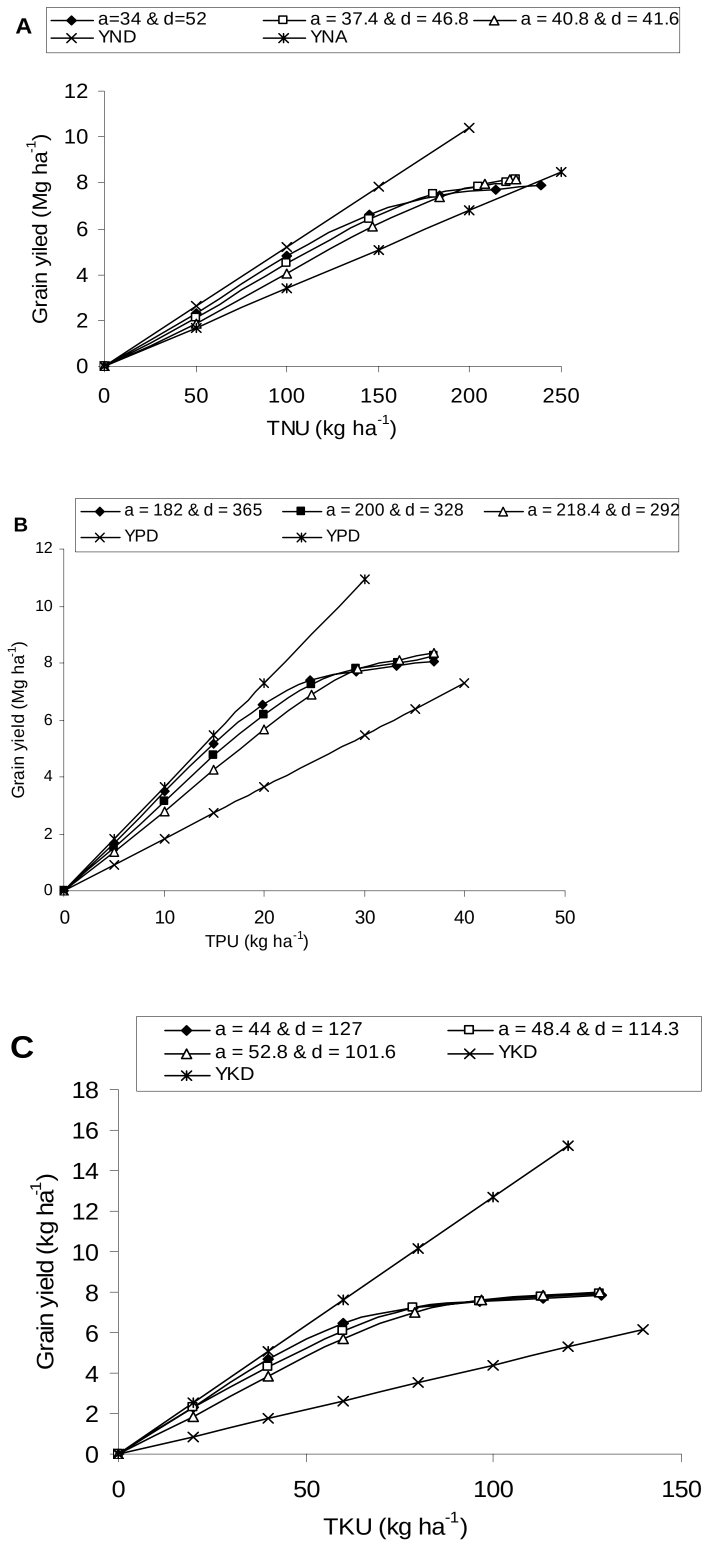

Figure 7. Yield of barley in relation to TNU (A), TPU (B) and TKU (C) for three sets of constants “a” and “d” (see text for definition of constants). The upper and lower lines indicate yields at maximum dilution and maximum accumulation of nutrients, respectively (Note that lines of YNA and YND, YPA and YPD and YKA and YKD change when we change constants “a” and “d”, but the lines shown here are the outer boundaries)

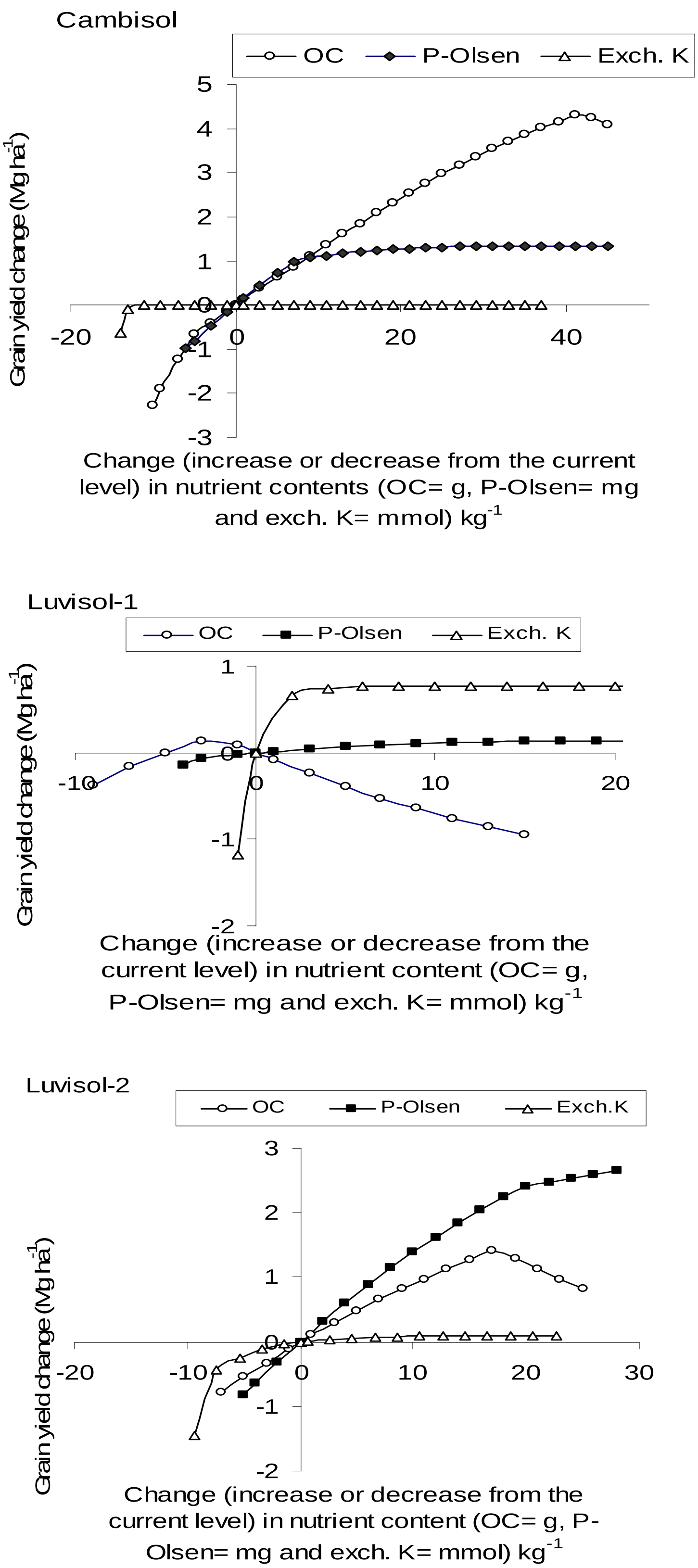

Figure 8. Yield of barley in relation to variations in OC, P-Olsen or exchangeable K (by fixing the other two nutrients at the current level) in the three soils of Teghane, Northern Highlands of Ethiopia

The results in Figure 8 suggest that an upper limit for exchangeable K for maximum yield can be estimated, but that requires further investigation. In the Cambisol, characterized by high values of OC, P-Olsen and exchangeable K (Table 1), grain yield varied considerable with variations in OC content. An increase of 9 g kg^{-1} OC resulted in an increase of 1 Mg grain yield ha^{-1}. For Luvisol-1, an increase in OC resulted in a reduction in estimated yield (Figure 8, Luvisol-1), because of its negative effect on the supply of K (Eqn. 9c). The range in yield with increasing P-Olsen was very narrow in Luvisol-1, widest in Luvisol-2 and intermediate in the Cambisol. Thus, the model is most sensitive to variations in OC and subsequently in P-Olsen; however, exchangeable K, either endogenously or from applied K fertilizer, should be high enough not to limit uptake of nitrogen and/or phosphorus.

3.5.3 Performance of the model

The calibrated and original QUEFTS models have been compared using barley grain yields from the experiment. Yield estimates by the calibrated QUEFTS better agree with the experimental results than yield estimates by the original model (Figure 9).

3.5.4 Fertilization and grain yield scenario

The calibrated model has been used to estimate barley grain yields for a factorial fertilizer experiment (0, 25, 50 and 75 kg P ha^{-1}) and (0, 25 and 50 kg ha^{-1}) each, for N and K (Figure 10). The calculated grain yields for the three soils indicate that N and P fertilizers are important in the Cambisol (Appendix B) and the combinations for highest grain yield is $N_{50}P_{75}(K_{0,\ 25\ \&\ 50})$. For Luvisol-1, maximum yield is calculated at $N_{50}P_{75}K_{50}$, whereas in Luvisol-2 maximum yield is calculated at $N_{25\&50}P_{75}K_{50}$. In Luvisol-2 the most important fertilizer is P (Figure 10 and Appendix B). The model generates a wide range of yields for different rates of fertilization and users can select the best combination for high yield or for high agronomic efficiency or for high economic returns. The QUEFTS model can calculate physiologically as well as economically optimum combinations of N, P and K, however not considered in this study.

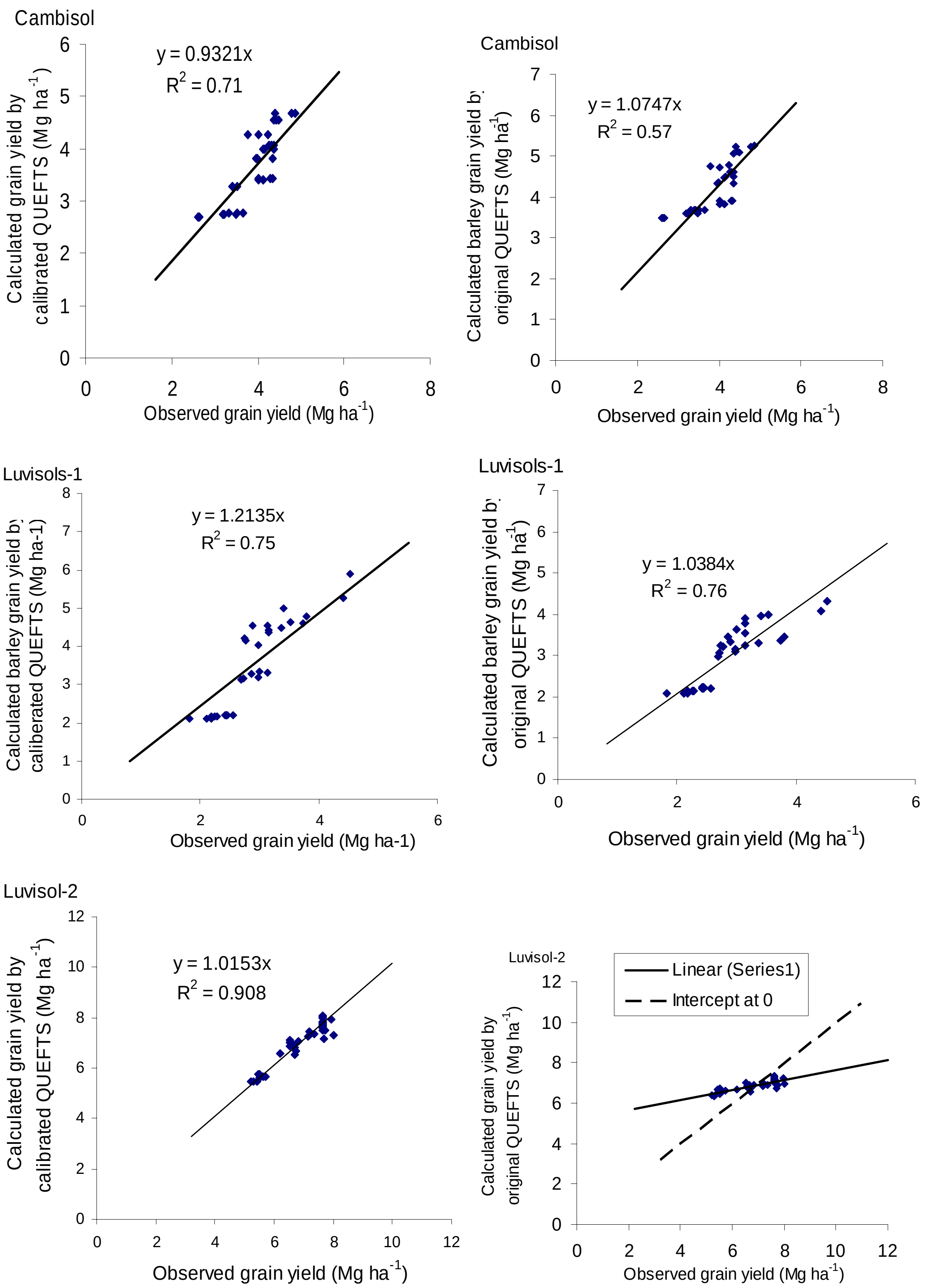

Figure 9. Observed and calculated barley grain yield by calibrated and original QUEFTS. The regression lines are drawn at intercept zero. But for Luvisol-2, since R^2 at intercept zero equals (-6), indicating that observed yields and calculated by the original QUEFTS have no relation, regression line at its normal intercept is included for comparison.

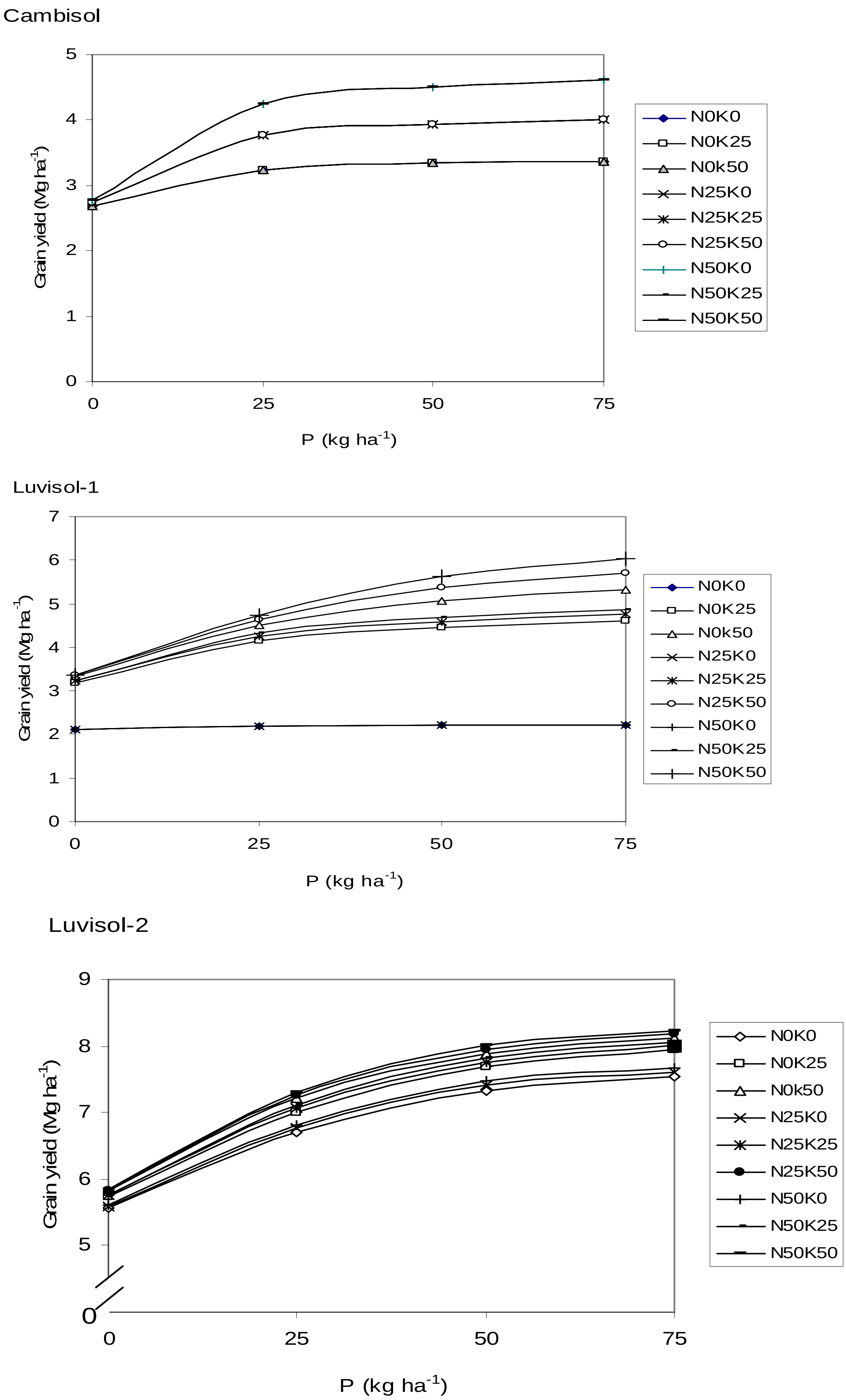

Figure 10. Selected results of calculated barley grain yields for the three soils of Teghane with different NPK fertilization rates (See data in Appendix B)

4 Conclusions

In this study, indigenous soil nutrient supply has been estimated from soil chemical properties, to derive fertilizer nutrient requirements for barley, for calibration of the QUEFTS model for the Northern Highlands of Ethiopia.

OC-content of Luvisol-1 is 1.7 times that of the Cambisol (Table 1); while TNU of Luvisol-1 is only 67% of that of the Cambisol, as a result of its substantially lower value of exchangeable K, which negatively affects the uptake of other elements (Fitzpatrick, 1986). Similarly, the recovery fractions of applied N and P fertilizers are lower in Luvisol-1. In the Cambisol and Luvisol-2, indigenous exchangeable K is about 15 mmol kg^{-1} and TNU, TPU and TKU, and GY in treatments $N_0P_0K_{25}$ and $N_0P_0K_{50}$ are not different from those in the control treatments ($P<0.05$). On the other hand, in Luvisol-1, TNU, TKU and GY in treatments $N_0P_0K_{25}$ and $N_0P_0K_{50}$ are significantly higher than those in the control treatments ($P<0.05$). In this soil, application of 25 and 50 kg K ha^{-1} resulted in an increase of about 50% in TNU and GY, compared to the average of the control treatments, whereas application of K fertilizer in the Cambisol and Luvisol-2 gave no yield response, however, TKU has increased. In Luvisol-1, TNU, TPU and TKU in treatments receiving only N or P fertilizer were not different from those in the control ($P<0.5$).

Agronomic efficiencies of applied nutrients were different for different values of indigenous soil nutrient supply and different NPK combinations. Average agronomic efficiency of N was highest in the Cambisol, in which indigenous N, P and K supply are balanced, and was lowest in Luvisol-1 with low exchangeable K. The best combinations for maximum agronomic efficiency of N were $N_{50}P_{75}K_{50}$, $N_{25}P_0K_{50}$ and $N_{25}P_{50\&75}K_{25}$ in the Cambisol, Luvisol-1 and Luvisol-2, respectively. Average agronomic efficiency of P was highest in Luvisol-2, which is characterized by high OC and exchangeable K contents. The best combinations for maximum agronomic efficiency of P were $N_{25}P_{25}K_{25}$, $N_{50}P_{25}K_{50}$ and $N_{25}P_{25}K_{50}$ in the Cambisol, Luvisol-1 and Luvisol-2, respectively. Average agronomic efficiency of K was generally high in the Luvisol-1, characterized by low exchangeable K. The best combinations for maximum agronomic efficiency of K were $N_{50}P_{75}K_{25}$, $N_{50}P_{75}K_{50}$ and $N_{50}P_{75}K_{25}$ in the Cambisol, Luvisol-1 and Luvisol-2, respectively.

Similarly, the best fertilizer combinations for maximum yield appeared different for soils with different indigenous nutrient supplies.

The results show that different rates of fertilizer application are required for different soils with different indigenous soil nutrient supplies for different objectives, i.e. either to attain maximum agronomic efficiency of a given nutrient or maximum yield or maximum economic returns. The calibrated QUEFTS model can be used as a tool to quantify indigenous soil nutrient supply and determine the best fertilizer combinations for targeted barley yields in the Northern Highlands of Ethiopia.

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Appendix A

Calculation of coefficients of q, r and s for QUEFTS calibration

Nutrients	Fertilization rate	Cambisol	Luvisol-1	Lunisol-2	Average		
					q	r	s
N							
	N0P50K25	90.4	76.1	179.5			
	N0P50K50	86.6	78.3	173.9			
	N0P75K25	93.6	65.2	175.8			
	N0P75K50	83.2	66.7	154.2			
	Average TNU	88.5	71.6	170.9			
	OC	11.0	19.0	37.0			
	q	8.0	3.8	4.6	6*		
P							
	N25P0K25		8.4	17.4			
	N25P0K50		8.0	16.2			
	N50P0K25		9.4				
	N50P0K50		9.1	17.8			
	average TPU		8.7	17.1			
	P-Olsen		5.0	6.0			
	PSOC		6.7	13.0			
	TPU-PSOC		2.1	4.2			
	r		0.4	0.7		0.55	
K							
	N25P25K0	58.6	27.1	107.7			
	N25P50K0	58.8	23.7	120.0			
	N25P75K0	72.0	23.6	126.5			
	N50P25K0	54.7	24.7	79.2			
	N50P50K0	66.1	23.3	93.1			
	N50P75K0	51.7	16.3	73.4			
	Average TKU	60.3	23.1	100.0			
	Exch.K	15.0	2.0	15.4			
	Exch.K/(2+0.9*OC)	1.3	0.1	0.4			
	s	47.9	220.8	229.2			166*

* rounded

Appendix B.

Fertilization and grain yield scenario in three soils of Teghane, Northern Highlands of Ethiopia (Figures in cells represent barley grain yield Mg ha^{-1}).

Cambisol

Fertilization rate	P0	P25	P50	P75
N0K0	2.7	3.2	3.3	3.4
N0K25	2.7	3.2	3.3	3.4
N0k50	2.7	3.2	3.3	3.4
N25K0	2.7	3.8	3.9	4.0
N25K25	2.7	3.8	3.9	4.0
N25K50	2.7	3.8	3.9	4.0
N50K0	2.8	4.3	4.5	4.6
N50K25	2.8	4.3	4.5	4.6
N50K50	2.8	4.3	4.5	4.6

Luvisol-1

Fertilization rate	P0	P25	P50	P75
N0K0	2.1	2.2	2.2	2.2
N0K25	3.2	4.1	4.5	4.6
N0k50	3.3	4.5	5.1	5.3
N25K0	2.1	2.2	2.2	2.2
N25K25	3.2	4.2	4.6	4.7
N25K50	3.4	4.6	5.4	5.7
N50K0	2.1	2.2	2.2	2.2
N50K25	3.2	4.3	4.7	4.9
N50K50	3.4	4.7	5.6	6.0

Luvisol-2

Fertilization rate	P0	P25	P50	P75
N0K0	5.6	6.7	7.3	7.5
N0K25	5.7	7.0	7.7	7.9
N0k50	5.8	7.2	7.9	8.1
N25K0	5.6	6.8	7.4	7.6
N25K25	5.8	7.1	7.8	8.0
N25K50	5.8	7.3	8.0	8.2
N50K0	5.6	6.8	7.5	7.7
N50K25	5.8	7.1	7.8	8.1
N50K50	5.8	7.3	8.0	8.2

Chapter 4

Forage availability and livestock performance at farm level in Teghane, Northern Highlands of Ethiopia

Submitted: Agricultural Systems

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Forage availability and livestock performance at farm level in Teghane, Northern Highlands of Ethiopia

Abstract

Limited quality feed availability is among the constraints that significantly limit livestock performance in the smallholder farms in the Northern Highlands of Ethiopia. The objective of this study was to examine the availability and quality of forage and their relationship with livestock performance in the smallholder farms in Teghane, Northern Highlands of Ethiopia. The study was conducted from September 2002 to August 2004. Three farm groups, classified in a participatory exercise, rich, medium and poor were studied. Average landholding was 1.63, 0.95 and 0.61 ha, respectively for the rich, medium and poor farms, with associated stocking rates of 5.6 Tropical Livestock Units (TLU) per ha for the rich, 4.5 for the medium and 3.3 for the poor. In the study area, no non-conventional feed resources and/or industrial by-products were available as livestock feed. The major proportion of feed dry matter originated from crop lands. Of the available forage, native grass was the best feed with 148 g kg^{-1} crude protein (CP), 640 g kg^{-1} organic matter digestibility (OMD) and 9.3 MJ kg^{-1} (DM). Faba bean haulms with 7.5 MJ kg^{-1} (DM) energy content was the second best feed. Average annual feed balances were 5.7, 6.0 and 16.0% below maintenance requirements for the rich, medium and poor groups, respectively, suggesting that live weight and milk production are not the major objectives. Comparison between observed liveweight gains (LWG) and the theoretical indicated that observed LWGs in the medium and poor farms were below the predicted and in the rich farms almost equal to the predicted. Performance of cows in terms of milk production was only slightly above 20% of the potential performance. In general, the strong seasonality of supply and the poor quality of forage are the major constraints for improved animal performance.

Key words: Mixed systems; participatory approach; feed quality; optimization

1 Introduction

Ethiopia has the largest livestock population in Africa (Kassa, 2003), of which about 75% (estimated at 45 million TLU[1]) is concentrated in the highlands, where smallholders practice livestock and crop production within the same farm unit. Integrated, also called mixed, crop-livestock farming is practiced to diversify household income sources through crop production, sales of meat and milk, to proved of draught power and manure production and to serve as

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[1] A Tropical Livestock Unit is a hypothetical animal of 250 kg live weight, used to bring all animal types under a common denominator (using conversion factors: 0.1, 0.36, 0.5, 0.8 and 1.1 TLU respectively for a sheep, a donkey, a heifer, a cow and an ox)

capital asset (savings account; investment) (cf. Udo and Cornelissen, 1998). Despite its large numbers, livestock in the smallholder farms has increasingly been unable to satisfactorily perform its most important functions.

For livestock to perform well, i.e. to realize the desired objectives, adequate supply of quality feed is a basic requirement. De Leeuw (1997) has reported that low quality residues from cereal crops and pulses, combined with post-harvest stubble grazing account for 35 to over 90% of all feeds in different animal production systems in tropical Africa. A study in the Eastern Highlands of Ethiopia (Kassa et al., 2003) indicated that the major part of the feed comes from cropped plots, and feed availability does not satisfy the annual requirements of livestock. Another study, in the Central Highlands of Ethiopia (Gryseels, 1988), indicated that 40% of the livestock feed intake originated from crop by-products, particularly cereal straws. Both studies indicated that lack of adequate farm level data on availability and quality of feed resources is among the major obstacles in designing innovative livestock development projects. Moreover, farmers and agricultural development agents differed widely in their identification of major constraints for livestock production and courses of action that need to be taken (Kassa, 2003). Knowledge of on-farm available feed resources and their quality is fundamental in exploring opportunities to increase farm productivity, for instance by targeting the available resources. The objective of this study was to examine availability and quality of forage and their relationship with livestock performance in smallholder farms in Teghane in the Northern Highlands of Ethiopia.

2 Materials and methods

2.1 The study area

The study was conducted during 2002-2004 in Teghane, Atsbi Wonberta district, situated between 13^0 52' 53" and 13^0 53' 37" N and between 39^0 42' 05" and 39^0 43' 57" E, in Tigray Regional State in the Northern Highlands of Ethiopia, covering an area of 13.56 km^2. Its altitude ranges from 2710 to 2899 m above mean sea level. The climate is "Dega" (WBISPPO, 2002), with average annual monomodal rainfall from July to September of 541 mm (coefficient of variation 53%, for the period 1901-2002, at a location near Teghane at 14^0 N and 40^0 E (Viner, 2003)). For the period 2000-2004, average annual rainfall was 532 mm (Atsbi World Vision, 2004), comparable to the long term average.

2.2 Methodology

Farm classification

Farmers were classified according to the community's viewpoint, during a village farmers' assembly, in three wealth groups (rich, medium and poor), on the basis of the socio-economic conditions in Teghane. Through stratified random sampling, 5 households from the rich, 7 from the medium and 12 from the poor group were selected from the list of all households of the village (Assefa et al., Chapter 2). The criteria used were land holding, herd size (HS) and the stock of seed/grain for planting and consumption, i.e., farmers in the 'rich' group possessed land > 1 ha, oxen ≥ 2, cows ≥ 2 and had enough seed/grain in stock to cover the requirements for planting and consumption, in the 'medium' group farmers possessed 0.75 – 1 ha, one ox and one cow and the 'poor' group possessed land holdings < 0.75 ha and owned one or no oxen, one or no cow and few other animals and insufficient seed/grain in stock for planting and consumption. The community's classification has been validated with data collected during the first survey (Assefa et al., Chapter 2).

Herd composition and dynamics

All animal on the selected farms were recorded in June 2003 and livestock dynamics were monitored by monthly visits during one year (till June 2004). The observations included animal number, sex and age and heart girth[2] circumference, using a measuring tape. All animals' weights were converted to Tropical Livestock Units. Discussions were held with three elderly local farmers (experts in local farming practices) to identify farmers' objectives in livestock keeping.

Available forage and feed balance

For each of the selected farms, the area of each field (plot) was measured and classified as either crop land (rainfed and/or irrigated) or pasture land. For determination of production, 90 sample plots (30, 30, 15 and 15 plots, respectively for barley, wheat, faba bean and field pea) were selected randomly at harvesting time (January and February 2004), and sampled (3 by 3 m in each plot by hand-cutting at ground level using a sickle (including weeds). Grain

[2]Heart girth is the circumference of the chest of an animal (TSC, 2004)

was separated from residue manually. Residues and seeds from each sample plot were collected in separate paper bags. Residue dry matter (DM) yield was computed per crop and per farm, by adding the yields from each of the plots with a particular crop. For determination of chemical composition, 7 composite[3] samples were collected for each residue type.

In September 2003, three grazing areas representative for the village were selected. At each selected site, three transect lines of 200 meter each were laid out. Along each transect line, five regularly spaced quadrats (0.5 x 0.5 m) were clipped at ground surface to determine standing herbage, and 45 grass samples were collected for dry matter determination. In addition, herbage species composition and cover were determined at 9 line intercept points along the same transect at the early flowering stage (late September). Cover was estimated by the straight line transect method (Stumpf, 1993) for each species separately. The sum of cover values for a particular spot can thus exceed 100%. Native grass availability per farm was estimated by multiplying its pasture area by the average DM yield determined for the village pasture land. For determination of chemical composition 27 samples were selected (Assefa et al., Chapter 5) and taken to the International Livestock Research Institute (ILRI) in Addis Ababa for chemical analyses.

Total available organic matter (OM) was calculated from total annual DM production per forage type (Native grass (grazed in the field or harvested and temporally stored as hay), straws of barley and wheat, and haulms of faba bean and field pea) by multiplication with its organic matter content. Intake of organic matter (IOM) was estimated from organic matter digestibility (OMD) and nitrogen content, using the transfer function developed for sheep by Ketelaars and Tolkamp (1991), multiplied by 1.33 to account for the higher metabolizable energy requirement of cattle. In the calculations, weighted[4] average values for OM digestibility and N content were used. Intake of metabolizable energy (IME) was calculated from intake of digestible organic matter (IDOM), assuming 1 g IDOM to be equivalent to 15.8 KJ ME (Zemmelink et al., 2003). ME for maintenance and liveweight gain were set to 512 KJ $kg^{-0.75}$ and 38.1 kJ g^{-1}, respectively (Zemmelink, 1995; Ifar, 1996;

[3] Samples from all plots per crop type were combined and thoroughly homogenized (USEPA, 2004), and sub-sampled

[4] Weighted OM digestibility = Σ (OM of each forage multiplied by its digestibility)/ Σ (OM of each forage). The same procedure has been applied to compute weighted N content.

Zemmelink et al., 2003). The annual farm feed balance (FBa) at maintenance was calculated as:

$$FBa = \{(DOMa - DOMm*HS)/DOMm*HS\}*100 \quad (1a)$$

(if the *ad libitum* daily DOM intake is greater or equal to the daily required DOM for maintenance)

Or

$$FBa = \{(IDOM*HS - DOMm*HS)/DOMm*HS\}*100 \quad (1b)$$

(if the *ad libitum* daily DOM intake is less than daily required DOM for maintenance)

where,

DOMm : annual DOM require for maintenance (kg TLU^{-1})

IDOM : intake of annual digestible organic mater, *ad libitum* (kg TLU^{-1})

'Optimal' herd size was computed for each farm on the basis of annually available feed resources and voluntary feed intake of an animal as:

$$HSop = DOMa/IDOM \quad (2)$$

where,

HSop : optimum herd size (TLU)

DOMa : annually available digestible organic matter (kg)

IDOM : annual voluntary intake of digestible organic matter TLU^{-1} (kg)

Laboratory analyses

DM was determined after oven-drying at 105 ^{0}C overnight and OM through dry ashing at 500 ^{0}C overnight. Digestibility was determined through *in vitro* rumen systems that simulate the digestion process, following the Tilley and Terry (1963) two-stage method. The modified Tilley-Terry system (Van Soest and Robertson, 1985) substitutes the second stage with a neutral-detergent extraction (Ogbai and Berhan, 1997). Neutral Detergent Fiber (NDF) was determined by neutral detergent extraction (van Soest and Robertson, 1985). Crude protein (CP) content was calculated from the nitrogen (N) content determined by the Kjeldahl procedure, by multiplying by 6.25.

Liveweight dynamics

Liveweight (LW) was estimated from heart girth circumference measurements (x, in cm) on 44 head of cattle, aged 2 to 10 years (16, 14 and 14 animals, respectively for the rich, medium and poor group), as (MOA, undated):

$$LW = -39.52 + 2.29x \qquad (3)$$

To set observed LW in perspective, potential LW was computed according to Bakker et al. (1996):

$$LW(t) = (PW - (PW - BW)) * e^{-rgr*age} \qquad (4)$$

where,

LW(t) : weight of an animal at age t (kg)
PW : potential weight of a mature animal (kg)
BW : weight at birth (kg)
rgr : relative growth rate (yr^{-1})

Weight at birth was set to 16 kg for female and 17 kg for male calves and relative growth rate for female animals to 0.3 and for male animals to 0.18 (Struif Bontkes, 1999). Mature weights of male (496 kg) and female animals (375 kg) were derived from Equation 3, using heart girth circumference measurements of mature, well-fed animals in the area.

Annual live weight gain of the animals ($ALWG_{age-t}$) was computed by:

$$ALWG_{age-t} = W_{age-t} - W_{age-t-1} \qquad (5)$$

where,

W_{age-t}; $W_{age-t-1}$: liveweight of the animal at the end and beginning of the monitoring period, respectively

Milk production

Different estimates of ME requirements for milk production have been given: for cattle indigenous to developing countries; suggested values kg^{-1} of milk with 40 g fat content are 4.73 MJ (NRC, 1971), 5.27 MJ (MAFF, 1979), 4.95 MJ (Patle and Mudgal, 1976) and 4.35 MJ (Kearl, 1982). According to Kearl (1982), differences in ME requirements between breeds and geographic regions are small. In this study, NE required for milk production is computed by (De Visser et al., 2000) and the NE is divided by 0.60 to arrive at ME (op.ct.):

$NE_{lac} = 1.509 + 0.0406*fa$ (6)

where,

NE_{lac} : net energy requirement for milk production (MJ kg^{-1})

fa : milk fat content (g kg^{-1})

Draught power and dry OM manure production

Energy requirements of draught animals are assumed to comprise energy for maintenance and for work. Various estimates for energy requirements for traction are given in literature, i.e. 21.3 kJ ME (kg LW)$^{-0.75}$ hr^{-1} (Goe, 1983), 10.0416 kJ ME (kg LW)$^{-1}$ hr^{-1} (Kearl, 1982), and 1.25 – 1.68 MJ ME hr^{-1} (Van der Lee et al., 1993). In this study, 1.25 MJ hr^{-1} for threshing and 1.68 MJ hr^{-1} for ploughing have been used (Van der Lee et al., 1993).

Manure production was estimated by:

$Mand = IOMd - IDOMd$ (7)

where,

Mand : manure production (kg d^{-1} TLU^{-1})

IOMd : IOM (kg d^{-1} TLU^{-1})

IDOMd : IDOM (kg d^{-1} TLU^{-1})

Economic returns

Based on observations and estimates of liveweight gain, milk production, manure production and draught power and their respective market prices in Teghane, gross revenues for livestock (GRL), disregarding costs for labor, feed and housing of livestock have been computed as:

$GRL = \Sigma\ (GRIA * NA)$ (8)

where,

GRIA : gross revenues per individual animal yr^{-1} (Birr)

NA : number of animals

GRIA is computed as:

$GRIA = \Sigma\ (IAP * VP)$ (9)

where,

IAP : annual individual animal performance (i.e., for ox: LWG, manure production and draught power; for cow: progeny, milk, LWG and manure; for heifer, young ox, calf and lamb: LWG and manure; for ewe: progeny and manure;

for ram: manure; for female donkey: progeny and manure and for male donkey: manure)

VP : values of performance under consideration (Birr)

Similarly, in the computation of returns on investment in sheep, labor, feed and housing costs are disregarded, and the annual rate of return (ARR) on investment in sheep is computed following the approach of Upton (1985) as:

ARR = (NRI /CI)* 100 (10)

where,

NRI : net return on investment ewe^{-1} (Birr)
CI : capital investment ewe^{-1} (Birr)

CI = PE + PR/NER (11)

where,

PE : price per adult ewe (Birr)
PR : price per adult ram (Birr)
NER : number of ewes per ram

NRI = GOP – BSD – CVC (12)

where,

GOP : gross output per ewe yr^{-1} (Birr)
BSD : breeding stock depreciation (Birr)
CVC : cost of veterinary care (Birr)

GOP = LWPE * PLW (13)

where,

LWPE : liveweight production ewe^{-1} (kg)
PLW : price kg^{-1} LW

BSD = CEM + CRM/NER (14)

where,

CEM : cost of ewe mortality (Birr)
CRM : cost of ram mortality (Birr)

Analysis of variance

Data on land holdings, livestock holdings, annual DOM availability, OMD and N content of feeds and annual OM manure production TLU^{-1} were subjected to analysis of variance using SPSS. Likewise, data on the relationship between available DOM and HS, 'optimal' and observed HS, and predicted and observed LWG were subjected to regression analysis.

3 Results

3.1 Integrated crop-livestock farming system

The subsistence mixed crop-livestock farming system in Teghane is schematically presented in Figure 1. The discussions with farmers indicated that smallholder farmers attempt to integrate crop and animal production to maximize returns from their limited land and capital, minimize production risk, diversify sources of income, provide food security and increase productivity, in agreement with the findings of Paris (2002). Furthermore, farmers ranked the objectives of keeping animals, in order of importance as: draught power, offspring, manure, milk and meat. The associated benefits were classified as: a) income generation, b) capital savings/investment and security account, c) food security and d) home consumption.

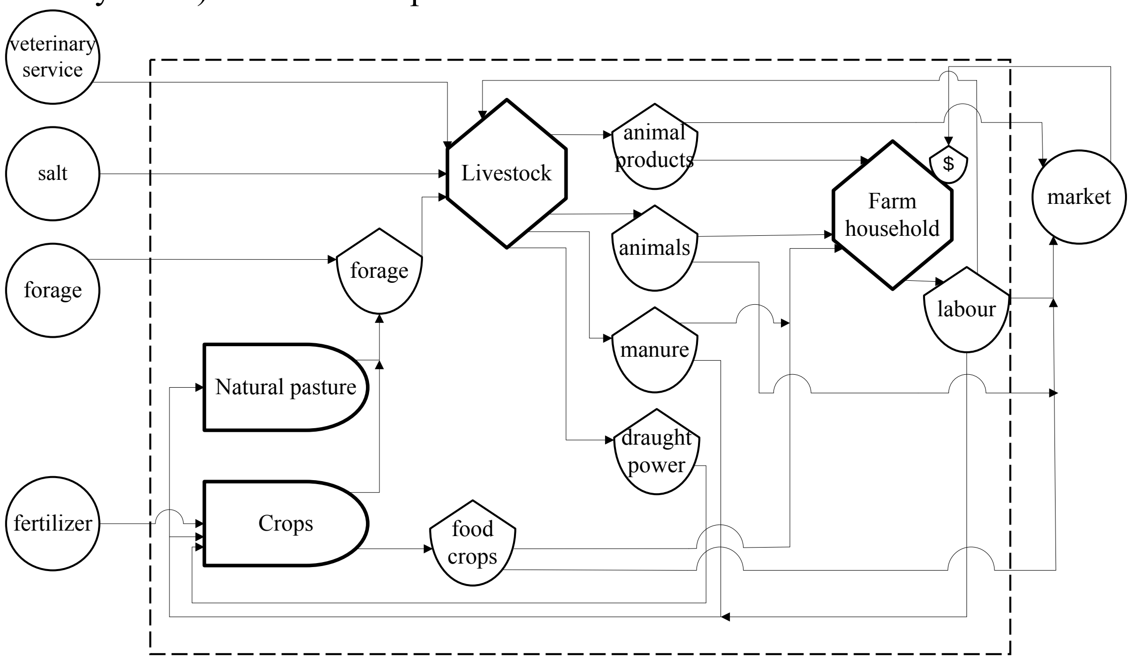


Figure 1. Integrated crop-livestock farming system in Teghane, Northern Highlands of Ethiopia

As indicated in Figure 1, the farm animals provide draught power for crops and fertilizer for crops and natural pasture lands in the form of manure. Dried animal manure is also used as fuel. Crop residues and grass are used as feed for livestock. Outputs from livestock, such as milk, meat and eggs are important sources of food for the farm household. Outflows from the farm livestock include sales of animal products and live animals. External inputs to the livestock include purchased forage (in rich and medium farms) and veterinary services. Moreover, livestock serves as a capital asset, in the form of a readily available source of cash and means of savings (Mohamed Saleem, 1998; Slingerland, 2000; Paris, 2002; Udo, 2002; Bebe, 2003).

Average land holding was 1.63 ha for the rich, 0.95 ha for the medium and 0.61 ha for the poor farms (Table 1), statistically significantly different ($P<0.05$). On the poor farms, 70.5% of the total area was cultivated, compared to 63.9% on the medium and 51.5% on the rich farms, the difference between the rich and the poor groups being statistically significant ($P<0.05$). Of the total cultivated land, 71.4, 69.4 and 69.8% was under barley for the rich, medium and poor farms, respectively. Natural pasture lands in the valley bottom, on deep and fertile Luvisols, are more important in terms of forage supply than pasture lands outside the valley bottom, on shallow Leptosols. Of the total pasture land holdings, 72.2, 27.8 and 39.4% was in the valley bottom for the rich, medium and poor farms, respectively. The differences in holdings of natural pasture in the valley bottom are statistically significant among the farm groups, whereas the pasture land holdings outside the valley bottom are not significantly different ($P<0.05$).

Table 1. Average area (ha; standard deviation in brackets) per farm group for different crops and pasture in Teghane, Northern Highlands of Ethiopia, 2004

		Rich (5*)	Medium (7*)	Poor (12*)
Cultivated land	Barley	0.60 (0.139)	0.43 (0.144)	0.30 (0.122)
	Wheat	0.09 (0.054)	0.08 (0.801)	0.10 (0.083)
	Faba bean	0.07(0.046)	0.06 (0.098)	0.02 (0.024)
	Field pea	0.08 (0.092)	0.06 (0.084)	0.01 (0.028)
	Subtotal	0.84 (0.179)	0.62 (0.237)	0.43 (0.154)
Pasture land	In the valley bottom	0.57 (0.137)	0.13 (0.080)	0.05 (0.049)
	Outside the valley bottom	0.22 (0.180)	0.20 (0.255)	0.13 (0.099)
	Subtotal	0.79 (0.148)	0.33 (0.263)	0.18 (0.120)
Total (cultivated + pasture land)		1.63 (0.80)	0.95 (0.221)	0.61 (0.190)

* Sample size

Animals graze native grasses, where 14 species were identified, of which *Cyperus* spp., *Clover* spp., *Polygonium* spp. and *Eragrostis* spp. were common throughout the grazing area. *Cyperus* spp. were most dominant with 50 to 80% cover, followed by *Clover* spp. with 5 to 89% cover and *Polygonium* spp. with

4 to 39%. Farmers reported that some less palatable species, such as *Cyperus* spp. (locally referred to as ketema) and species low in nutrient content, such as *Polygonium* spp. (tult) and *Hyperenia* spp. (muja), in recent years have been invading their grazing fields. Prickly pear is another important feed in the coping strategy when other feeds are finished.

Grazing of aftermath in crop fields takes place after harvest of the rainfed crops from the end of November to February and after harvest of the irrigated crop in June. In the dry season, January to June, animals are fed crop residues in the stable. Working oxen are provided with the largest quantities of hay and crop residues. Cows in milk and donkeys active in transport are supplemented with crop residues or hay at night.

3.2 Herd size (HS), herd composition and livestock dynamics

Farmers inherited livestock from their parents, or obtained them through purchase or as a present. The most common farm animals are cattle, sheep and donkeys (Table 2). Rich farmers owned almost three times as many animals as the medium farmers between June 2003 and June 2004. In 2004, the mean differences in cattle numbers among farm groups were statistically significant ($P<0.05$). Sheep, donkey and oxen numbers were statistically significantly different ($P<0.05$) between the rich and the medium and the rich and the poor groups.

From June 2003 to June 2004 deaths, sales, purchases and births occured in all animal groups, with deaths, sales and slaughter compensated by births and purchases, except for sheep and donkeys that declined in number. Farmers sold some animals from these species to supplement household income for food purchases, because yields of the 2003 food crop was insufficient to meet the requirements. Medium and poor farmers sold less sheep than rich farmers, because the former were collecting 25 to 50 kg of wheat and/or sorghum per month (January 2003 to October 2003) in the framework of food-for-work from Atsbi World Vision and the Atsbi-Wonberta district office of the Ministry of Agriculture.

Table 2. Herd dynamics (number of animals, standard deviation in brackets) per farm group in Teghane, Northern Highlands of Ethiopia, 2003-2004

Farm group / Animal species	Monitoring time	Rich (5*)	Medium (7*)	Poor (12*)
Calves[1], young oxen and heifers[2]	June 2003	3.4 (1.34)	1.6 (0.53)	0.5 (0.52)
	June 2004	3.4 (1.52)	1.7 (1.28)	0.25 (0.45)
Cows	June 2003	2.8 (1.09)	1.3 (0.95)	0.75 (0.75)
	June 2004	3.0 (0.71)	1.1 (0.35)	0.5 (0.52)
Oxen	June 2003	2.6 (0.55)	1.1 (0.69)	0.75 (0.62)
	June 2004	2.8 (0.84)	1.0 (0.53)	0.5 (0.52)
Sheep	June 2003	30.4 (17.98)	17.7 (3.90)	12.6 (3.48)
	June 2004	13.6 (2.19)	12 (4.07)	7.3 (4.27)
Donkeys	June 2003	2.6 (0.89)	1.6 (1.51)	0.6 (0.67)
	June 2004	2.2 (1.10)	1 (0.93)	0.5 (0.80)

*Sample size

[1]calf = cattle aged 0-2 yr, [2]young oxen and heifers = cattle aged 2-4 yr

3.3 Livestock management

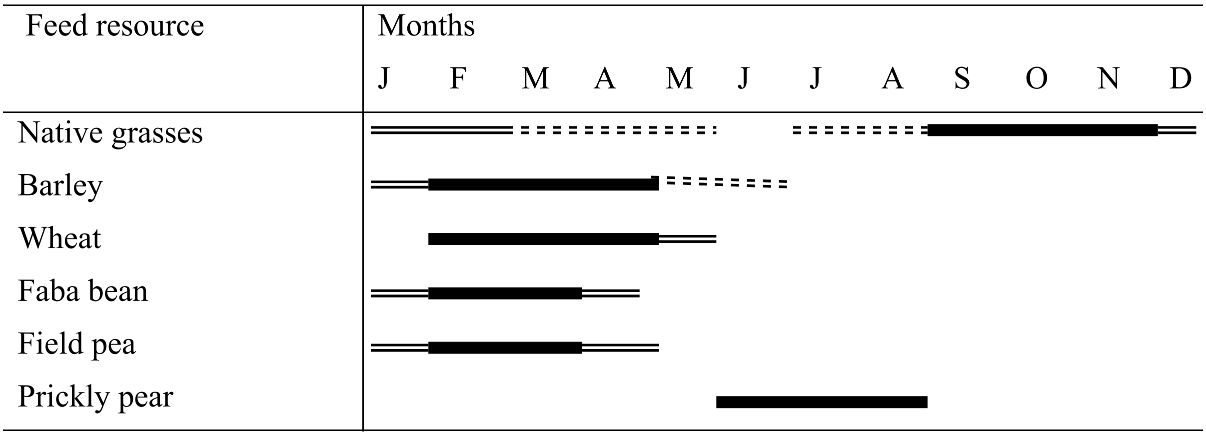
All animals belong to local breeds and are kept under traditional livestock management. Farmers indicated that breeding in all species is uncontrolled and natural. The age at first mating for heifers ranges between 3 and 5 years, depending on level of management, calving interval is 2 years and lifetime production 4 to 6 calves. Culling, because of age is between 14 and 16 years. The calf is allowed to suckle its dam without interference for one month. For the next two weeks, the calf is allowed to suckle half of the milk and subsequently it only stimulates the cow before it is being milked.

Sheep are important in the system (easy to convert to cash, lower capital requirements for investment and lower feed requirements), as indicated by their share in the total herd (Table 2). Each farmer owns at least one ram joining the flock throughout the year. Average annual lambing rate is 120% and peak lambing time between October and January.

3.4 Forage availability, nutrient concentration and digestibility

The livestock ration consists of natural pasture, grazed crop aftermaths, collected crop residues and prickly pear. The availability calendar of the various forage types is shown in Table 3.

Table 3. Schematic livestock feed availability in Teghane, Northern Highlands of Ethiopia



Note: Lines show availability: solid thick lines indicate major period of availability, two parallel solid lines represent limited availability and broken lines represent low availability.

Annual forage production from pasture fields was estimated at 10.3 Mg (DM) ha^{-1} in the valley bottom and 3.5 Mg outside the valley bottom. Table 4 shows the availability of forage resources from natural pasture lands and different crop fields. In terms of DOM availability per ha, in all farm groups the most important source was natural pasture, followed by barley straw, whereas pea haulms were the least important. Of the total available DOM per farm, the contribution of native grasses, the most important feed, was 69.7, 56.3 and 38.9% for rich, medium and poor farmers, respectively (Figure 2). For the native grass and barley the differences among farm groups are statistically significant ($P<0.05$).

Table 4. Annual DOM availability (Mg ha^{-1}, standard deviation in brackets) per farm type in Teghane, Northern Highlands of Ethiopia, in 2003-2004

Farm type	Rich (5*)	Medium (7*)	Poor (12*)
Natural pasture	5.0 (0.77)	4.0 (0.84)	3.2 (1.23)
Barley straw	2.1 (0.41)	2.1 (0.23	1.9 (0.18)
Wheat straw	2.1 (0.33)	1.6 (0.73)	1.6 (0.78)
Faba bean haulms	1.6 (0.91)	1.0 (0.76)	1.1 (0.96)
Field pea haulms	0.9 (0.87)	0.9 (0.67)	0.7 (0.86)

*Sample size

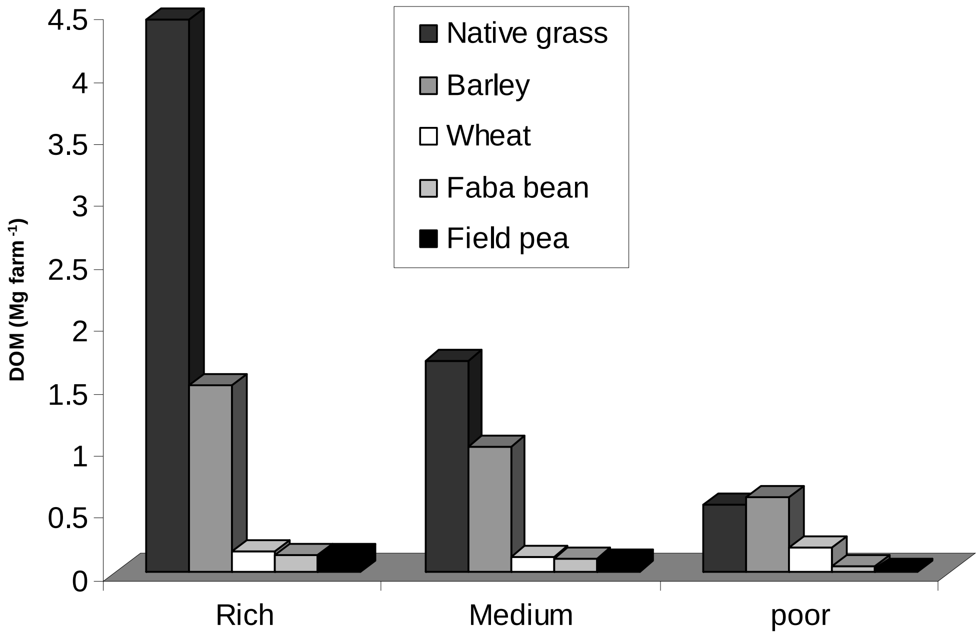


Figure 2. DOM supply by feed type and farm group from September 2003 to August 2004 in Teghane, Northern Highlands of Ethiopia

In terms of feed quality, the native grasses represent the best feed (Table 5), with 148 g kg^{-1} CP, 640 g OMD kg^{-1} OM and 9.3 MJ ME $(kg\ DM)^{-1}$. Faba bean haulms, with 7.5 MJ ME $(kg\ DM)^{-1}$ and 65 g CP kg^{-1} DM also represent good quality forage, while barley straw, with 7.2 MJ ME $(kg\ DM)^{-1}$ is reasonable in terms of energy content. However, CP-content in barley straw, i.e., 34 g kg^{-1} DM is lower than in field pea haulms. Wheat straw is lowest in CP and ME. In terms of OMD, wheat straw and field pea haulms are most unfavorable. On the basis of the CP/OMD ratio, forages can be classified in three classes: native

Table 5. Forage quality (standard deviation in brackets) in Teghane, Northern Highlands of Ethiopia in 2003/04

Forage type	OM (g kg^{-1} DM)	CP (g kg^{-1}DM)	NDF (g kg^{-1} DM)	OMD (g kg^{-1} OM)	ME MJ (kg^{-1} DM)
Native grass (27*)	913 (40.5)	148 (26.7)	521(110.7)	640 (73.2)	9.3 (1.32)
Faba bean (7*)	806 (67.9)	65 (8.7)	567 (72.1)	592 (29.4)	7.5 (0.74)
Field pea (7*)	806 (89.4)	63 (3.0)	644 (15.0)	505 (74.4)	6.3 (1.48)
Barley (7*)	869 (58.9)	34 (6.0)	707 (63.4)	524 (27.8)	7.2 (0.64)
Wheat (7*)	853 (25.0)	23 (6.5)	759 (23.0)	504 (34.5)	6.8 (0.39)

*Sample size, OM = organic matter, CP = crude protein, NDF = neutral detergent fibre, OMD = organic matter digestibility, ME metabolizable energy grasses, CP/OMD > 0.2, faba bean and field pea haulms, CP/OMD 0.1-0.2 and barley and wheat straw, CP/OMD < 0.1. Mean differences between rich and poor farm groups in OMD, N contents, IOM (kg d^{-1} TLU^{-1}) and IDOM (kg d^{-1} TLU^{-1}) of pooled feeds (Table 6) are statistically significant ($P<0.05$).

Table 6. Forage quality, IOM and IDOM (standard deviation in brackets) by farm group in Teghane, Northern Highlands of Ethiopia in 2003/04

	Rich	Medium	Poor
OMD (g kg^{-1})	600 (8.1)	579 (23.2)	562 (25.5)
N (g kg^{-1})	17 (1.1)	14 (3.4)	11 (3.8)
IOM (kg d^{-1} TLU^{-1})	4.2 (0.10)	3.9 (0.33)	3.6 (0.39)
IDOM (kg d^{-1} TLU^{-1})	2.5 (0.10)	2.3 (0.28)	2.0 (0.31)

OMD = organic matter digestibility, N = nitrogen content, IOM = organic matter intake, IDOM = digestible organic matter intake

3.5 Available DOM, HS and feed balance

Average herd size in the survey period was 9.1 TLU for the rich, 4.3 for the medium and 2.0 for the poor group, and the associated stocking rates per ha, 5.6 TLU for the rich, 4.5 for the medium and 3.3 for the poor. The coefficients of the regression lines between annually available DOM per ha and actual stocking rate for the three farm groups (Figure 3) indicate a positive correlation for the rich and poor farms and a negative correlation for the medium group. However, neither of the coefficients for the individual groups is statistically different from zero, whereas the overall regression coefficient is significant ($P<0.05$). Average annual feed balances were below maintenance requirements for all farm groups (Table 7) suggesting indeed that LW and milk production are not major objectives.

Table 7. Annual feed balance by farm group in Teghane, Northern Highlands of Ethiopia in 2003/04

Farm group	HS (TLU)	Available DOM (Mg $farm^{-1}$ yr^{-1})	DOM required for maintenance (Mg $farm^{-1}$ yr^{-1})	Balance (%)
Rich	9.0	6.38	6.77	-5.7
Medium	4.3	3.01	3.21	-6.0
Poor	2.0	1.25	1.49	-16.0

Note: Maintenance requirement = 2.037 kg DOM d^{-1} TLU^{-1}

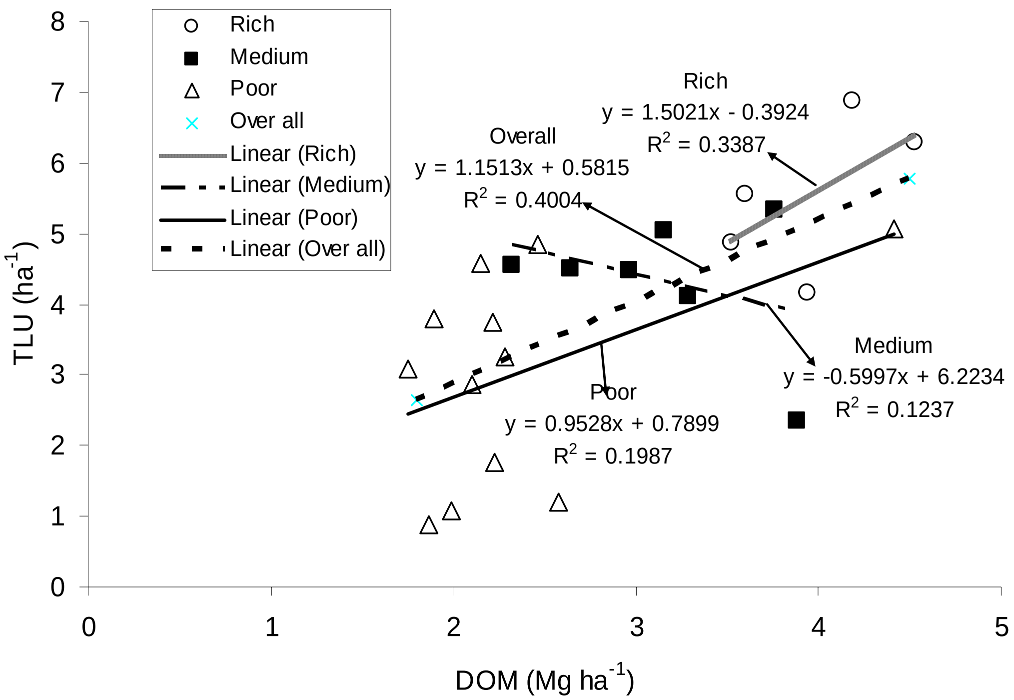


Figure 3. The relation between annually available DOM per ha and stocking rate (September 2003 to August 2004) for three farm groups in Teghane, Northern Highlands of Ethiopia

On a per farm basis, the regression coefficients of the relationships between available DOM and HS (Figure 4) per farm group (2.28 for the rich, 1.25 for the medium and 2.32 for the poor) and the intercepts (-5.61 for the rich, 0.50 for the medium and -1.34 for the poor) are not statistically different ($P<0.05$), whereas the overall regression coefficient (1.45 with standard error of 0.104) is significantly different from zero ($P< 0.01$).

The linear regression coefficients (Figure 5) between actual HS and 'optimal' HS for the rich (2.67), the medium (1.66) and the poor (1.42) are statistically significant ($P<0.05$).

3.6 Liveweight dynamics

The highest average daily liveweight gains per month were recorded in October for the rich (344 g) and the medium (289 g) group and in September (203 g) for the poor group (Figure 6). Subsequently, it gradually decreases, to reach negative values in April for the medium and poor farm groups and in May for the rich group. Liveweight loss was strongest in August for all farm groups, with values of 225, 159 and 154 g animal^{-1} d^{-1} for the medium, rich and poor farm group, respectively.

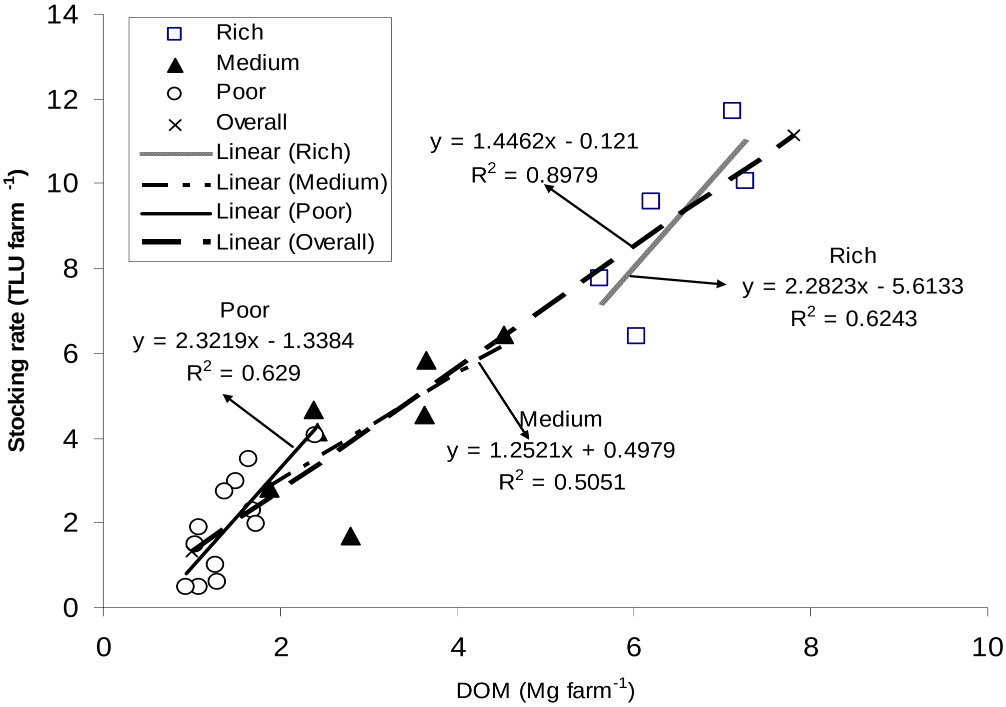


Figure 4. The relation between annually available DOM per farm and herd size (September 2003-August 2004) for three farm groups in Teghane, Northern Highlands of Ethiopia

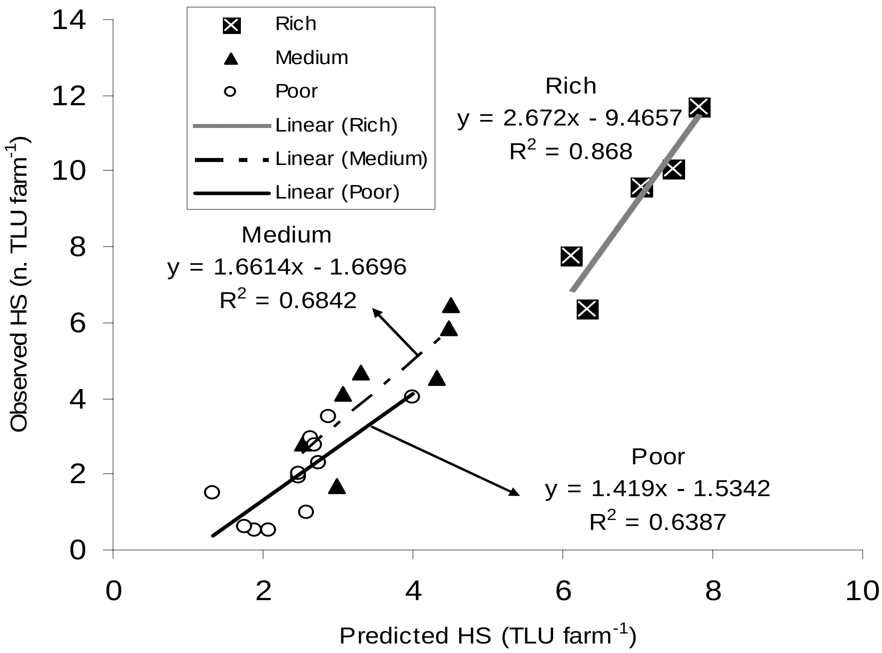


Figure 5. Observed and predicted HS in Teghane (September 2003 to August 2004)

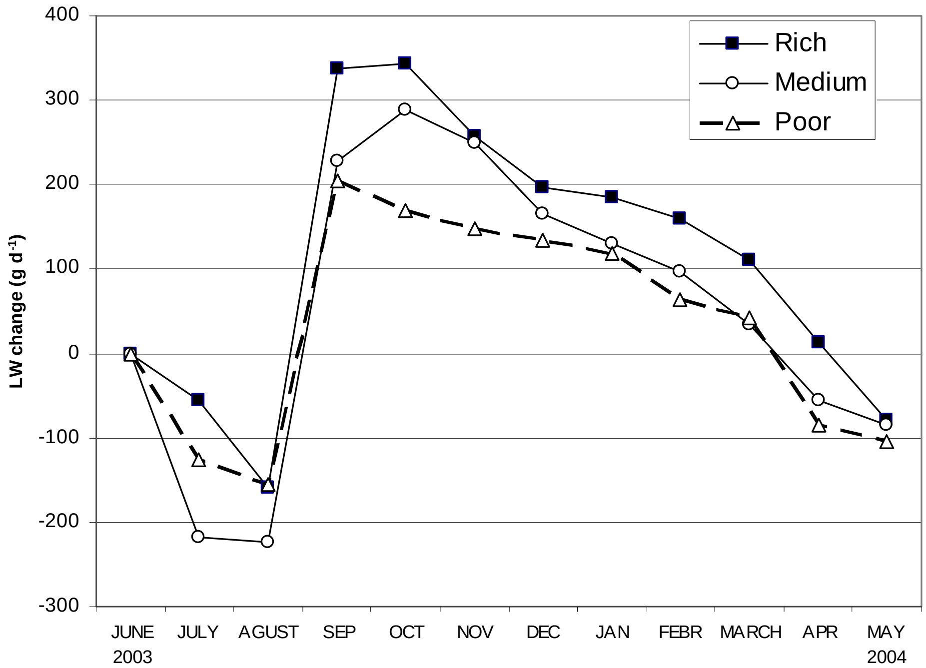


Figure 6. Observed average daily LW change per month of cattle for three farm groups in Teghane, Northern Highlands of Ethiopia

The correlation between 'potential' and observed annual LWG (Figure 7) was high (R^2= 0.74) for the rich farm group, but low for the two other groups (i.e., R^2 = 0.57 for the medium and 0.56 for the poor group). The points for the rich farm group are close to the x = y-line, and substantially below that line for the medium and poor groups.

3.7 Draught, milk and manure production

In the Northern Highlands of Ethiopia, land is normally tilled using a pair of indigenous Zebu oxen, pulling the local traditional plough, the "maresha". In Teghane, on average the land is tilled in 3 rounds (two rounds before seeding and a final round directly following seeding). For the first, second and third round 8, 7 and 6 days, respectively are required with 6 working hours per day, adding to 252 h ha^{-1} during the study time. In addition, for threshing of a hectare of crop product, on average 144 h are required (four rounds of 6 h, using 6 oxen). For transport, donkeys are used, hence cattle draught power is excluded.

Farmers in the survey reported that milk production is on average restricted to 4 months after calving because of nutritional constraints. Daily milk offtake was estimated at between 1 and 1.5 kg. At a calving interval of 2 years and a milk yield of between 120 and 180 kg per lactation, annual milk yield is 60 to 90 kg cow^{-1}. Estimated annual dry OM manure production was 612, 597 and 575 kg yr^{-1} TLU^{-1}, respectively for rich, medium and poor farm groups and the differences between rich and poor and poor and medium are statistically significant (P<0.05).

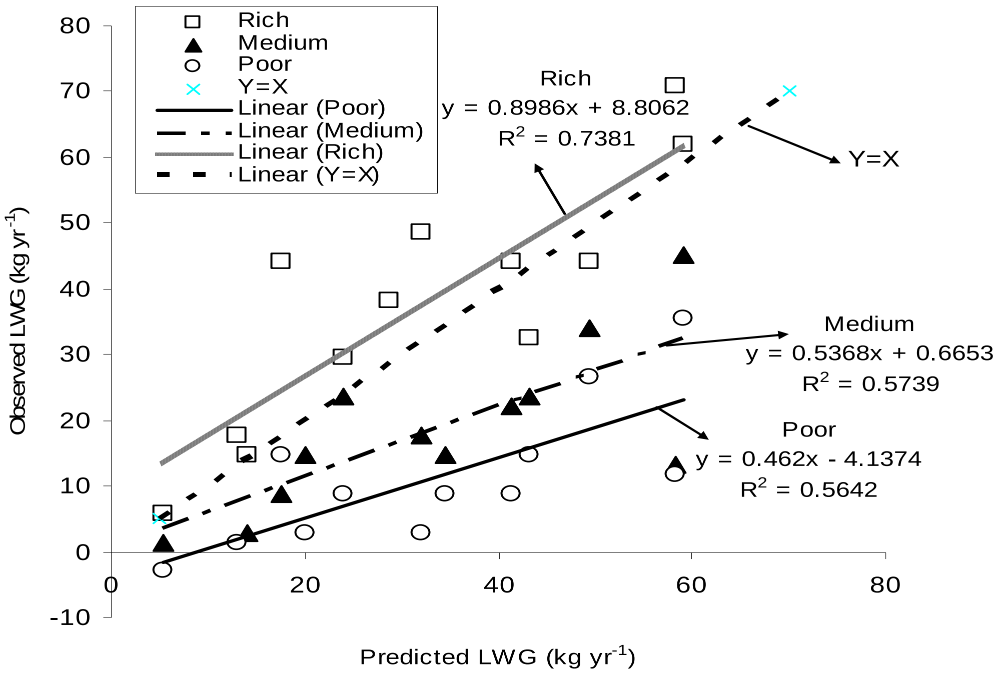


Figure 7. Predicted and observed LWG (kg yr^{-1}) by farm group in Teghane, Northern Highlands of Ethiopia

3.8 Gross revenues from livestock

Average livestock holdings of the sampled households per farm group at the end of the monitoring period (Table 8), combined with information on individual animal production performance (Table 9), and on market prices of live animals, animal products, draught power and fertilizer (Table 10) were used as a basis for estimation of gross annual returns from livestock.

Annual gross revenues per animal ranged from 8 Birr for a ram to 363 Birr for a cow (Table 11). Out of 284 Birr gross revenues per ox, about 40% is contributed by manure production. For a cow, 41% of the gross revenues is from milk production. For the young ox, calf, ewe and lamb, meat production is the major source, accounting for 67, 81, 77 and 91% of the total gross revenues, respectively.

Table 8. Average livestock numbers per farm group in Teghane, Northern Highlands of Ethiopia in June 2004

Livestock	Rich (5*)	Medium (7*)	Poor (12*)
Oxen	2.8	1.0	0.5
Cows	3.0	1.1	0.5
Heifers	1.0	--	--
Young oxen	1.0	1.2	0.25
Calves	1.4	0.5	--
Lambs	6.0	5.0	2.3
Ewes	6.6	6.0	4.0
Rams	1.0	1.0	1.0
Donkeys female	1.2	1.0	0.5
Donkeys male	1.0	--	--

*Sample size

Table 9. Individual animal production performance in Teghane, Northern Highlands of Ethiopia (2004)

	Ox	*Cow*	*Heifer*	*Young ox*	*Calf*	*Lamb*	*Ewe*	*Ram*	*Donkey female*	*Donkey male*
Progeny[1]	-	0.5	-	-	-	-	1.2	-	0.5	-
Annual milk offtake (kg)	-	75	-	-	-	-	-	-	-	-
LWG yr^{-1} (kg)	16	17	19	38	20	10	-	-	-	-
Average LW (kg)	300	250	150	200	50	10	22	22	90	90
Manure output (kg DM yr^{-1})[2]	690	575	345	460	115	23	51	51	207	207
Draught power (d)[3]	21	-	-	-	-	-	-	-	-	-

[1]Progeny: calf for cow, lamb for ewe, foal for donkey
[2]Manure output estimated at 1% of body weight DM equivalent (Gryseels, 1988). Nutrients in manure: 15, 6 and 19 g kg^{-1} of manure DM for N, P and K respectively. Nutrients in manure are valued on the basis of fertilizer prices (2004): N: 7.6 Birr kg^{-1}, P: 19.55 Birr kg^{-1}, K: 5.29 Birr kg^{-1}. To account for the labor costs of manure management in the manure pit, transport of manure from stable to cultivated fields and its application in the field half of the nutrient costs are accounted (i.e., 1 kg DM manure = {(1*0.015 N* 7.6 Birr) + (1*0.006P * 19.55 Birr) + (1*0.019 K*5.29)}/2 = 0.166).
[3]Draught-power estimated at 252 h/ha for ploughing. This is equivalent to 21 days of 6 working hours. Cost of an oxen day set to 5 Birr.

Overall gross revenues per farm from livestock, estimated by summing the gross revenues of all animals (Table 12), equalled 3116 Birr for the rich, 1602 for the medium and 694 for the poor farm group. For all farm groups, the largest contribution was from the cows (35% for the rich, 25% for the medium and 26% for the poor), followed by the oxen (25%) for the rich and by lambs for both the medium (23%) and the poor (24%) farm groups.

Table 10. Average market prices of animals and animal products, fertilizers and draught power in Teghane, Northern Highlands of Ethiopia, 2004

Item	Price[b] (Ethiopian Birr[a])
a. Calf	100
b. Lamb	15
c. Foal	50
d. Milk (kg)	2.00
e. Beef (kg LW)	4.00
f. Mutton (kg LW)	7.00
g. N fertilizer (kg^{-1})	7.60
h. P fertilizer (kg^{-1})	19.55
i. K fertilizer (kg^{-1})	5.29
j. Draught power (oxen-day)	5.00

[a]One Ethiopian Birr ~ 0.12 US$

[b]Average market price in Atsbi market in the survey period

Table 11. Gross revenues per unit livestock (Birr[a]/animal) in Teghane, Northern Highlands of Ethiopia, 2004

Source of revenue	Ox	Cow	Heifer	Young ox	Calf	Lamb	Ewe	Ram	Donkey female	Donkey male
Progeny		50					18		25	
Milk		150								
Meat	64	68	76	152	80	90	--			
Manure	115	95	57	76	19	4	8	8	34	34
Draught power	105									
Total revenues	284	363	133	228	99	94	26	8	59	34

[a]One Ethiopian Birr = ~ 0.12 US$

3.9 Returns on investments in sheep

In Teghane, farmers invest in sheep whenever surplus money is available. The model parameters and computational procedure to calculate the returns on such investments are indicated in Table 13, i.e., productive performance of sheep (items A to K), average market prices (items L to N) and the estimation procedure (items O to V).

Table 12. Gross revenues from livestock (Birr[a] farm^{-1}) per farm group in Teghane, Northern Highlands of Ethiopia (2004)

	Rich	Medium	Poor
Ox	794	284	142
Cow	1090	400	182
Heifer	133	--	--
Young ox	228	274	57
Calf	139	50	-
Lamb	443	369	170
Ewe	174	158	106
Ram	8	8	8
Donkey (female)	71	59	30
Donkey (male)	34	--	--
Total revenues	3116	1602	694

[a]One Ethiopian Birr = ~ 0.12 US$

Table 13. Model parameters and calculation procedure to estimate annual rate of return from investments in sheep in Teghane, Northern Highlands of Ethiopia (2004)

Parameter	Coefficients
A. Average litter size	1
B. Parturition interval[a]	300 days
C. Annual reproduction rate=1x365/300[a]	1.22
D. Survival rate to three months[a]	0.72
E. Survival rate from three to twelve months[a]	0.90
F. Survival rate zero to twelve months (D x E)[a]	0.65
G. Effective lambing rate (C x F)[a]	0.79
H. Liveweight at twelve months[a]	15 kg
I. Liveweight production per ewe (G x H)	11.85kg
J. Number of ewes per ram	7[1], 6[2], 4[3]
K. Mortality of breeding stock[a]	0.18
L. Mean price per kg liveweight[b]	7.0
M. Price per adult ewe[b]	154 Birr
N. Price per adult ram[b]	154 Birr
O. Gross output per ewe (I x L)	82.95 Birr
P. Cost of ewe mortality (K x M)	27 Birr
Q. Cost of ram mortality (K x N)	28.8 Birr
R. Breeding stock depreciation (P + Q/J)	31.7[1], 32.3[2], 34.7[3] Birr
S. Cost of veterinary care sheep^{-1} per year[b]	5 Birr
T. Net returns per ewe per year (O - R -S)	46.27[1], 45.61[2], 43.30[3] Birr
U. Capital Investment per ewe (M + N/J)	176.00[1], 179.67[2], 192.50[3] Birr
V. Annual rate of return (T/U x 100)	26.3%[1], 25.4%[2], 22.5%[3]

[1]Rich farm; [2]Medium farm; [3]Poor farm

Source: [a]Gryseels, 1988, [b]Survey market price (Atsbi) (2003-2004)

Required capital investment was 176, 180 and 193 Birr, respectively for the rich, medium and poor farm group. To estimate the true returns on investment, allowance must be made for replacement of the breeding stock to maintain a steady-state flock structure (Upton, 1985). This is taken into account through the breeding stock depreciation (Table 13 item R), estimated at 31.7 Birr for the rich, 32.3 for the medium and 34.7 for the poor farm group. Net returns per ewe amount to 46.3 Birr for the rich, 45.6 for the medium and 43.3 for the poor farm group. The annual rate of return on investments on sheep was 26.3% for the rich, 25.4 for the medium and 22.5 for the poor farm group.

4 Discussion and conclusion

In the Northern Highlands of Ethiopia farmers engage in integrated crop-livestock systems within the same management unit, where both components interact through exchange of inputs and outputs as illustrated in Figure 1, similar to the farming system in the Central Highlands of Ethiopia as described by Gryseels (1988). In these systems, livestock support arable farming (draught, manure), while serving additional objectives, such as income generation, insurance and food security, and investments.

In Teghane, in the medium and poor farm groups more than 40% of the total feed DOM derived from crop residues, in agreement with the findings of Gryseels (1988), De Leeuw (1997) and Kassa (2003), whereas in the rich farm group they accounted for 30%. All crop residues in the study area are characterized by a low metabolizable energy content (<8 MJ kg^{-1} (DM)) and low crude protein content (<7 g kg^{-1} DM), similar to the results of Daniel (1993) (i.e., 6.8 MJ kg^{-1} (DM) for barley and 6.2 MJ kg^{-1} (DM) and 40 g CP kg^{-1} DM for wheat) and Shanahan et al. (2004) (36 and 41g CP kg^{-1} DM, respectively for wheat and barley).

Availability and quality of forage and hence live weight dynamics show a distinctly seasonal pattern. In the early rainy season, feed availability is very low and animals are tethered or closely herded to prevent crop damage and allow undisturbed growth of grasses, and during this period liveweight losses are observed in all animal groups. In the late wet season (September to November) cattle graze natural pasture, and the high availability and quality of this feed resource is reflected in the high observed rates of liveweight increase. In the dry season, from crop harvest (end of December) to the start of land preparation (April), animals graze aftermaths in crop fields and are supplemented with collected residues in the stable. Available feed in the field gradually decreases (in both quantity and quality), as does the rate of liveweight gain. From May to July herbaceous feed resources are hardly available and the coping strategy consists of feeding leaves of prickly pear. From April onwards, animals loose live weight, and the maximum loss is observed in August. In very critical times, animals die due to lack of feed. These results are in agreement with those of Gryseels (1988) in the Central Highlands of Ethiopia, who reported live weight losses from 275 kg to 240 kg in the critical season and increases to 294 kg in the season with relatively abundant feed availability.

Comparison of observed live weight gain with the optimal showed that both values were in close agreement ($R^2 = 74$) for the rich farms, implying favorable nutritional conditions and their animal growth rate matches with the growth rate calculated from equation 4, whereas observed LWG in the medium and poor farm groups was significantly below the optimal, associated with low quality feed.

Smallholders sell surplus grain. They do not have access to banking facilities. On the other hand, savings in cash create social pressure to share with/borrow to others. This problem is avoided by investing in animals, which the farmers consider a reliable and secure capital savings asset. An average rate of return above 22% has been observed (but involves high risk when feed is critically unavailable) which is considerably higher than the interest rate on most formal credits and investing in sheep is thus worthwhile for smallholders, which is in agreement with the findings of Upton (1985), who found an average rate of return of 30% for goat enterprises in South West Nigeria.

As can be deduced from the feed balances, meat production (LWG) and milk production are not the main objectives of livestock keeping for smallholders, but manure, draught power, progeny and capital asset are more important. Depending on the objective, the optimal pattern of use of the available feed resources is different, supporting different livestock numbers (Ifar, 1996; Savadogo, 2000). If manure production was the sole objective, actual herd size in 2004 would be optimal. For optimization of other objectives, either HS should be reduced to the level that can be supported by the best quality feed (Zemmelink et al., 2003 and Assefa et al., Chapter 5) or production of quality feed be increased. For instance, if the objective would be optimum milk production from the local Zebu cattle, i.e., 3 kg milk cow^{-1} d^{-1} for 6 months, only the good quality feed, i.e., native grass or hay would be used and hence herd size should be reduced by 25% for the rich, 60% for the medium and 75% for the poor farm group, compared to the values in 2004.

To improve animal performance on smallholder farms in the Northern Highlands of Ethiopia, restricted availability of feed, that moreover is of low quality is a major constraint that needs to be tackled. Feed quality and quantity can be increased in two ways. First, about 43% of the currently cultivated land in the area is on Leptosols. These soils are generally located on sloping land, are very shallow, and crop production on these soils is extremely low. Discontinuing cultivation of this land, and using it in cut and carry feeding systems would significantly increase quality feed supply for livestock. Secondly, rainfall is monomodal and grass growth thus restricted to one season (August to October). Much of the current pasture land is located in the valley bottom, where gravity irrigation is possible. Approximately in the middle of the valley bottom a micro dam has been constructed to irrigate cultivated fields in the dry season for vegetable and cereal crop production. Not all the available water is being used, thus introducing proper water management would allow irrigation of pasture lands on the lower slope side of the dam in the dry season to increase quality and quantity of the feed supply.

In this study quality of feed (OMD and N contents) has been used as a base for estimation of daily feed intake and calculation of feed balance whereas in Kassa et al. (2003) a fixed daily DM intake rate of all feeds has been considered, disregarding the quality of feed. The correlation between total available DOM and number of TLU per farm (Figure 4) shows similar trends for all farm groups, whereas feed balances and observed LWG in poor farms are significantly lower than in the rich. From this we can deduce that considering a fixed intake rate of DM or relating available DM to HS is inaccurate for evaluating the performance of livestock in relation to available feed resources. The presence of large quantities of low quality feed (straws) does not insure enough IME, because voluntary intake and digestion of such feeds are generally low (Oosting, 1993).

The annual feed balance was negative for all farm groups but more for the poor farms. The result in this study for poor farm group is in contrast to the findings of Kassa et al. (2003), who reported positive feed balances (i.e., 22 % excess of the demand) in the Eastern Highlands of Ethiopia. The balances for the medium and rich farms in this study are slightly below maintenance requirements whereas Kassa et al. (op. cit.) have reported 87% and 81% below the demand respectively for the medium and the well-to-do farm groups and yet, they have reported that, with this much deficit livestock survive, produce and reproduce. Similarly, in this study, whereas feed balances are negative, on average, annual LWG has been observed in cattle in all farm groups, though prickly pear contribution has not been accounted for, because it is used as a coping strategy, the feed obtained from this resource would not be sufficient to cover the deficit and ME requirement for the observed LWG. Thus, the findings of this study suggests that there is a knowledge gap and much remains to be known about the ME requirement of tropical livestock in light of the quality, quantity and availability of feeds and how local stock produce and reproduces under feed stress environment in smallholder tropical farms.

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Chapter 5

Feed resources, livestock production and soil carbon dynamics in Teghane, Northern Highlands of Ethiopia

Submitted: Agricultural systems

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Feed resources, livestock production and soil carbon dynamics in Teghane, Northern Highlands of Ethiopia

Abstract

In the Northern Highlands of Ethiopia, integrated crop-livestock production is the dominant form of agricultural production within the smallholder farms. Feed availability and quality are serious constraints to livestock production in Ethiopia in general, and in its Northern Highlands in particular. The objective of this study was to describe the relationship between feed availability and quality and live weight, milk and manure production and soil C balance in Teghane, Northern Highlands of Ethiopia. The so-called JAVA model procedure, that essentially predicts metabolizable energy intake on the basis of feed quality and quantity and estimates animal production, has been used. Forages ranked according to their quality (on the basis of metabolizable energy intake by livestock) in descending order were stepwise included in mixed rations to calculate the trade-offs between feed quantity and quality. In the model, soil C balance is described in relation to soil organic matter decomposition and C input from roots, grazing and/or harvesting losses and feed residues and manure. Moreover, an analysis of monetary values of liveweight production/loss, manure and draught power are included. The results of the model show that with complete use of all available feed 2579 tropical livestock unit (TLU) can be fed at a mean liveweight loss of 55 g TLU^{-1} d^{-1}, mean manure carbon production of 0.88 kg TLU^{-1} d^{-1} and a negative soil C balance, suggesting that the system is not sustainable in terms of soil quality. Mean daily liveweight and milk production per TLU continuously increase with decreasing herd size, while total annual liveweight production reaches a maximum (62 Mg) at the use of the 30% best feeds and a herd size of 630 TLU. The model estimated optimum herd size to attain maximum monetary value of liveweight production, manure and draught power combined at 926 TLU, associated with 50% feed use. Actual herd size in the study area was 1506 TLU. Our results indicate that in areas where feeds of very different quality are available, maximum benefits from livestock and soil C balance can be attained by selective utilization of the best quality feeds, through storage and carry-over. Sustainable development of livestock production in terms of natural resources quality requires increased production per head associated with smaller total herd size. However, such a strategy would jeopardize additional functions that livestock serve, such as that of a capital asset and manure production for fuel.

Additional keywords: Optimum feed utilization, optimum herd size, feed quality, JAVA program, village scale

1 Introduction

Ethiopia has the largest livestock population in Africa (Kassa, 2003), of which about 75% (estimated at 45 million TLU[1]) is concentrated in the highlands, where smallholders practice livestock and crop production within the same farm unit. In these mixed crop-livestock systems, livestock are kept to support crop production (providing powers and manure), diversify household income sources through sales

[1] TLU = Tropical Livestock Unit, a 'hypothetical' animal of 250 kg liveweight

of meat and milk, while moreover, they serve as a capital asset (savings account, investment) (cf. Udo and Cornelissen, 1998). Despite their large numbers, it has become increasingly difficult for livestock in the smallholder farms to satisfactorily perform these various functions (Assefa et al., Chapter 4).

For livestock to perform well, i.e. to realize the desired objectives, an adequate supply of quality feed is a basic requirement. When quality is low, forages alone may not be able to support the desired level of animal performance (Moore and Sollenberger, 2002). In tropical Africa, low quality residues from cereal crops and pulses, either fed in the stable or through post-harvest stubble grazing, account for 35 to over 90% of all feed intake in different animal production systems (De Leeuw, 1997). A study in the Eastern Highlands of Ethiopia (Kassa et al., 2003) indicated that the major part of the feed originated from by-products from cropped plots, and that feed availability is insufficient to cover the annual requirements of livestock. In the Central Highlands of Ethiopia, 40% of the livestock feed intake originated from crop by-products, particularly cereal straws (Gryseels, 1988).

In Teghane, Northern Highlands of Ethiopia, over 70% (survey in 2003-2004) of the available feed dry matter (DM) consisted of crop residues with inherently low nutritive value (De Leeuw, 1997; Zemmelink, 1995; Oosting, 1993). Animal production is a function of both amount and quality of feed intake (Kamalzadeh et al., 1997; Ryan et al., 1993). Availability of high quality feed will lead to intake in accordance with the animal's energy requirements, so that potential liveweight and/or milk production can be achieved (Van de Ven et al., 2003). In situations where both low and high quality feeds are available, farmers have to select the best quality feeds, or a limited number of animals should be allowed to select, to achieve optimum production for a given production objective (Zemmelink, 1995). Optimum feed use and herd size is defined here as the best possible use of available feed and commensurate herd size for maximum herd productivity.

The objective of the current study was to describe the relationships between feed availability (quantity and quality) and feed intake on the one hand and live weight and milk production and carbon (C) output in manure on the other in Teghane, Northern Highlands of Ethiopia and to assess the best feed utilization pattern in view of various production objectives of farmers, i.e. liveweight production (LWP), milk production, draught power and maintenance of soil carbon stock, often used as an indicator of soil fertility.

2 Materials and methods

2.1 The study area

The study was conducted during 2002-2004 in Teghane, Atsbi Wonberta district, situated between 13^0 52' 53" and 13^0 53' 37" N and between 39^0 42' 05" and 39^0 43' 57" E, in Tigray Regional State in the Northern Highlands of Ethiopia, covering an area of 13.56 km^2. Its altitude ranges from 2710 to 2899 m above mean sea level. The climate is "Dega" (WBISPPO, 2002), with average annual monomodal rainfall from July to September of 541 mm (for the period 1901-2002, coefficient of variation 53%, a nearby place to Teghane at 14^0N and 40^0E (Viner, 2003)) (Figure 1). For the period 2000-2004, average rainfall was 532 mm (Atsbi World Vision, 2004), comparable to the long term average.

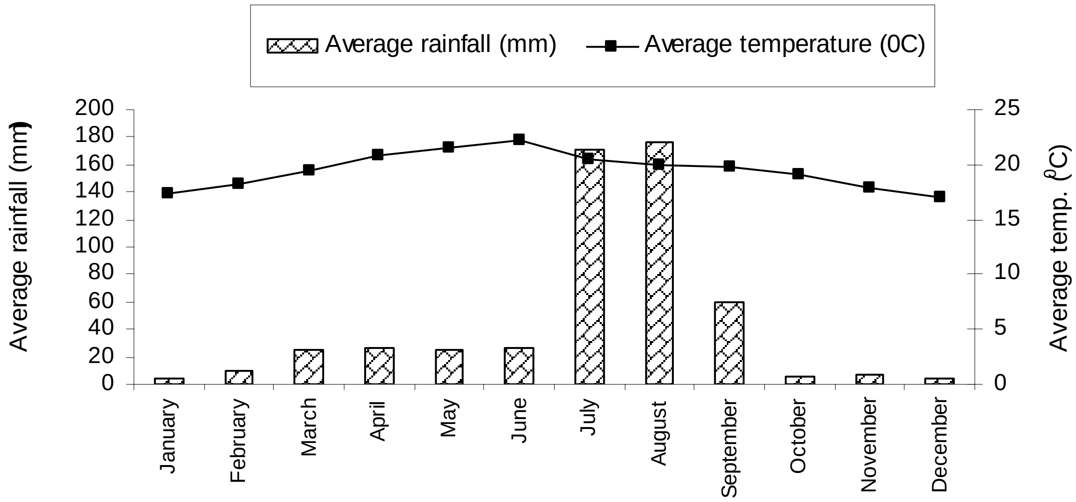


Figure 1. Average monthly rainfall and temperature for Teghane, 1901-2002 (Source: Viner, 2003)

2.2 Methodology

Village feed availability

A field survey was conducted in December 2002 to delineate the boundaries of land use/cover (LUC) types of the study area using a GPS, on the basis of the micro-catchment outline of Teghane. Topographic maps (Eth 4-1339 B1, Wikro and Eth 4-1339 B2, Koneba) (EMA, 1997) and aerial photographs of 1994 were used to assist in the field delineation. The GPS records were imported into ArcView GIS, and digitized as polygons. During digitizing, aerial photographs were used to check GPS records of salient physical features (churches, stream confluences, road branching points). Following digitizing of its boundaries (Figure 2), the area of each LUC-type was calculated (Table 1), using the facilities in ArcView (ESRI, 2002).

Table 1. Land use parameters and feed production in Teghane, Northern Highlands of Ethiopia, July 2003 – August 2004

Land use/cover type	area (ha)	Fraction of area of cultivated land/ natural pasture	DM feed availability[1] (Mg yr^{-1})
Cultivated land	925.5		-
Faba bean		0.07*	121.5
Wheat		0.16*	410.9
Field pea		0.08*	100.0
Barley		0.69*	2059.4
open woodland	168.4		-
Natural pastureland	195.7		-
Valley bottom		0.52**	786.0
Outside valley bottom		0.48**	246.5
Rock out crop	44.4		-
Micro-dam	22.5		-
Total	1356.4		3724.3

[1]Takes into account harvest/grazing losses of 25%, *Fraction of total cultivated land
**Fraction of total pasture area

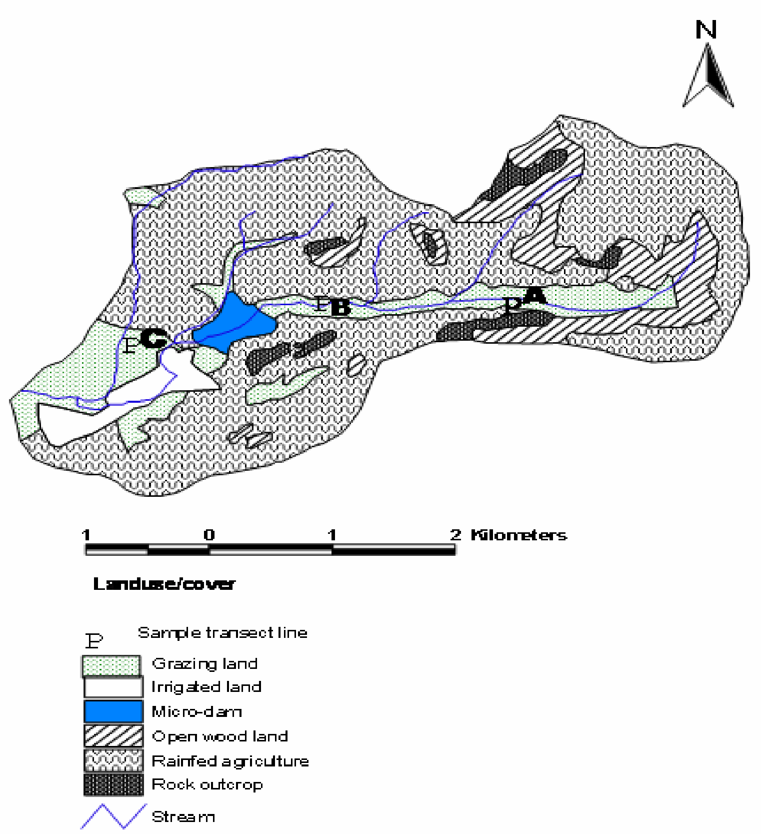


Figure 2. Land use/cover (LUC) and sampling transect lines in Teghane, Northern Highlands of Ethiopia

Areas under different crops (in the period between July 2003 and June 2004) in the study area were estimated by multiplying the total area of cultivated land by the average fraction of the crops in farmers' holdings, determined from an extensive farm survey. Similarly, the areas of pasture land in the valley bottom and outside the valley bottom were estimated by multiplying the total pasture area by the average fraction of pasture land in the valley bottom and outside in the holdings of the sampled farmers (Table 1).

Three grazing areas, representative for the village were selected. At each selected site (A, B and C in Figure 2), three transect lines of 200 meter each were laid out. Along each transect line, five regularly spaced quadrats (0.5 x 0.5 m) were clipped at ground surface to determine standing herbage, and 45 samples were collected for dry matter determination. Pasture DM production in the valley bottom was estimated at 10.3 Mg ha^{-1}, and outside the valley bottom at 3.5 Mg ha^{-1}. Native grass forage availability for the village was estimated by multiplying the pasture area by the estimated DM yield.

Farmers classified the quality of the grasses in their fields into three groups on the basis of observations on feed selection by their livestock: native grass1 (NG1), grasses selected first in the case of abundant pasture availability, including cocksfoot, *Cynodon* spp. and clover spp.; native grass2 (NG2), selected subsequently and including *Pennisetum pilosum*, *Poa annua*, *Andropogon schirensis*, *Setaria* spp., *Eragrostis* spp., *Cyperus* spp. and *Phalaris* spp.; and native grass3 (NG3), grazed last, such as *Cyperus* spp., *Polygonium* spp., *Hyparrhenia* spp. and forbs. The field samples were partitioned into the three classes in the Mekelle University laboratory, and DM of each class determined. The contribution of the three quality classes NG1, NG2 and NG3 was estimated at 12.5, 25.8 and 61.7% of the total DM of all samples, respectively, from which biomass production of the three groups was estimated. Total DM availability for each forage type was estimated by subtracting 25% unavoidable grazing and/or harvesting losses in the field (Zemmelink, 1995).

For determination of chemical composition, 27 samples (7 from NG1, 13 from NG2 and 7 from NG3) were randomly selected and analyzed at the International Livestock Research Institute (ILRI) in Addis Ababa. Residues of wheat, barley, faba bean and field pea were collected from farmers' fields for determination of dry matter and chemical composition.

Laboratory analyses

DM was determined after oven-drying at 105 ^{0}C overnight and organic matter (OM) through dry ashing at 500 ^{0}C overnight. Digestibility was determined through *in vitro* rumen systems that simulate the digestion process, following the Tilley and Terry (1963) two-stage method. The modified Tilley-Terry system (Van Soest and Robertson, 1985) substitutes the second stage with a neutral-detergent extraction (Ogbai and Berhan, 1997). Neutral Detergent Fiber (NDF) and Acid Detergent Fiber (ADF) were determined by neutral detergent and acid detergent extraction, respectively (van Soest and Robertson, 1985). Crude protein (CP) content was calculated from nitrogen (N) content determined by the Kjeldahl procedure, by multiplying by 6.25.

Model calculations

Productivity of livestock is affected by a large number of factors, in addition to quantity and quality of available feed, such as genetic characteristics of the animal, the physical environment and health, but these are not considered in this study.

Calculations have been performed following the JAVA program procedure (Zemmelink et al., 2003; Ifar, 1996; Zemmelink et al., 1992), modified and re-written in Excel. Model calculations include: i) intake of organic matter (IOM), g (kg LW)$^{-0.75}$ d^{-1}, ii) intake of digestible organic matter (IDOM), g (kg LW)$^{-0.75}$ d^{-1}, iii) intake of metabolizable energy (IME), kJ (kg LW)$^{-0.75}$ d^{-1} , iv) herd size (HS) (TLU) at a given level of feed use, v) mean liveweight gain (MLWG), g TLU^{-1} d^{-1} and total annual liveweight production (TLWP) of the herd, Mg yr^{-1}, vi) mean milk production (MMP), kg TLU^{-1} d^{-1}, total annual milk production (TMP) of the herd, kg yr^{-1} and vii) mean manure C production (MMCP), kg TLU^{-1} d^{-1} and total annual manure C production (TMCP) of the herd, Mg yr^{-1}, total annual C production from unused feed and total annual manure C losses via use of manure for fuel.

Calculations have been performed for one year, comprising 12 months, following two approaches: i) pooling all feeds at the beginning of the year and assuming appropriate storage and carry-over between seasons where necessary, and ii) dividing the year into three periods of 4 months each, and taking into account seasonal variation in feed availability (Table 2).

Intake of organic matter is estimated from organic matter digestibility (OMD, g/100g) and N content (N, g/100g) of the feed, using the transfer function developed for sheep by Ketelaars and Tolkamp (1991), multiplied by 1.33 to account for the higher metabolizable energy requirements of cattle (Zemmelink et al., 2003; Ifar, 1996):

$$IOM = -42.78+2.3039OMD-0.0175OMD^2-1.8872N^2+0.2242OMD*N \quad (1)$$

In the calculations for mixed feeds, weighted[2] average values of OMD and N content were used. IOM is multiplied by OMD to arrive at IDOM. IDOM is converted to IME by assuming 1 g IDOM to be equivalent to 15.8 kJ ME (Zemmelink et al., 2003; Ifar, 1996). In the program, available feeds are assumed to be consumed in order of decreasing IME.

Table 2. Intake of metabolizable energy (IME) and availability of various feed resources in Teghane, Northern Ethiopian Highlands, during 2003 (season I*) and 2004 (seasons II* and III*)

Feed	IME (kJ (kg LW)$^{-0.75}$)	Available dry matter (Mg) I	II	III
Native grass-1	876	109.7	-	9.4
Native grass-2	781	247.0	-	19.4
Native grass-3	621	519.5	71.2	56.4
Faba bean haulms	548	-	121.5	-
Field pea haulms	410	-	100.0	-
Barley straw	394	-	1906.6	152.8
Wheat straw	348	-	410.9	-
Total		876.2	2610.2	238.0

* Season I: September, October, November & December; Season II: January, February, March & April; Season III: May, June, July & August

Total herd size (HS, TLU) that can be supported at a given proportion of feed use is estimated by:

$$HS = TOMafu/IOM \quad (2)$$

where,

TOMafu : total available feed OM at a given proportion of feed use (Mg yr^{-1})

IOM : estimated OM intake (Mg TLU^{-1} yr^{-1})

[2] Weighted OM digestibility = Σ (OM of each forage multiplied by its digestibility)/ Σ (OM of each forage). The same procedure has been applied to compute weighted N content.

MLWG is computed as:

$$MLWG = [(IME - 512)/38.1]*(250^{0.75}) \quad (3)$$

where,

512	: maintenance energy requirement (kJ (kg LW)$^{-0.75}$ d^{-1})
38.1	: ME needed per unit of liveweight gain (kJ g^{-1}) (Zemmelink et al., 2003; Ifar, 1996)
250	: liveweight of a TLU, a hypothetical animal, used to bring all animal types under a common denominator.

TLWP for the current herd size (HS) was estimated from observed average LW increase per TLU of each farm group and multiplying by the corresponding HS (TLU) (Assefa et al., Chapter 4).

The monetary value of LWP, valued at 4 Birr[3] kg^{-1} (Assefa et al., Chapter 4) was compared with the value of the combined objectives of LWP (after subtracting the energy requirement of 1.68 MJ hr^{-1} for ploughing (Van der Lee et al., 1993)), manure production and draught power, for different optimum feed resource levels. Nutrient contents of 15, 6 and 19 g kg^{-1} of manure DM for N, P and K were considered, respectively. Nutrients in manure were valued on the basis of fertilizer prices (2004): N: 7.6 Birr kg^{-1}, P: 19.55, K: 5.29 after subtracting half the value to account for the labor costs of manure management in the manure pit, transport and its application to the fields. Annual draught-power requirements were estimated at 252 hrs ha^{-1}, which is equivalent to 21 days of 6 working hours ha^{-1} by an oxen team of two. Total cultivated land area was 926 ha and maximum of 926 oxen are considered for draught power for the village. An oxen day was valued at 5 Birr (Assefa et al., Chapter 4).

Milk production (MMP) is assumed to last for 180 days, with a calving interval of 2 years, with IME in excess of maintenance being used for milk production:

$$MMP = (IME - MN)/[(NE_{lac})/0.6] \quad (4)$$

where,

IME	: intake of metabolizable energy (MJ TLU^{-1} d^{-1})
MN	: maintenance energy requirement (MJ TLU^{-1} d^{-1})
NE_{lac}	: net energy requirements for milk production (MJ kg^{-1})

[3] One Ethiopian Birr = ~ 0.12 US$ (2004)

0.6 : conversion factor from net energy to ME (De Visser et al., 2000)

Net energy requirement for milk production was estimated on the basis of a milk fat content of 40 g kg^{-1} according to De Visser et al. (2000) as 3.133 MJ kg^{-1} milk.

Mean manure carbon (C) production is estimated by:

$$MMCP = (IOM – IDOM)/1.78 \quad (5)$$

where,

IDOM : intake of digestible organic matter (kg TLU^{-1} d^{-1})

1.78 : conversion factor from OM to C (Sweet, 2004)

In the soil C balance computation, C input from manure is estimated in two ways: (i) assuming that all C from manure is incorporated in the soil, and (ii) assuming that the C from manure deposited in the stable (estimated at 58%: livestock are in the stable and in the field for 14 and 10 hrs d^{-1}, respectively) is lost via burning of manure as fuel. By considering the top 0.20 m of soil[4], a relative decomposition rate of soil organic carbon of 0.06 kg kg^{-1} yr^{-1} and humification coefficients (yr^{-1}) of 0.5 for crop residues, roots and leftovers and 0.3 for manure (de Ridder and van Keulen, 1990), the soil C balance is computed as:

$$C_b = (C_{mn} + C_{uf} + C_{rcy} + C_{ram}) – C_{sd} \quad (6a)$$

where,

C_{mn} : C from manure (Mg ha^{-1})

C_{uf} : C from unused feed (Mg ha^{-1})

C_{rcy} : C from 25% unavoidable grazing and/or harvesting losses in the field (Mg ha^{-1})

C_{ram} : C from roots (Mg ha^{-1})

C_{sd} : weighted average soil C loss via decomposition (Mg ha^{-1})

$$C_b = (C_{mn} + C_{uf} + C_{rcy} + C_{ram}) – C_{sd} - Cf \quad (6b)$$

where,

Cf : C loss via manure fuel (Mg ha^{-1})

[4] Soil units include: Cambisols (covering 335.5 ha, with an organic carbon (OC) content of 23.54 g kg^{-1} and bulk density of 1.285 g cm^{-3}), Luvisols (covering 330.2 ha, with an OC content of 13.97 g kg^{-1} and bulk density of 1.300 g cm^{-3}) and Leptosols (covering 455.5 ha with an OC content of 9.78 g kg^{-1} and bulk density of 1.121 g cm^{-3})

Approximate C from roots (C_{ram}) is derived from the harvest index and a shoot-root ratio of 6 (van Keulen, 1995; Boons-Prins et al., 1993).

Analysis of variance

Data on crude protein content, OMD and metabolizable energy of feeds were subjected to analysis of variance using SPSS (SPSS, 2001).

3 Results

3.1 Feed availability and chemical composition

In the Northern Highlands of Ethiopia, the primary feed resources for ruminants are grasses, forbs and hay from natural pastures, and crop residues (Tables 1 and 2). Animals graze native grasses in the pastures, where 14 species were identified (Assefa et al., Chapter 4). Prickly pear (*Opuntia* spp.) is used as feed in a coping strategy, when other feeds are finished, but has been neglected in this study.

The differences in crude protein content among the grass groups and between grasses and crop residues (Table 3) are significant ($P < 0.05$). Crude protein contents of haulms of faba bean and field pea were higher than those of straws of barley and wheat ($P < 0.05$).

Table 3. Feed quality (g kg^{-1} DM) of various feed resources in Teghane, Northern Ethiopean Highlands, during 2003/2004

Forage type	OM[a]	CP[b]	NDF[c]	OMD[d]	DOM[e]	ME[f] (MJ)
Native grass 1 (n = 7)	922	179	485	681	629	9.94
Native grass 2 (n = 13)	908	146	484	652	593	9.38
Native grass 3 (n =7)	908	121	619	585	533	8.43
Faba bean haulms (n =7)	805	65	567	592	455	7.53
Barley straw (n = 7)	869	34	707	524	503	7.20
Wheat straw(n = 7)	853	23	759	504	407	6.77
Field pea haulms (n = 7)	806	63	644	505	430	6.34

[a]OM = Organic matter, [b]CP = Crude protein, [c]NDF = Neutral detergent fibre, [d]OMD = in vitro organic matter digestibility, [e]DOM = Digestible organic matter (OMD * OM), [f]ME = Metabolizable energy

NG1 and NG2 have the highest OMD of all feeds ($P < 0.05$), while faba bean was the third ‘best’ feed, with an OMD (592 g kg^{-1} DM) that is significantly greater than that of all other feeds ($P < 0.05$). Field pea and wheat had least OMD ($P < 0.05$).

ME content of NG1 and NG2 (> 9 MJ kg^{-1} DM) was higher than that of NG3 and crop residues (< 9 MJ kg^{-1} DM) ($P < 0.05$). ME content of faba bean haulms (7.5 MJ kg^{-1} DM) was higher than that of field pea haulms (6.3 MJ kg^{-1} DM) ($P < 0.05$).

3.2 Effects of selective utilization of feed on livestock productivity

Pooled feeds/carry-over

It is implicitly assumed that labor availability to collect, store and chop mixtures of feeds for livestock is as sufficient. With increasing proportion of feed DM utilization, the average nutritive value decreased (Figures 3A-C). Thus, at 5% feed dry matter utilization, the ration was of high quality, with 167 g CP kg^{-1} DM and 672 g DOM kg^{-1} OM. For this ration, IME is 847 kJ (kg LW)$^{-0.75}$ d^{-1}. At this level of feed use, daily MLWG and annual TLWP are 553 g TLU^{-1} and 18.6 Mg, respectively (Figure 4A), and 4 kg of milk TLU^{-1} d^{-1} and 34 Mg of milk annually (Figure 4B) can be produced. Calculated mean daily manure C production (MMCP) and total annual manure C production (TMCP) are 923 g TLU^{-1} and 31.1 Mg, respectively (Figure 4C).

On the other hand, if a large proportion of the feed is used, its average quality was much lower and so are daily MLWG and MMP TLU^{-1}. With increasing utilization of feed, production TLU^{-1} gradually decreased, but total live weight production and total milk production increased up to 30% feed utilization, due to compensation by increasing herd size (Figures 4A and B). At this level of feed use, 630 TLU can be supported at a daily mean live weight gain of 274 g TLU^{-1} and a milk production of 2.0 kg TLU^{-1} d^{-1}. Daily MMCP increases from 911 g (at 1% feed use) to 966 g (at 30% feed use) and subsequently decreased to 877 g TLU^{-1} at 100% feed use (Figure 4C). TMCP continuously increases with increasing feed use until complete utilization.

At 70% feed use, average CP content of the feed was 76 g kg^{-1} DM and DOM 563 g kg^{-1} OM. At this level of feed use, daily IME (kg LW)$^{-0.75}$ was 522 kJ, slightly above maintenance requirements, resulting in a total live weight production of 10.8 Mg yr^{-1} from a HS of 1706 TLU (Figure 4A). HS can increase up to 2579 TLU at

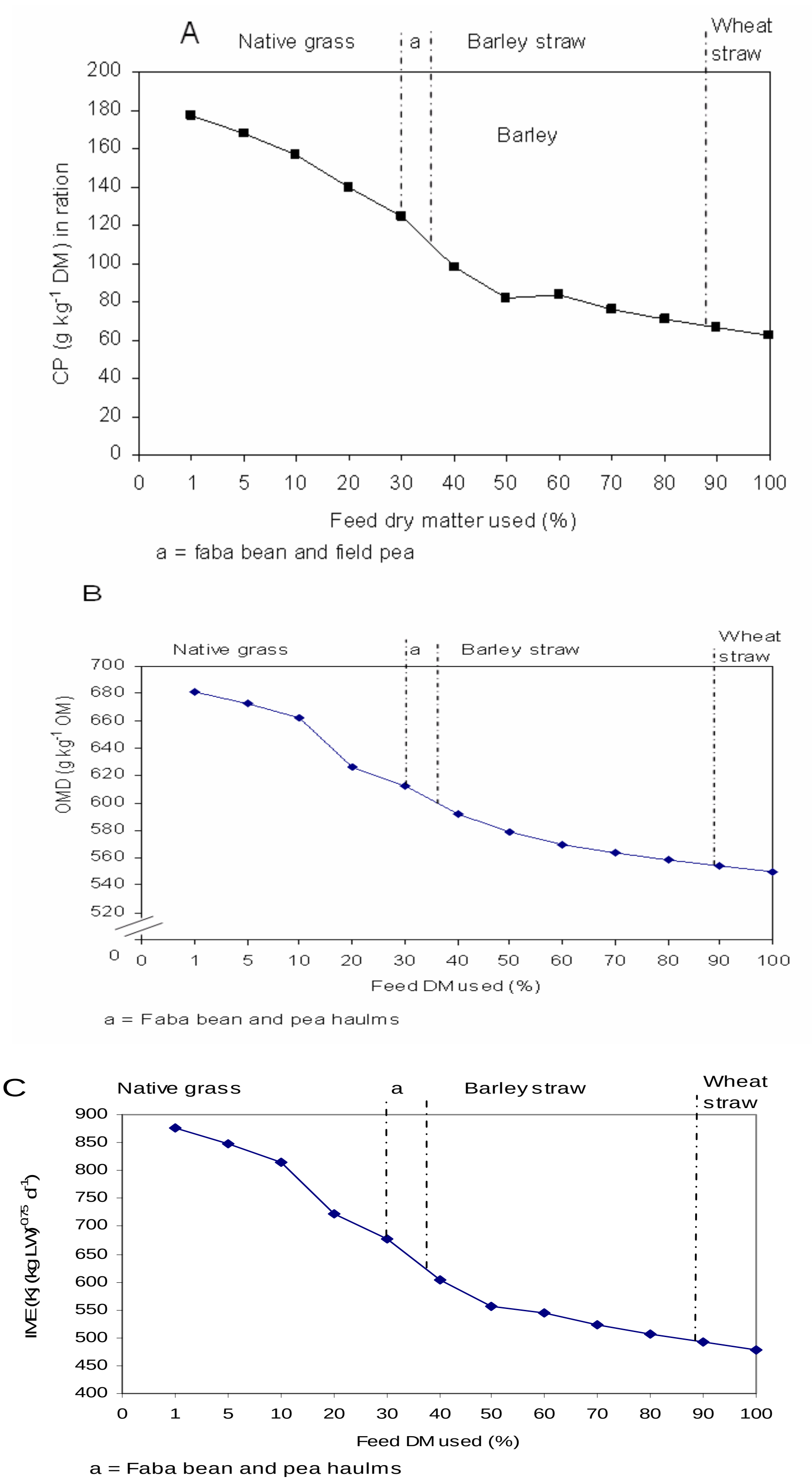


Figure 3. Effect of using various proportions of total feed DM on concentration of crude protein (A), organic matter digestibility (B) and intake of metabolizable energy (C)

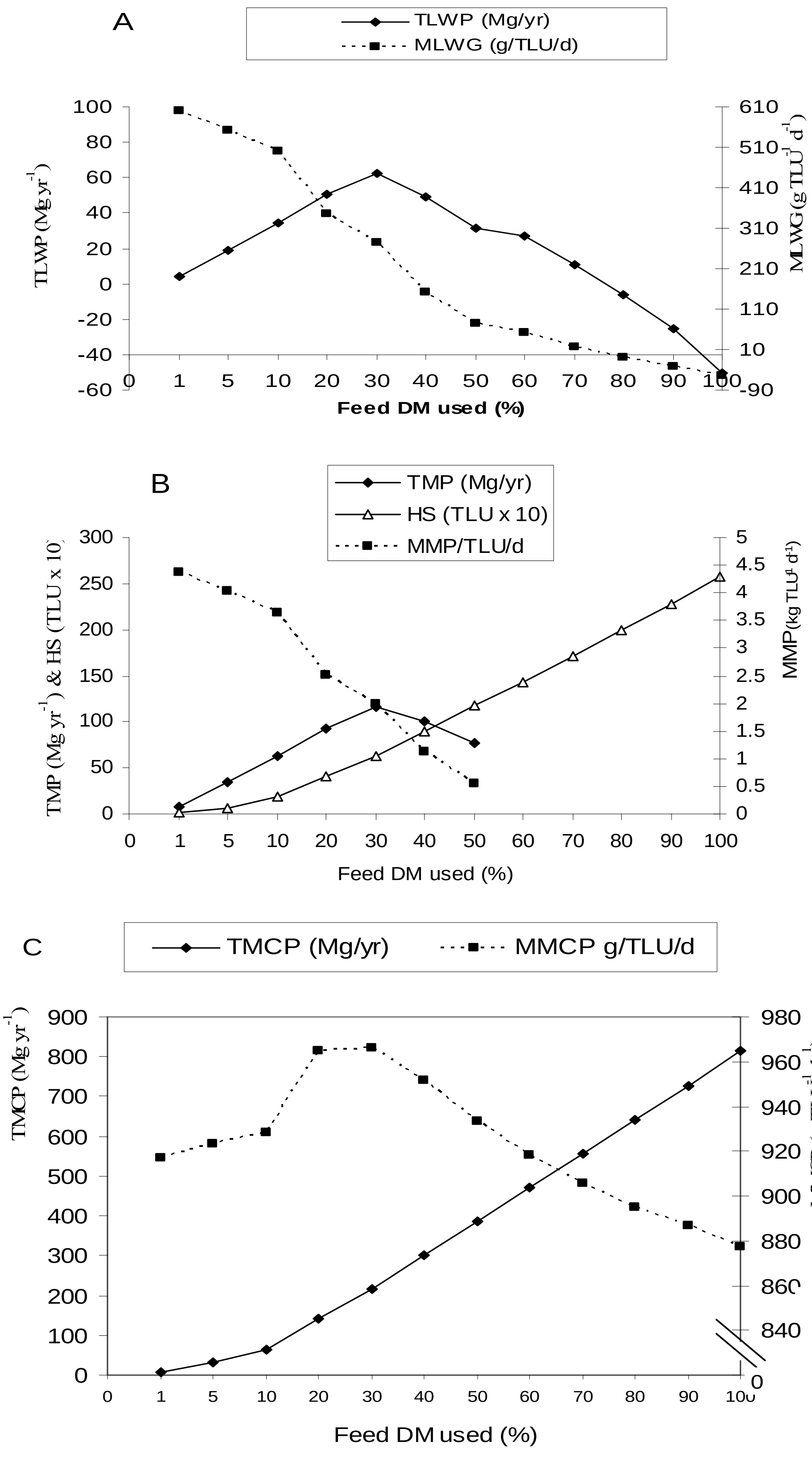


Figure 4. Effect of using various proportions of total feed DM on mean daily live weight production, total liveweight production (A), mean daily and total annual milk production and HS (B) and daily mean and total annual manure C production (C). HS in 4B is also referenced for 4A and 4C

100% feed utilization, but in that situation the average quality of the feed was so poor that IME is 479 kJ (kg LW)$^{-0.75}$ d^{-1}, leading to daily live weight losses of 55 g TLU^{-1} and TLW losses of 50.7 Mg yr^{-1}.

When the monetary value of the combined objectives of LWP, manure production and draught power are considered, 50% feed resource use was the optimum, with 926 TLU, and at 100% feed use the overall result was positive, at a negative value for TLWP (Figure 5).

Seasonal feed availability

When feed availability pooled per season (Table 2), HS varied (Table 4) between 7157 TLU (with MLW loss of 183 g TLU^{-1} d^{-1} and TLW loss of 157.1 Mg) in season II and 574 (with MLW loss of 83 g TLU^{-1} d^{-1} and TLW loss of 5.8 Mg) in season III. IME varied between 720 kJ (kg LW)$^{-0.75}$ d^{-1} in season I and 401 in season II. The quality of much of the feeds in seasons II and III is so poor that animals lose weight.

Table 4. Feed use and some production parameters if all available feeds in each season are used and if the use of available feed is optimized

Feed use	Production parameters	Season I	Season II	Season III
All feeds used	IME kj per kg LW$^{0.75}$	720	401	461
	HS (TLU)	1224	7157	574
	MLWG (g TLU^{-1} d^{-1})	344	-183	-83
	TLWP (Mg season^{-1})	50.5	-157.1	-5.8
	MMP (kg TLU^{-1} d^{-1})	2.5	0	0
	TMP (Mg season^{-1})	92.0	0	0
	MMCP (kg TLU^{-1} d^{-1})	1.0	0.8	0.9
	TMCP (Mg season^{-1})	146.3	718.4	58.8
Optimum use of feed	% DM used	100	7.4	33.0
	IME kj per kg LW$^{0.75}$	720	580	601
	HS (TLU)	1224	410	161
	MLWG (g TLU^{-1} d^{-1})	344	112	14.6
	TLWP (Mg season^{-1})	50.5	5.5	2.8
	MMP (kg TLU^{-1} d^{-1})	2.5	0.8	1.1
	TMP (Mg season^{-1})	92.0	10.1	5.2
	MMCP (kg TLU-1 d-1)	1.0	0.9	0.8
	TMCP (Mg season^{-1})	146.3	45.9	16.8

Note: IME = intake of metabolizable energy (kJ per kg LW$^{0.75}$ d^{-1}); HS = herd size; MLWG = mean liveweight gain; TLWP = total liveweight production; MMP = mean milk production, TMP = total milk production, MMCP = mean manure carbon production, TMCP = total manure carbon production, Season I = September to December (2003); Season II = January to April (2004) and season III = May to August (2004)

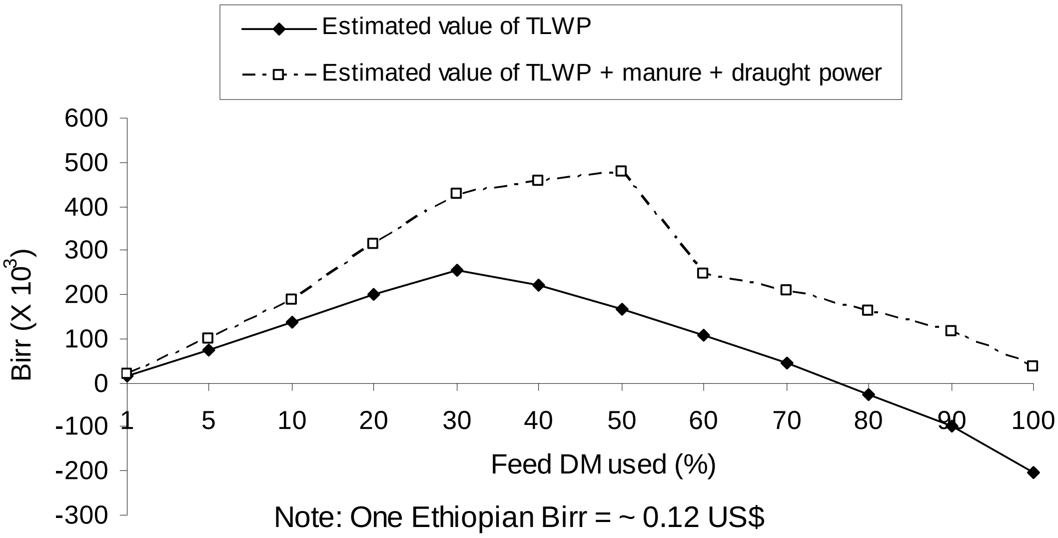


Figure 5. Effect of using various proportions of total feed DM on the monetary value of TLWP and the combined monetary value of TLWP, manure and draught power

On the other hand, if feed selection was aimed at maximum LWP per season, optimum HS varied from 1224 TLU in season I to 161 in season III (Table 4). In season I, the available feed was completely consumed by 1224 TLU at ad libitum intake. At larger HS, productivity decreases because a larger proportion of the energy intake was used for maintenance. In seasons II and III, herd productivity decreases with increasing HS, beyond 410 and 161 TLU, respectively, because of decreasing quality of the feed ingested. For maximum TLWG and TMP, 100% feed use in season I should be combined with 7.4% in Season II and 33.0% in season III (Table 4). MMCP in this situation is 0.96, 0.90 and 0.84 kg TLU^{-1} d^{-1}, respectively in seasons I, II and III. TMCP is highest in season II, because a large HS can be supported.

Adjusting herd size each season to complete use of seasonally available feed, resulted in a total annual loss of 113.4 Mg live weight, whereas 100% use of the pooled feeds resulted in losses of 50.7 Mg yr^{-1} (Figure 4A). On the other hand, a TLWP of 58.8 Mg yr^{-1} can be attained when HS is adjusted seasonally to optimum use of the feed, slightly less than the calculated TLWP at 30% utilization of the pooled feeds (62.0 Mg yr^{-1}) (Figure 4A).

In the pooled feed situation, for maximum TMP, MMP is 2.0 kg TLU^{-1} d^{-1}, whereas in the seasonal feed situation it was 2.5, 0.8 and 1.1 kg in seasons I, II and III, respectively. Maximum total milk production was 113.2 Mg at 30% feed use when all feeds are pooled, whereas 107.2 Mg was produced when HS was adjusted seasonally to realize optimum feed utilization. When HS was adjusted each season to realize complete feed use, total estimated manure C production was 911.9 Mg yr^{-1}.

3.3 Effect of HS on individual animal and herd productivity

MLWG and MMP TLU^{-1} d^{-1} decreased with increasing HS (Figure 4A-B). At a HS of 18 TLU, MLWP and MMP were 600 g and 4.4 kg TLU^{-1} d^{-1}, respectively and decreased to 75 g and 0.5 kg TLU^{-1} d^{-1} at a HS of 1181 TLU. On the other hand, at smaller HS, annual TLWP and TMP were small and increased with increasing HS to the level of optimum feed resource use and optimum HS. For carry-over (pooled) feed use, optimum herd size was 630 TLU which gave the maximum TLWP (62.0 Mg yr^{-1}), whereas seasonal feed variation resulted in an optimum herd size of 500 TLU for a maximum TLWP of 30 Mg yr^{-1} (Figure 6). In carry-over feed use, at a herd size of 1991 TLU the available forage provided only ME for maintenance and with further increases in herd size, the animals lose live weight, whereas in the no carry-over system production was zero at 860 TLU. Actual estimated TLWP for 1506 TLU for the village was 25.2 Mg yr^{-1} which was comparable to the TLWP estimated by the model for the same HS in the carry-over system (Figure 6).

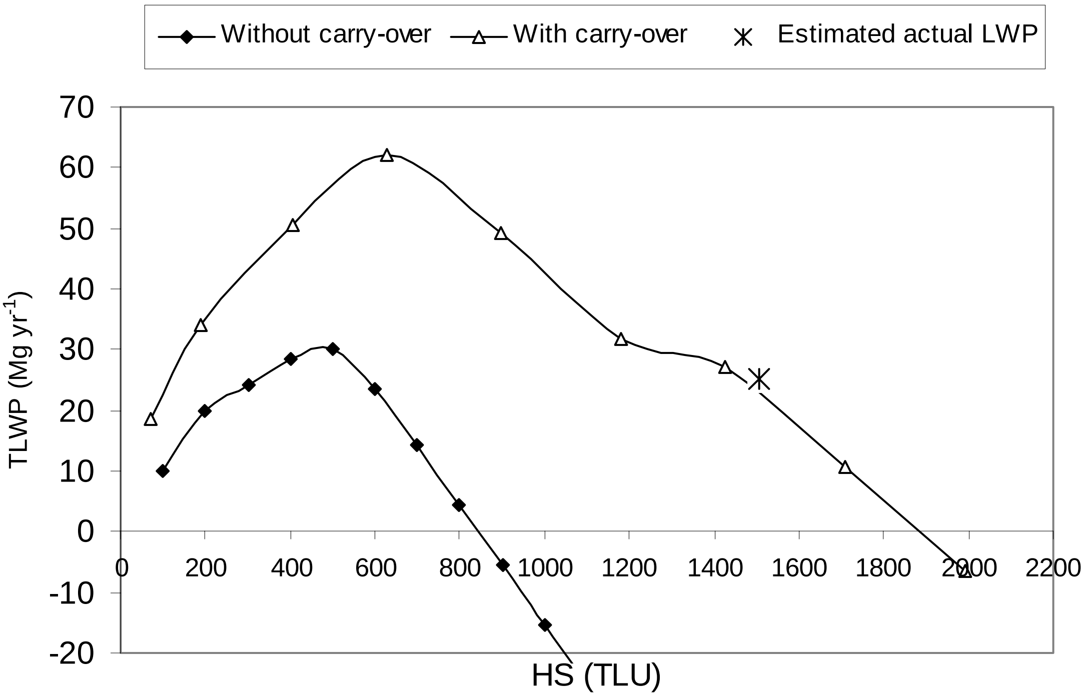


Figure 6. Herd size and TLWP with and without carry-over of feed resources and estimated actual TLWP

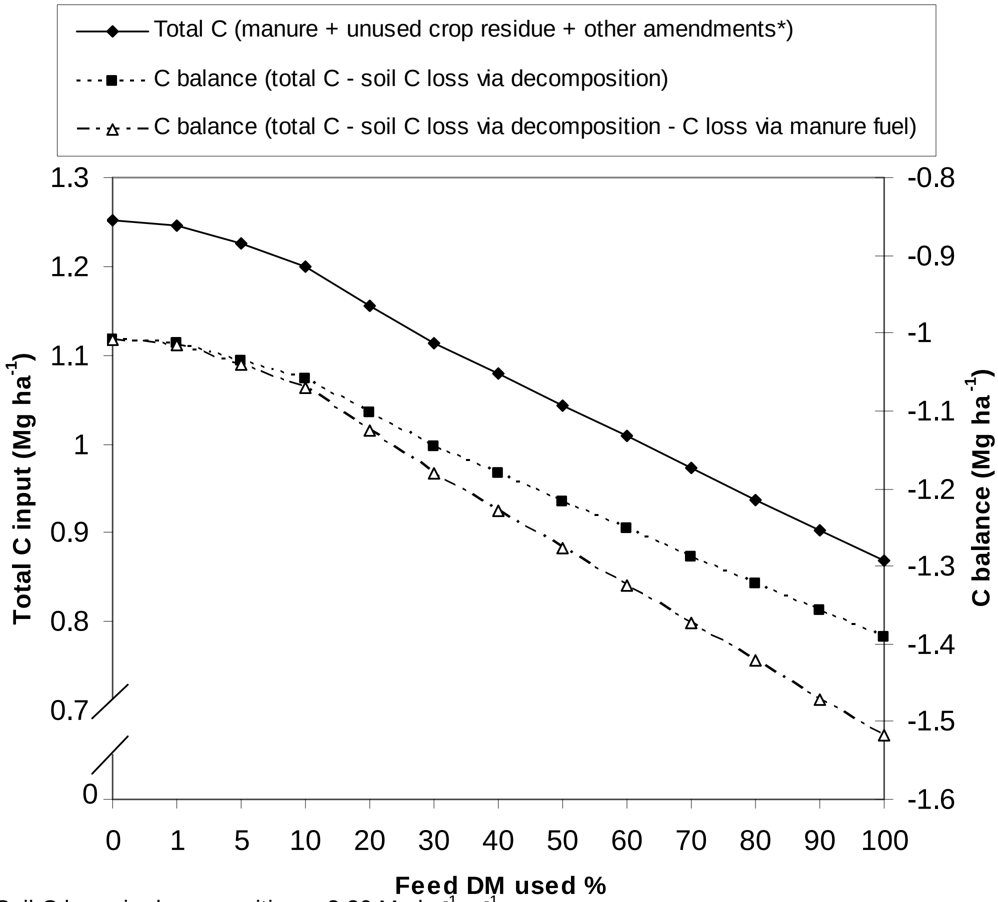
3.4 Soil C dynamics

Figure 7 presents the effect of selective feed utilization on the soil C balance by accounting for i) total C inputs in manure (or net C input in manure, taking into account C losses via use of manure as fuel), unused crop residues, 25% grazing and harvesting losses, recycled in the field and roots and ii) annual soil carbon losses in the form of CO_2 during decomposition of soil organic matter. Crop residues should be composted, since direct application of material with a high C/N ratio may have negative effects due to immobilization of N during its decomposition (de Ridder and van Keulen, 1990).

For the top 0.20 m soil, annual weighted C loss via decomposition was estimated at 2.26 Mg ha^{-1}, whereas total C input at 100% feed use was 0.87 Mg ha^{-1}, resulting in a negative soil carbon balance (0.87-2.26 = -1.39 Mg C ha^{-1} yr^{-1}). At 30% feed use (the best for LWP and milk), input comprised 0.06 Mg of C ha^{-1} from manure (all manure assumed to be applied to the field) and 1.06 Mg of C ha^{-1} from crop residues and other amendments. Total C input at this level of feed use was 1.3 times higher than at 100% feed use. To maintain the current soil C content, application of 13.0 Mg of manure OM or 9.2 Mg of crop residue yr^{-1} is required. Figure 7 shows that at all levels of feed use, soil C balances are negative, suggesting that in terms of soil carbon, the system is not sustainable.

4 Discussion and conclusions

Animal performance, such as liveweight gain (LWG) and milk production, is a function of quality feed availability and intake, nutrient concentration, digestibility and metabolic efficiency (Cherney and Mertence, 1998). Tropical forages are generally of lower quality than their temperate counterparts due to their physiology that leads to very early lignification (Chenost and Kayouli, 1997) and straws of grain crops and stems of grasses are of lower nutritional quality. These low quality forages pose three major nutritional problems: i.e. a high level of complex cell wall carbohydrates, a low protein level and low levels of minerals and vitamins (Chenost and Kayouli, 1997). In the study area, over 70% of the annual feed supply is from crop residues, which are characterized by low quality (De Leeuw, 1997; Zemmelink, 1995; Oosting, 1993). Particularly wheat and barley straws are of low quality, with 23 and 34 g CP kg^{-1} DM and high hemicellulose contents that is only partially digestible. A survey in the UK indicated that the response of DM intake to increasing diet CP content was on average 0.34 kg unit^{-1} increase in CP% across all diets (Chamberlain et al., 1989). Content of DOM kg^{-1} DM in all crop residues was less than 504 g.



Soil C loss via decomposition = 2.26 Mg ha^{-1} yr^{-1}

*Other amendments = roots and 25% unavoidable grazing and/or harvesting leftovers in the fields

Figure 7. Effect of using various proportions of total feed DM on soil C balance

Seasonal variation in the availability and quality of feed is a serious constraint. From September to December animals graze natural pastures. These feeds have high CP contents (121 g kg^{-1} DM in NG3 to 179 g in NG1) and relatively low contents of neutral detergent fiber (NDF) (<500 g kg^{-1} DM). The native grasses allowed energy intake of 1.5 to 2.1 times maintenance requirements. In season II, crop residues were the dominant available feed sources. The faba bean haulms allowed energy intake to cover maintenance requirements, whereas all other residue feeds result in sub-maintenance energy intake levels. The lowest quality feed, wheat straw, provides only 68% of the maintenance requirements.

Little feed was available in the field in the late dry and early wet season, season III (May to July) and in August animals remained in the stable. The inability of farmers to feed animals adequately throughout the year remained the main constraint for increasing meat and milk production (Reddy et al., 2003). In tropical areas, such as the Northern Highlands of Ethiopia, where many feeds are of low quality, maximum liveweight production and milk production can be obtained if either the farmer selectively uses the better feeds or the animals are allowed to select (Zemmelink, 1995). This is on the assumption that all feeds can be pooled and are available throughout the year.

Individual animal productivity decreases with increasing HS, because low quality feeds are included in the feed ration. On the contrary, at a smaller HS, annual TLWP and TMP are smaller and increase with increasing HS up to the optimum level of feed resource use. Beyond that point, both individual animal and herd productivity decrease and eventually a situation characterized by losses of liveweight is reached. The result of this model study is in agreement with the farm scale study by Assefa et al. (Chapter 4) on liveweight dynamics.

IFPRI's (International Food Policy Research Institute) global food model, known as an international model for policy analysis of agricultural consumption (IMPACT) projects that consumption of meat and milk in developing countries will grow at 2.8 and 3.3% yr^{-1} between the 1990s and 2020. It is indicated that a 'livestock revolution' might well be a key means of attaining these rates and alleviating poverty in the next 20 years (Delgado et al., 1999). The projected increase in production cannot be attained through feeding more of the biomass, but by providing good quality feeds to fewer animals. How to produce such good quality feeds is a big question, however. The suggestion by Winrock (1978) that livestock production in tropical developing countries could be considerably increased by using all feed resources is not valid. Moreover, though the soil C balance is negative at all levels of feed use, the balance at optimum feed use for TLWP and TMP is 30% smaller than at 100% feed use. Increasing HS beyond the point of optimum feed use also creates pressure on the environment and leads to resource degradation such as overgrazing, soil compaction and erosion. It is also important to note that keeping large numbers of animals is associated with high risks of large losses due to death during periods of feed shortage, resulting from drought, a common phenomenon in the Northern Highlands of Ethiopia.

In terms of live weight and milk production and soil C inputs, almost equal amounts can be produced either by pooling all feeds annually or by seasonally adjusting herd size to the optimum feed use level. The problem in the latter case is that farmers can not adjust herd size to fluctuating feed availability. The optimum fraction DM feed use for combined monetary value of live weight production, manure and draught power differed from that which was optimal for meat and milk production.

Actual HS in the study area (micro-catchment) was 1506 TLU, which is lower than the HS that could be supported at maintenance when all feeds are pooled. The estimated optimum HS i) for maximum TLWP, TMP and soil C input and ii) for TLWP, manure and draught power is significantly lower than the actual HS, suggesting that in areas where most feeds are of low quality, optimum benefits from livestock can be obtained by selective utilization of quality feeds, through proper storage and carry-over systems. Environmentally-friendly development of livestock production can be maintained by increasing production per ruminant for optimum HS and not through increased numbers. Alternatively, production of quality feed could be increased. For individual farmers, reducing herd size may conflict with other objectives such as savings and capital asset (Assefa et al., Chapter 4). This objective can be satisfied by facilitating savings and credit services. In the absence of functioning formal financial markets, livestock keeping appears a most interesting alternative (Slingerland, 2000). Technical and institutional arrangements, such as better banking facilities should be introduced, and farmers should be encouraged to use the banking facilities for their savings, on the one hand, and get credits which might be directly related to the amount of their savings, on the other, and hence, optimum feed resource use can be maintained for possible maximum meat and milk production.

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Chapter 6

Soil nutrient dynamics under alternative farm management practices in integrated crop-livestock systems in the Northern Highlands of Ethiopia: A simulation study

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Soil nutrient dynamics under alternative farm management practices in integrated crop-livestock systems in the Northern Highlands of Ethiopia: A simulation study

Abstract

Agricultural development in the Northern Highlands of Ethiopia, one of the agro-ecologically and economically less-favoured areas of the world is slow or stagnant and unsustainable. The low quality of the natural resources, especially the soils, is one of the underlying reasons. It is important therefore, to examine to what extent modifications in farm management can lead to improved resource (land) qualities. Summary simulation modules for soil N-, OC- and P-dynamics are described, and empirical data from local soil types, identified as Cambisols, Luvisols and Leptosols, crop N and P uptake from field experiments and long-term average annual rainfall of Teghane, Northern Highlands of Ethiopia, have been used for model calibration. The N and OC module has been validated on the basis of an empirical data set comprising data for fields continuously cultivated for 7-53 years in smallholder farms in the Highlands of Ethiopia.

Subsequently, the model has been applied for exploration of long-term dynamics of soil N, OC and P and crop available N and P under four alternative farm management regimes, i.e. i) continuous cultivation of cereal crops with complete removal of crop residues and without external nutrient inputs (control), ii) cultivation of cereal crops with input of the current level of organic amendments and recommended chemical N and P fertilization rates (Alt1), iii) composting all crop residues and the vegetation from pasture land, and applying the resulting compost to cultivated fields (Alt2) and, iv) include leguminous crops in the rotation (legume-->cereal--->cereal-->) (Alt3).

The simulation results indicate that, in terms of OC, only Alt2 in Cambisols and Alt1 and Alt2 in Leptosols and in terms of soil N, Alt1 and Alt2 in Leptosols are sustainable. In terms of total soil P, Alt2 (the recommended application rate of P) results in soil P accumulation in Cambisols and consequently increasing plant-available P. All other management regimes are not 'sustainable' in terms of soil N, OC and P, and lead to 'soil mining'. Finally, the model has been used to estimate the required organic and inorganic P inputs to maintain the current status of soil OC and P, as a benchmark of management practices. To maintain soil OC and P at the current levels, in combination with higher availability of N and P for crop growth, annual required inputs per ha increase with increasing current nutrient contents. The modelling approach developed in this study to explore the dynamics of sustainability indicators can support the design of appropriate management practices that eventually would lead to improved land qualities and higher yields.

1 Introduction

Agriculture is the basis of the Ethiopian economy, accounting for 46% of its GDP and 90% of its export earnings and employing 85% of the country's labour force (UNDP, 2002). About 95% of the agricultural output is produced on subsistence smallholder farms in the highlands (ADF, 2002). In the country's long-term economic development strategy, "Agricultural Development-Led-Industrialization" (ADF, 2002), these smallholders' private agricultural economies are targeted to maintain food security and strengthen economic growth. They are also supposed to initiate development of home industries, stimulate the service sectors and create additional purchasing power. These broad indicators underline the importance attached to agriculture in general and to smallholder farms in particular in the Ethiopian economy (Block, 1999). However, most of the environmental problems facing the country are associated with subsistence agriculture-related activities (UNEP, 2002), resulting from inappropriate land management practices associated with low external nutrient inputs and population pressure (UN, 2002). Agricultural practices with low external inputs carry the risk of depleting soil nutrient stocks, seriously threatening future agricultural production potentials (Tellarini and Caporali, 2000; Elias et al., 1998; Harris, 1998; Bojo and Cassels, 1995, Stoorvogel and Smaling, 1990).

In the Ethiopian Highland agricultural system, only small quantities of manure are applied to arable crops (dung cakes are used for fuel) and most crop residues are used for animal fodder and burned for household fuel. Fallowing, for natural soil fertility replenishment, has almost completely disappeared from agricultural practice, due to the small farm sizes associated with high population growth. In general, soil nutrient balances in the farming systems of the Northern Highlands of Ethiopia are strongly negative. Thus, agricultural development in this region, one of the agro-ecologically and economically less-favoured areas of the world, is slow or stagnant and not sustainable. For attainment of the goals formulated for agriculture, sustainable agricultural development is a pre-requisite, which in turn requires development of appropriate soil fertility management systems to maintain the quality of the resource base.

A wide range of sustainability indicators for agricultural production systems has been proposed, including soil chemical and physical characteristics (Arshad and Martin, 2002; Nambiar et al., 2001; Hartemink; 1998; Wang and Gong, 1998), among which especially soil organic matter (SOM) content is considered important (Bessam and Mrabet, 2003; Freixo et al., 2002; Rosell et al., 2001; Doran and Parkin, 1994; Larson and Pierce, 1991). Soil fertility is intimately linked to soil organic matter content, which influences soil physical, chemical and biological properties, as well as indigenous soil nutrient supply (Bessam and Mrabet, 2003; de Ridder and van Keulen, 1990). For example, 95% of soil N and S, 60-80% of soil P and 70% of Zn and Cu in soils are present in organic form (cf. Katyal et al., 2001). Thus, depletion of soil organic matter implies impoverishment of the reserves of these nutrients and a decline in cation exchange capacity, while it also hampers formation of well-aggregated soil structural elements and consequently reduces soil water holding capacity (de Ridder and van Keulen, 1990). It has been said that the importance of soil organic matter content exceeds that of any other of its properties (Young, 1976).

Low availability of nitrogen and phosphorus, associated with low SOM-contents limits plant growth and dry matter production, since crop demand for these macro nutrients is high (de Visser et al., 2000). For example, nitrogen status affects (van Keulen and Seligman, 1987): i) dry matter production per unit of water consumption, ii) rates of photosynthesis and dry matter production and iii) stomatal response to water stress. Moreover, limited nitrogen supply limits uptake of P by crops and vise versa (Janssen et al., 1990; Penning de Vries and van Keulen, 1982). Therefore, appropriate soil organic matter management (Katyal et al., 2001; de Ridder and van Keulen, 1990; Martin et al., 1990), combined with N and P management, implies maintenance of soil fertility as a basis for sustainable agricultural development. Therefore, in this study, long-term dynamics of soil C, N and P are considered important sustainability indicators that can be influenced by farmers and other land managers through land management practices.

Since soil nutrient dynamics are influenced by human use and management decisions (Doran, 2002; Pierce and Larson, 1993; Larson and Pierce, 1991), inappropriate farm management practices result in soil nutrient mining. Therefore, information about long-term soil nutrient dynamics in relation to management options is important for evaluating and judging the sustainability of management practices (Wang and Gong, 1998; Brinkman, 1998) and can support appropriate decision-making.

In earlier studies, such as on global assessment of human-induced soil degradation (UNEP, 1990; Oldeman et al., 1990) and soil degradation studies in the Highlands of Ethiopia (Hawando, 1995; 1989; NCS, 1992; Hurni, 1988; FAO, 1984), neither the dynamics of important indicators nor impacts of different farm management regimes have been addressed. Some studies (for example, Amsal et al., 1999; 1997; Tanner et al., 1993; Asnakew et al., 1991) have addressed the impact of different farm management practices on crop production within the same time period. Such studies can not explain the temporal dynamics that are essential for understanding the mechanisms underlying change (Wang and Gong, 1998).

Long-term agricultural experiments have been used to study long-term impacts of different farm management practices on land qualities and crop yields. However, such long-term experiments are laborious and time-consuming and take too long to produce relevant results within the time frame of present priorities and it is difficult to extrapolate site-specific results to other areas (Van Keulen, 1995). As an alternative, simulation models are suitable tools to gain insight for explaining long-term dynamics (Hengsdijk, 2001; Van Keulen, 1995).

Thus, in the last decades, dynamic simulation models have been developed for the assessment of long-term dynamics, such as CREAMS (Knisel, 1980), PERFECT (Littleboy et al., 1989), CENTURY (Parton et al., 1989), EPIC (Sharpley and Williams, 1990) and SWHEAT (van Keulen and Seligman, 1987), that contain detailed quantitative descriptions of the interacting processes in agricultural systems. However, extensive data requirements that often cannot be easily satisfied, difficulty in validation and partial knowledge of certain processes that may lead to unbalanced descriptions, are major disadvantages of such models (van Keulen, 1995; Wolf et al., 1989). For exploration of long-term dynamics of important sustainability indicators such as soil N, OM and P and the consequences for crop-available N and P, summary simulation models are more attractive (Hengsdijk and van Ittersum, 2003; Nicolardot et al., 2001; Van Keulen, 1995; Matus and Rodríguez, 1994; Wolf et al., 1989).

The objective of this study is to explore long-term dynamics of soil C, N and P and the consequences for crop-available N and P under alternative farm management practices in the Northern Highlands of Ethiopia, using a summary simulation model that can support the design of appropriate management practices that eventually might lead to improved land qualities, higher yields and improved livelihoods.

2 Materials and methods

2.1 The model

2.1.1 Model description

Soil nitrogen and organic carbon

Soil organic carbon and soil organic nitrogen dynamics are closely linked (Struif Bontkes, 1999; van Keulen, 1995; Jenkinson, 1990; Parton et al., 1989; 1983). Organic carbon (OC) dynamics in the soil are extremely complex. Concurrently, processes of *transformation*, *conversion* and *dissimilation* take place, mediated through soil microbes. For the purpose of describing long-term organic matter dynamics, simplifying assumptions can be made, such as equilibrium in the soil microbial population.

In this study therefore, a simplified dynamic model has been applied[1], based on the soil organic nitrogen model described by Wolf et al. (1989), validated by Wolf and van Keulen (1989) and applied by Hengsdijk and van Ittersum (2003). Organic carbon dynamics have been linked to the dynamics of organic N via the C:N ratio. In the model, four organic pools are distinguished in the soil (Figure 1): i) stable organic N (NSP), (ii) stable organic carbon (OCSP), iii) labile organic N (NLP) and (iv) labile organic carbon (OCLP). Inputs into the system include four external N sources, inorganic fertilizer (Ninorf), organic fertilizer (Norgf), rain (Nrain) and biological fixation (Nfix), and one external OC input (OCorgf).

During decomposition of labile organic material, part of the carbon is transformed into carbon dioxide in respiratory processes to provide energy for microbial functioning. Carbon from the labile pool is transferred to the stable pool in association with the nitrogen, using the C:N-ratio of the labile material.

In the model, 18 transfer coefficients have been defined (Figure 1), describing: (i) the partitioning of the external nitrogen inputs among losses, crop uptake and the labile pool; (ii) the partitioning of nitrogen transferred from the labile pool among losses, crop uptake and the stable pool and (iii) the transfer of nitrogen from the stable pool to the labile pool. Values for 16 transfer coefficients (except transfers 2 and 6) are presented in Table 2 for a situation with moderate risks for losses (Wolf et al., 1989). Losses of organic N from the stable and labile pools via soil loss

[1] All model equations are given in Appendix A of this Chapter.

through water erosion are estimated from the rate of OC loss via erosion by dividing by their respective C:N ratios.

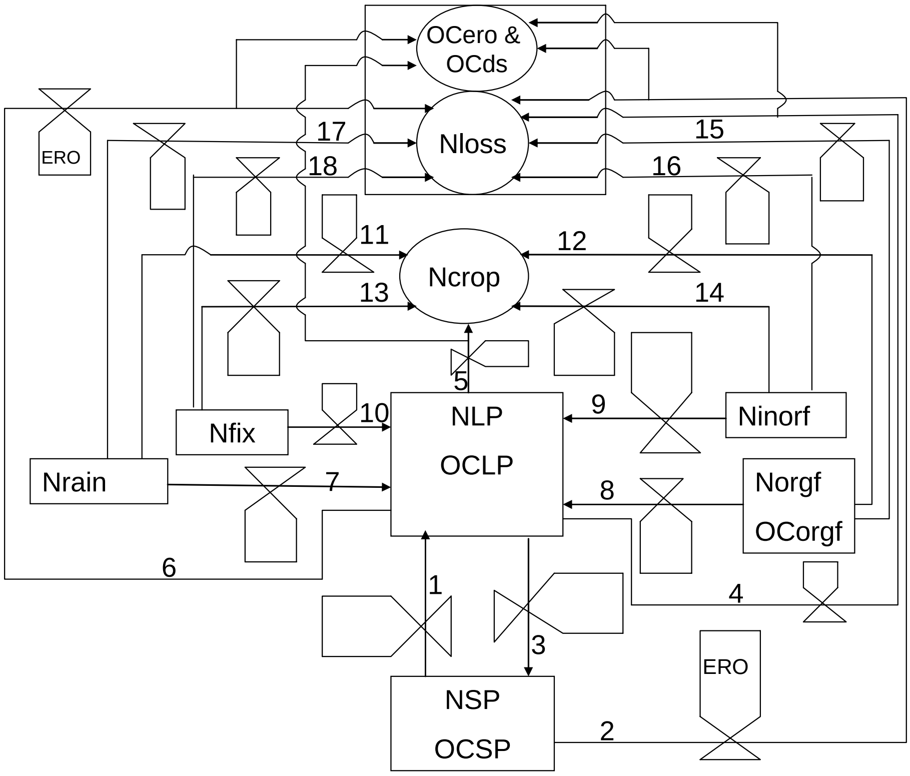


Figure 1. Structure of the organic N and C module with four pools, stable N and OC (NSP & OCSP) and labile N and OC (NLP & OCLP), and 18 transfer coefficients, describing: the transfer of nitrogen from the stable pool to the labile pool (1), the loss of stable organic N via soil erosion (2), the partitioning of nitrogen transferred from the labile pool among the stable pool (3), losses (4) and crop uptake (5), the loss of labile organic N via soil erosion (6), the partitioning of nitrogen input from rain (Nrain) among the labile pool (7), losses (17) and crop uptake (11), the partitioning of nitrogen input from organic fertilizer (Norgf) among the labile pool (8), losses (15) and crop uptake (12), the partitioning of nitrogen input from inorganic fertilizer (Ninorf) among the labile pool (9), losses (16) and crop uptake (14), the partitioning of nitrogen input from biological fixation (Nfix) among the labile pool (10), losses (18) and crop uptake (13)

Soil loss through water erosion depends on rainfall, soil erodibility, topography, crop cover and the effect of anti-erosion measures (Renard and Ferreira, 1993; Roose, 1977). In the model, the annual rate of soil loss (Sloss) is calculated using the Soil Loss Equation developed by Roose (1977) (Eqn. 15, Appendix A). OC losses through soil erosion (OCero) are calculated from the annual rate of soil loss and soil bulk density, using an enrichment factor (Knisel, 1980), as the top soil layer is richer in organic matter (Eqn. 14, Appendix A).

Soil phosphorus

For the description of soil phosphorus dynamics, phosphorus chemistry and phosphorus transformations in the soil have also been simplified (Van Keulen, 1995; Wolf et al., 1987). Unlike nitrogen, P is present in the soil in substantial quantities in inorganic forms, that can be schematically divided in labile, stable and soil mineral, whereas organic P is divided into stable and labile pools (Van Keulen, 1995; Wolf et al., 1987). All these pools interact directly and indirectly and the quantitative relationships are poorly understood (Wolf et al., 1987). To explore long-term P dynamics a module commensurate with the N and OC module has been incorporated in the model. A stable and a labile pool are distinguished, each containing both organic and inorganic P. Three sources of P are distinguished: weathered soil minerals (Pw), organic fertilizer (Porgf) and inorganic fertilizer (Pinogf) (Figure 2).

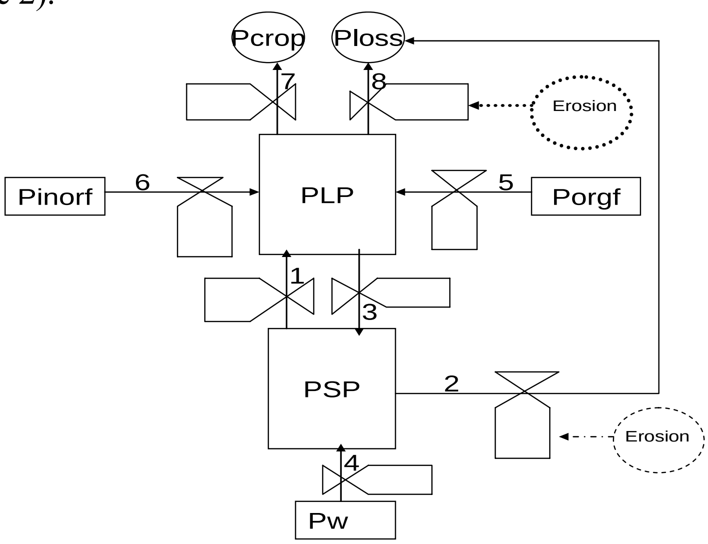


Figure 2. Structure of the phosphorus module with two pools, stable P (PSP) and labile P (PLP), and 8 transfer coefficients, describing: the transfer of phosphorus from the stable pool to the labile pool (1), the loss of stable organic P via soil erosion (2), the transfer from the labile pool to the stable pool (3), the transfer from soil minerals to the stable pool (weathering, 4), the transfer from organic fertilizer (Porgf) to the labile pool (5), the transfer from inorganic fertilizer (Pinorf) to the labile pool (6), the transfer from PLP to crop (7) and the transfer from PLP to erosion (Ploss) (8).

In the model, 8 transfer coefficients have been defined (Figure 2), describing: (i) transfer from the stable to the labile P pool, (ii) transfer from the labile to the stable P pool, (iii) transfer from inorganic and organic fertilizer/amendments to the labile P pool, (iv) transfer from the labile P pool to crop uptake and losses, (v) transfer from soil mineral P to the stable P pool, (vi) loss of P through soil erosion.

2.1.2 Data requirements

Soil nitrogen and carbon

Required data are i) initial sizes of NSP, NLP, OCSP and OCLP, ii) the time constants of conversion of NSP and NLP, iii) size of the external sources (applied nitrogen from inorganic and organic fertilizer, supply of nitrogen via rainfall and biological fixation) and iv) transfer coefficients from NSP to NLP and vice versa, from NLP to Ncrop and Nloss, and from Ninorf, Norgf, Nrain and Nfix to NLP, Ncrop and Nloss, the enrichment factor for calculation of organic carbon loss from the stable and labile pools via erosion (OCero) and the C:N ratios of the stable and labile pools and the organic fertilizer.

The initial pool sizes of soil organic N and OC are computed for the top 0.20 m from total initial organic N and C and the equilibrium ratio of 3 between both pools (i.e. NSP/NLP and OCSP/OCLP). The time constant of conversion of the labile N pool is calculated from its size and its rate of mineralization (Eqn. 4, Appendix A). The time constant of conversion of stable N can not be directly calculated, however, a ratio between the time constants of conversion of the stable and the labile N pools of 20 worked satisfactorily for dry land soils under a range of environmental conditions (Wolf and van Keulen, 1989). Input rates of Ninorf and Norgf should be specified by the user. N supply via biological fixation can generally be derived from results of long-term trials on unfertilized fields (Wolf et al., 1989), whereas N supply via rainfall can be estimated from annual rainfall in the area using a transfer function; N deposition = 0.0065* rainfall, mm yr^{-1} (Van Duivenbooden, 1992).

Soil phosphorus

Required data are i) initial sizes of the stabile and labile P pools, ii) the rate and type of applied fertilizer, iii) total crop uptake of P from unfertilized and fertilized soil during the first year after P application, iv) input of weathered mineral P from soil parent material, v) the time constants of transfer between the labile and stable P pools, vi) P content of applied organic fertilizer and vii) enrichment factor for calculation of P loss via erosion.

Initial sizes of the P pools are estimated from P uptake from unfertilized and fertilized soil (Eqns. 18 and 22, Appendix A). Rate and type of P fertilizer applied should be specified by the user. P uptake from fertilized and unfertilized soil can be derived from one season P fertilizer trials where crop production with and without

P fertilizer is established (Wolf et al., 1987; Janssen et al., 1987). Input of mineral P from soil parent material to the stable pool is set to 1 kg ha^{-1} yr^{-1} (Van der Pol, 1992). The time constants of conversion between the labile and the stable P pool and *vice-versa* were found to be 5 and 30 yr, respectively, under a wide range of environmental conditions (Janssen et al., 1987). The enrichment factor for P loss via erosion has been set to 1 assuming that total P distribution in the top 0.20 cm is uniform.

2.2 The study area

2.2.1 General description

The study was conducted during 2002-2004 in Teghane, Atsbi Wonberta district, situated between 13^0 52' 53" and 13^0 53' 37" N and between 39^0 42' 05" and 39^0 43' 57" E, in Tigray Regional State in the Northern Highlands of Ethiopia, covering an area of 13.56 km^2. Its altitude ranges from 2710 to 2899 m above mean sea level. The climate is "Dega" (WBISPPO, 2002), with average annual monomodal rainfall from July to September of 541 mm (for the period 1901-2002, coefficient of variation 53%, at a location near Teghane at 14^0 N and 40^0 E (Viner, 2003)). For the period 2000-2004, average rainfall was 532 mm (Atsbi World Vision, 2004), comparable to the long term average.

2.2.2 Soil data

In February 2003, soils of Teghane have been surveyed to determine their physical and chemical characteristics. Following the topo-sequence survey method, nine representative soil pits have been opened and described following the FAO-UNESCO (1990) guidelines. From each profile, samples were taken for laboratory determination of physico-chemical properties. The samples were bulked for each soil type and analyzed in either the National Soil Research Center (NSRC), Addis Ababa, International Livestock Research Institute (ILRI), Addis Ababa or the soils laboratory of Mekelle University. Subsequently, a field survey was conducted to delineate the boundaries of soil units and land use/cover (LUC) types, using GPS, on the basis of the micro-catchment outline of Teghane. Topographic maps (Eth 4-1339 B1, Wikro and Eth 4-1339 B2, Koneba) (EMA, 1997) and aerial photographs of 1994 were used in support of the field work. The GPS records were imported into ArcView GIS, and digitized as polygons. During digitizing, aerial photographs were used to check GPS records of salient physical features (churches, stream confluences, road branching points). Following digitizing of their boundaries, the soil map was prepared (Figure 3) and the area of each soil unit was calculated, using the facilities in ArcView (ESRI, 2002).

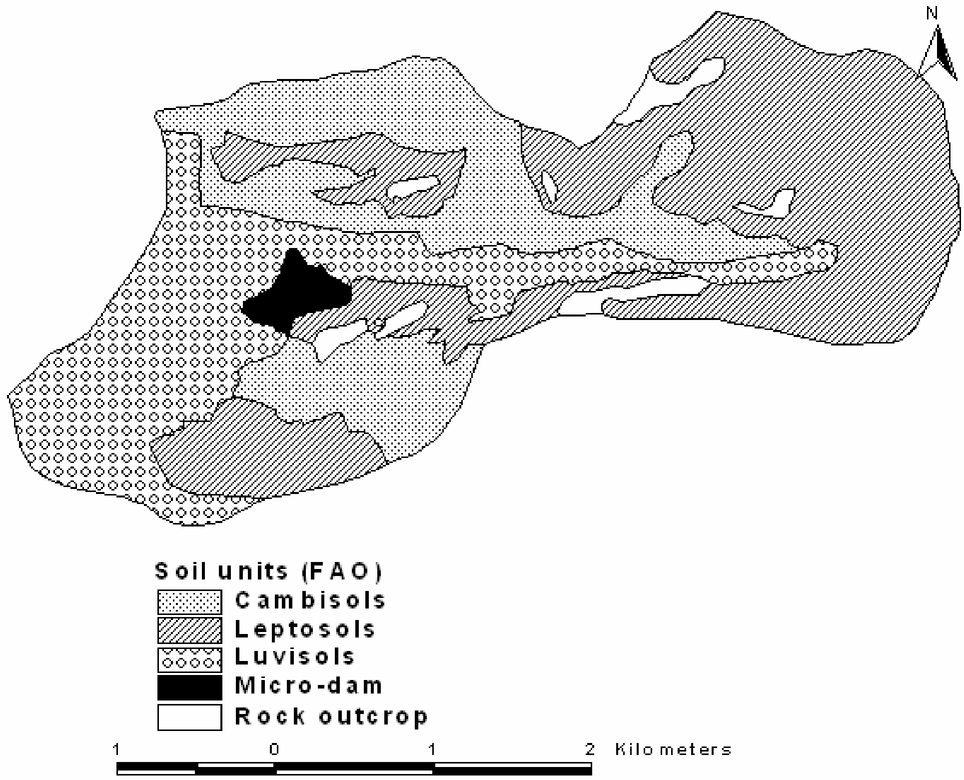


Figure 3. Soil map of Teghane, Northern Highlands of Ethiopia

Soils of the study area were classified as Cambisols, Luvisols and Leptosols (FAO-UNESCO, 1990). Cambisols, covering 26% of the area, located on the colluvial terrace slopes, are intensively cultivated. Much of the Luvisols are located in the valley bottoms or flood plains. They are relatively deep, with favorable physical and chemical characteristics. Traditionally, these soils were under grassland, but in recent years a significant proportion has been transformed to arable land in response to the shortage of land for food crop production. Leptosols, covering 46% of the area, are located on the elevated plateau and on hill slopes, crests and ridges, interspread with rock outcrops and patches of Luvisols. They are limited in depth to about 25 cm by an underlying continuous hard sedimentary rock, or they contain less than 20 percent fine particles to a depth of 75 cm (FAO-UNESCO, 1990). Sandstone sedimentary rock of the Mesozoic formation, which overlies Precambrian rocks on plateau and meta-volcanic material on hills, crests and ridges constitutes the parent material of this soil unit (Kazmin, 1975). The soils are degraded and eroded and characterized by coarse texture, low nutrient content and low moisture holding capacity and therefore this soil unit is less suitable for crop production.

Four fields, two each on Luvisols and Cambisols, designated as Cambisols-1, Cambisols-2, Luvisols-1 and Luvisols-2 have been selected for field experimentation. The two Cambisols fields and Luvisols-1 had been under continuous cultivation for over 50 years. The Luvisols-2 field has been under grazing until seven years ago. Experimental data from Cambisols-1 and Luvisols-2 were used for model calibration. In early July 2003 just before sowing, from each field composite soil samples from the 0-20 cm surface layer were collected for laboratory determination of OC (Walkley and Black, 1947), available P (Olsen et al., 1954), total N (Bremner and Mulvaney, 1982), exchangeable K (Thomas, 1982), soil pH-H_2O (1:2 soil:water ratio) and bulk density in the earlier mentioned laboratories. Soil chemical characteristics and bulk density of the experimental fields are presented in Table 1

Table 1. Soil chemical characteristics and bulk density in the 0-20 cm soil layer of three soils in Teghane, Northern Highlands of Ethiopia, 2003.

Soil unit	OC (g kg^{-1})	Total N (g kg^{-1})	P-Olsen (mg kg^{-1})	Exch. K (mmol kg^{-1})	pH (H_2O)	Bulk density (kg m^{-3})	Average slope (degree)
Cambisols	11.0	1.4	7.0	15.0	6.4	1285	7
Luvisols	37.0	3.2	6.0	15.4	6.4	1201	3
Leptosols	9.8	1.0	7.4	-	7.4	1121	25

3 Results and discussion

3.1 Model calibration

The model was calibrated on the basis of OC and N for three soils (Cambisols, Luvisols and Leptosols) and on the basis of P for two soils (Cambisols and Luvisols) (Table 1) in Teghane, Northern Highlands of Ethiopia. Two sources of external organic fertilizer, manure and composted crop residues and two sources of external inorganic fertilizer, urea and DAP were considered. Both, manure and composted crop residues are incorporated in the soil shortly before sowing. Crops in rotation are faba bean/field pea ----> barley/wheat ---> wheat/barley. Transfer coefficients were used as given in Table 2.

3.1.1 OC and N module

Initial pool sizes of N and OC (Table 3) have been calculated from total soil N and OC content in the 0-20 cm layer, based on average bulk density (Table 1). Initial sizes of the labile and stable pools were estimated, applying an equilibrium ratio of 3 (Wolf et al., 1989), at 899.5 and 2698.5 kg ha^{-1} for Cambisols, 1921.5 and 5764.8 kg ha^{-1} for Luvisols and 582.9 and 1748.0 kg ha^{-1} for Leptosols. Initial sizes of the stable and labile soil C pools were calculated from the stable and labile N pools by multiplying by their C:N ratio (Table 3).

Table 2. Transfer coefficients (situation with moderate risks for losses, Wolf et al., 1989; see text for explanation) for nitrogen from inorganic fertilizer (Ninorf), organic fertilizer (Norgf), biological fixation (Nfix), rain (Nrain) and the labile organic pool (NLP) to crop, loss, labile and stable pool and from the stable pool (NSP) to the labile pool. Numbers in brackets refer to the flow diagram in Figure 1.

Input	crop	loss	labile pool	stable pool
Ninorf	0.40 (14)	0.40 (16)	0.20 (9)	-
Norgf	0.15 (12)	0.15 (15)	0.70 (8)	-
Nfix	0.15 (13)	0.15 (18)	0.70 (10)	-
Nrain	0.40 (11)	0.40 (17)	0.40 (7)	-
NLP	0.425 (5)	0.425 (4)	-	0.15 (3)
NSP	-	-	1.00 (1)	-

Table 3. Some soil N and P characteristics for model initialization: Soil N and P in the 0-20 cm depth, crop-N and P uptake, initial sizes of stable and labile pools of N and P and time constants of conversion of stable and labile pools for three soils in Teghane, Northern Highlands of Ethiopia, 2003

	Soil unit		
	Cambisols	Luvisols	Leptosols
Soil-N in 0-20 cm soil depth (kg ha^{-1})	3598.0	7686.4	2331.7
Initial stable N pool (kg ha^{-1})	2698.5	5764.8	1748
Initial labile N pool (kg ha^{-1})	899.5	1921.6	582.9
Initial C:N ratio	7.9	11.6	9.4
Initial stable P pool (kg ha^{-1})	384.0	600.0	Na
Initial labile P pool (kg ha^{-1})	58.9	95.2	Na
Total crop-N uptake from unfertilized soil (kg ha^{-1})	67.0	129.1	18.2
Total crop-P uptake from unfertilized soil (kg ha^{-1})	10.5	20.0	Na
Total crop-P uptake from fertilized soil (75 kg ha^{-1})	21.2	32.6	Na
Time constant of conversion of labile N (yr)	5.8	6.4	14.7
Time constant of conversion of stable N (yr)	116.6	127.9	294.9

Na = no data

The time constant of conversion of N from the labile pool (Table 3) was estimated on the basis of total mineralized N, derived from average crop N uptake from unfertilized soil (Table 3), taking into account N deposition via rainfall (3.5 kg N ha^{-1} yr^{-1}), and the appropriate transfer coefficients (Table 2). The time constant of conversion of the stable pool (Table 3) was calculated by applying Eqn. 3 (Appendix A).

3.1.2 P-module

Total crop-P uptake from unfertilized soils was 10.5 and 20 kg ha^{-1} from the Cambisols and Luvisols, respectively. The system represents a non-steady state situation, as crop-P uptake is higher than net input of P from weathered parent material (1 kg ha^{-1} yr^{-1}). Crop-P uptake, following application of 75 kg P ha^{-1} as fertilizer, was 21.2 and 32.6 kg ha^{-1} yr^{-1} at Cambisols and Luvisols, respectively. The initial size of the labile pool was calculated from crop-P uptake from the unfertilized soil by dividing by the uptake fraction of the labile pool, calculated by dividing the recovery of applied P by the fraction of fertilizer P transferred to the labile pool, at 58.9 kg ha^{-1} for Cambisols and 95.2 for Luvisols. The initial size of the stable pool equals its time constant of conversion multiplied by the P transfer from the stable to the labile pool, i.e. 384 kg ha^{-1} for Cambisols and 600 for Luvisols.

3.2 Model validation

The N dynamics module has been validated by Wolf and van Keulen (1989) on the basis of long-term field data from Germany, UK and Japan and further tested by Hengsdijk and van Ittersum (2003) for a tropical region with data from Saria in Burkina Faso. Similarly, the P module has been validated by Janssen et al. (1987) using experimental data sets from Brazil, Australia and Madagascar. For both modules it was concluded that model performance was satisfactory and that it can be used in exploring long-term effects of different soil and crop management regimes.

In this study, the N and OC modules were validated on the basis of an empirical data set for fields continuously cultivated for 7-53 years in smallholder farms at Lepis in the Highlands of Ethiopia (Lemenih et al., 2005a, b). Unfortunately no data were available for validation of the P module under Ethiopian conditions.

The farming system of Lepis, described by Lemenih et al. (2005a) is similar to that of Teghane: Neither mixed cropping nor rotations with legumes are common practice. Pressure on the land has resulted in shortening or even complete abandonment of fallow periods. Soil erosion in the area is insignificant, because of its flat topography. Crop cultivation involves the traditional “maresh”, i.e. plowing with a pair of oxen, following burning of weeds and residues from the preceding crop(s). Major crops grown are maize (*Zea mays L.*), sorghum (*Sorghum bicolor* L. Moench), wheat (*Triticum* spp.), teff (*Eragrostis tef*) and barley (*Hordeum* spp.). Beginning from 10-15 years after reclamation of the land from forest, chemical fertilizers are used in crop cultivation, i.e. urea in combination with diammonium phosphate (DAP) at the rate of 50 kg each ha^{-1} yr^{-1} (32 kg N and 10.5 kg P); however, farmers sometimes use half of this amount or even none, mainly due to economic constraints.

Initial pool sizes and time constants of conversion of N and OC were estimated on the basis of information on farm management systems and relevant empirical soil data from the two villages. For both, Lepis and Teghane, the model was initialized with measured soil C and N contents of cultivation period 7 (and for Lepis not the values of the forest soil), for two reasons. First, in the model, crop N uptake and OC decomposition are calculated for the top 0-20 cm soil layer. Plowing disturbs this layer, allowing rapid O_2 and CO_2 exchange with simultaneous incorporation of organic materials, which stimulates microbial growth (Reicosky et al., 1995). On the other hand, OC and N contents in the 0-10 cm layer of forest soils in Lepis are very high at 78.7 and 7.9 g kg^{-1}, respectively, abruptly changing to 21.7 and 2.1 g kg^{-1} in the 10-20 cm layer. In cultivated soils, in the 10-20 cm soil layer, the minimum reported OC and N contents were 31.7 and 2.1 g kg^{-1} after 53 cultivation periods. Freixo et al. (2002) reported the highest soil C and N contents in non-cultivated soils in the 0-5 cm depth. Secondly, in this way simulated results for the two locations (Lepis and Teghane) are comparable, as the soil data for Luvisols in Teghane were also from cultivation period 7.

Soil carbon decomposition is calculated on the basis of N mineralization and the C:N ratios of both organic matter pools. Annual organic matter amendments set to 1.6 Mg ha^{-1} (equivalent to the quantity estimated from a harvest index of 0.4 and a shoot-root ratio of 6 (Van Keulen, 1995; Boons-Prins et al., 1993) for Teghane (Assefa et al., Chapter 5)) with a C:N ratio of 26.61, assuming that most crop residues are removed in Teghane, whereas they are burnt in Lepis). External inorganic N input has been set to 32 kg ha^{-1}, starting from cultivation period 10 (as reported by Lemenih et al. (2005a) for Lepis).

Simulated soil C dynamics are in close agreement with observed values (Figure 4A), as are simulated N dynamics, albeit the simulated average relative rate of decline exceeds the observed value by 2.5% (Figure 4B[2]). As indicated in Figure 5, the simulated rates of change in OC and N for the soils of Lepis and Teghane are very similar, although the relative rate of decrease in Lepis soil is higher by 2.1 and 1.0%, respectively for OC and N, because of its higher initial contents.

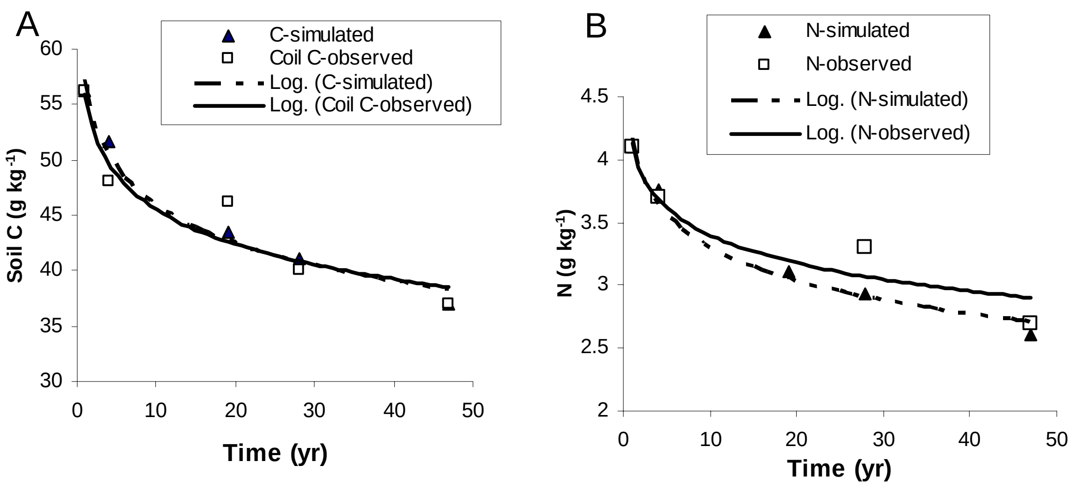


Figure 4. Observed and simulated soil C (A) and N (B) dynamics for 47 years for the soil of Lepis in the Highlands of Ethiopia

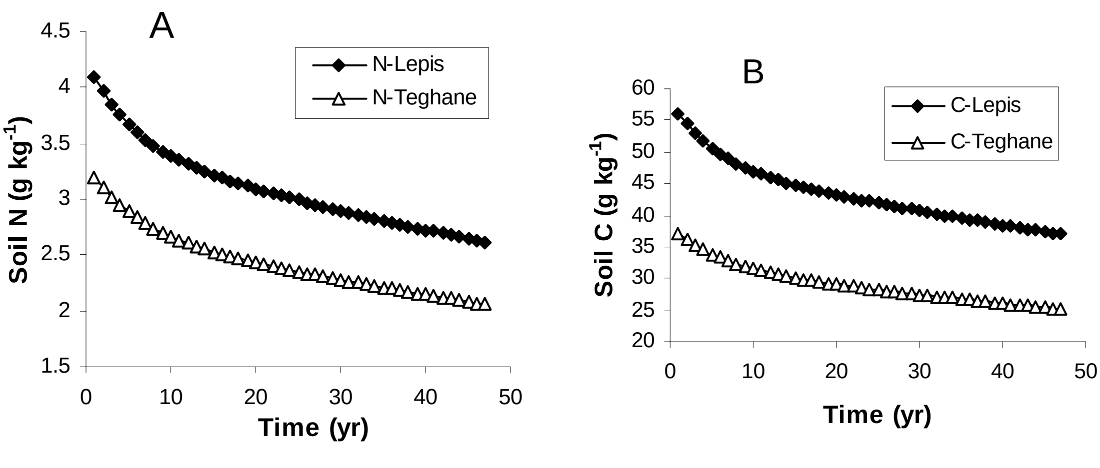


Figure 5. Simulated soil N (A) and C (B) dynamics over 47 years for soils of Lepis and Teghane in the Highlands of Ethiopia

3.3 Sensitivity analysis

To test the robustness of a model, Pervanchon et al. (2005; 2002) and Girardin et al. (1999) have proposed to test the sensitivity of indicators to input variables. In

[2] Observed soil N of cultivation period 20 was excluded from the analysis as the values in both the 0-10 and 10-20 cm layers were higher than those in cultivation period 10.

our model, annual organic amendments were set to 1.6 Mg ha^{-1} and inorganic N inputs to 32 kg ha^{-1}, whereas Lemenih et al. (2005a, b) reported that farmers sometimes used less. To examine the sensitivity of model results to the level of organic amendments, five assumptions were tested: i) 100% of C lost during burning of leftovers (used in the model validation), ii) 80% of C lost, iii) 70% of C lost, iv) 60% of C lost and v) leftovers not burnt. Leftover amendments set to 2.0 Mg ha^{-1} (equivalent to the quantity estimated as unavoidable field losses and animal excreta (Assefa et al., Chapter 5)) Simulated soil carbon contents appear relatively in sensitive to the variation in level of C inputs tested (Figure 6A). For example, the difference between no burning and complete loss of C upon burning is 4.7 g C kg^{-1} after 47 years, i.e. slightly over 10%.

Similarly, three levels of inorganic N inputs were tested, i.e. 0, 16 and 32 kg N ha^{-1} yr^{-1}, at 1.6 Mg ha^{-1} organic input. Soil N-contents are not very sensitive to this variation in inorganic N-input, i.e. a difference of 0.052 g kg^{-1} between 0 and 32 kg N ha^{-1} yr^{-1} after 47 years (Figure 6B). In this test we have fixed organic amendments at 1.6 Mg ha^{-1} for all the three levels of N inputs, whereas in reality higher N input would result in higher dry matter production including roots and higher amendments in the soil and then the variation in the sensitivity test between zero and 32 kg N ha^{-1} might have been relatively higher than the computed value.

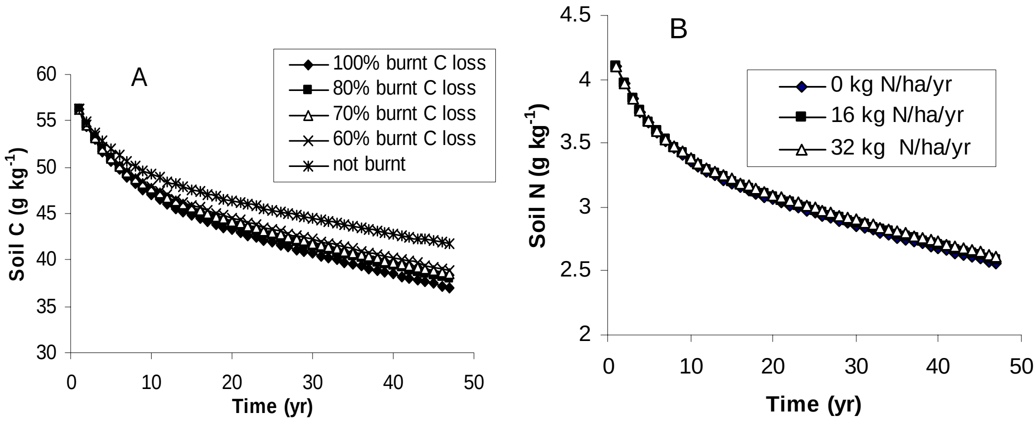


Figure 6. Results of sensitivity analyses for C contribution from burnt organic leftovers (A) and external inorganic N input levels (B) for Lepis, Highlands of Ethiopia

3.4 Management options

As the model satisfactorily reproduces the behavior of the agricultural system under common management, it may be used with confidence for exploration of the effect of alternative farm management practices on long-term dynamics of soil C, N and P and the consequences for crop-available N and P in the Highlands of Ethiopia. The model has been applied to three soils in Teghane, varying in chemical characteristics (Table 1), under five alternative farm management regimes:

i) Control: A farming system of continuous cereal crops with complete removal of crop residues and without external nutrient inputs,

ii) Alternative 1 (Alt1): Cultivation of cereal crops with input of the current level of organic amendments, set to 3.6 Mg ha^{-1} yr^{-1} (Assefa et al. (Chapter 5)) and recommended chemical N and P fertilization rates (urea in combination with DAP each at a rate of 100 kg ha^{-1} yr^{-1} (64 kg N and 21 kg P).

iii) Alternative 2 (Alt2): Composting all crop residues and the vegetation from pasture land (set to 5.4 Mg ha^{-1} yr^{-1}, Assefa et al. (Chapter 5)) and applying this compost to cultivated fields. This is on the assumption that power for traction and other farming practices can be supplied from sources other than animals and only arable farming is practiced, producing crops and/or vegetables, or if livestock production is included, animal feed originates from silage production from cultivated fields and/or concentrates and application of all manure in cultivated fields.

iv) Alternative 3 (Alt3): Including leguminous crops in the rotation (legume--> cereal--->cereal) to control. Under this management regime, net N input of 60, 40 and 20 kg ha^{-1} yr^{-1} from biological N fixation has been set for Luvisols, Cambisols and Leptosols (as biomass production in these soils varies). Amanuel et al. (2000) have reported net N inputs of 12-58 kg ha^{-1} yr^{-1}.

v) Alternative 4 (Alt4): Applying the required composted organic amendments and inorganic P fertilizer to maintain the current levels of soil C and P. The C:N ratio of composted organic amendments was set to 17.8, with N content = 0.01687 (Assefa et al., Chapter 5) and C content of composted crop residues = 0.30 (de Ridder and van Keulen, 1990).

3.4.1 Soil OC and N dynamics

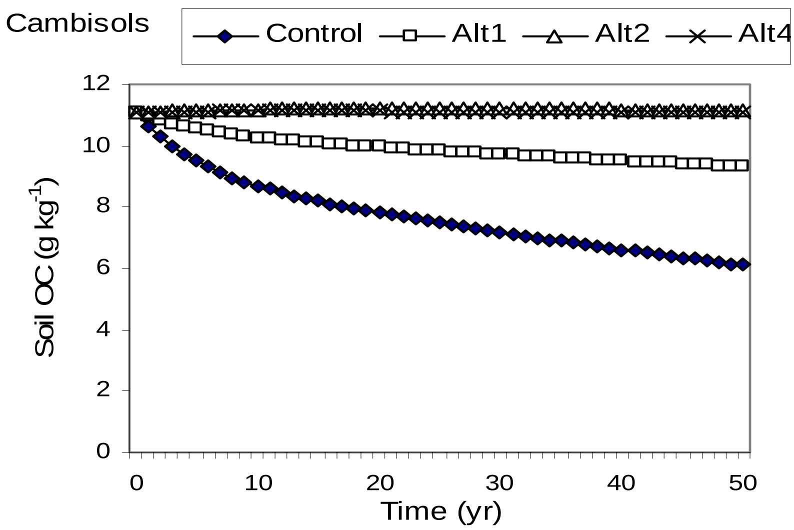
Organic *carbon* dynamics are similar for the control and Alt3 (Figure 7), because in Alt3 only biological N fixation is added. Initial C-content is higher in Luvisols (37.0 g kg^{-1}) than in Cambisols (11.0 g kg^{-1}) and Leptosols (9.8 g kg^{-1}), as a consequence of differences in history of cultivation (see soil data section). These differences result in different rates of reduction (or increase) in OC at similar input levels. Figure 7 shows that control management results in 44, 42, and 38%

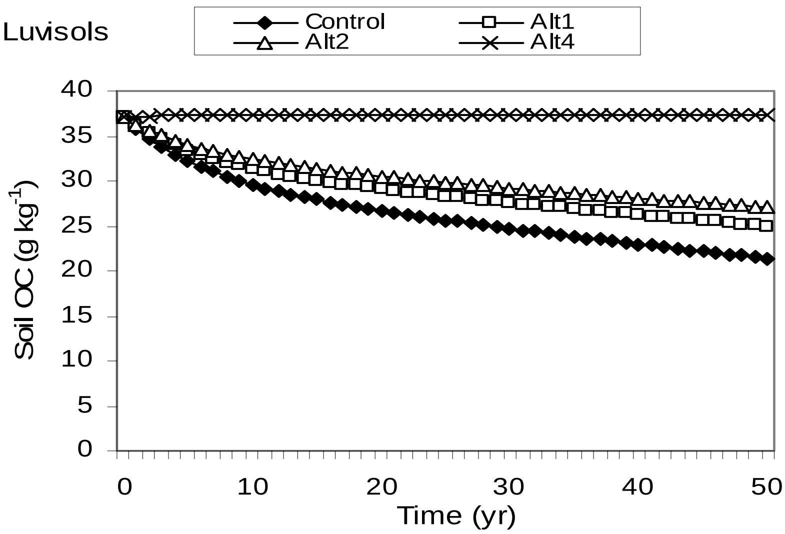
depletion of soil OC after 50 years of cultivation in Cambisols, Luvisols and Leptosols, respectively. Despite the higher rate of erosion in Leptosols caused by its steeper slopes (Table 1; Eqn. 15, Appendix A), the rate of decline in soil OC is lower, due to its lower initial content. In all three soils, the rate of decline is highest in the first 10 years, i.e., 20, 19 and 13% in Cambisols, Luvisols and Leptosols, respectively, compared to 7, 6 and 6%, respectively for the period between 40 and 50 years. Alt1 results in 16% reduction in OC in Cambisols, 32% in Luvisols, whereas it results in 22% increase in Leptosols. Alt2 results over 50 years in 27% reduction in OC content in Luvisols, whereas in Cambisols and Leptosols it increases by 1 and 57%, respectively.

To maintain a steady state in terms of organic carbon (i.e. annual outputs, the sum of OC decomposition and losses by erosion, equal external inputs), required annual input is higher for soils with higher OC content. Hence, under Alt4, composted organic amendments of 5.3, 15.0 and 2.1 Mg ha^{-1} are required annually for Cambisols, Luvisols and Leptosols, respectively. Inputs above these levels for each soil will result in build-up of OC and vice versa. Under a given management regime, in terms of nutrient recycling and external inputs, soil nutrient depletion is stronger on soils with higher nutrient contents than on soils with lower nutrient contents and the reverse is true for the rate of build-up of soil nutrients.

The rates of reduction in soil N under current management (Figure 8) are similar to those in OC, as the C:N ratio of the soil organic matter changes only slightly over the 50 years. For both, Cambisols and Luvisols all management options result in N depletion, whereas under Alt1 and Alt2 the N stock in Leptosols gradually increases. In absolute terms, N increases less than OC in agreement with the C:N ratio of the applied organic fertilizer. For example, under Alt4, initial C:N ratios of 7.9 in Cambisols, 11.6 in Luvisols and 9.4 in Leptosols increase to 10.5 in Cambisols, 13.6 in Luvisols and 11.3 in Leptosols.

Since under Alt4 the input level of organic amendments serves to maintain the soil OC contents, soil N contents after 50 years are 24, 14 and 18% lower than the initial values in Cambisols, Luvisols and Leptosols, respectively. Under Alt1 and Alt2, after 50 years, soil N contents are 26 and 24% (in Cambisols) and 33 and 32% (in Luvisols) lower than the initial values. In Leptosols, over the same period, the N contents increase by 7 (Alt1) and 13% (Alt2).





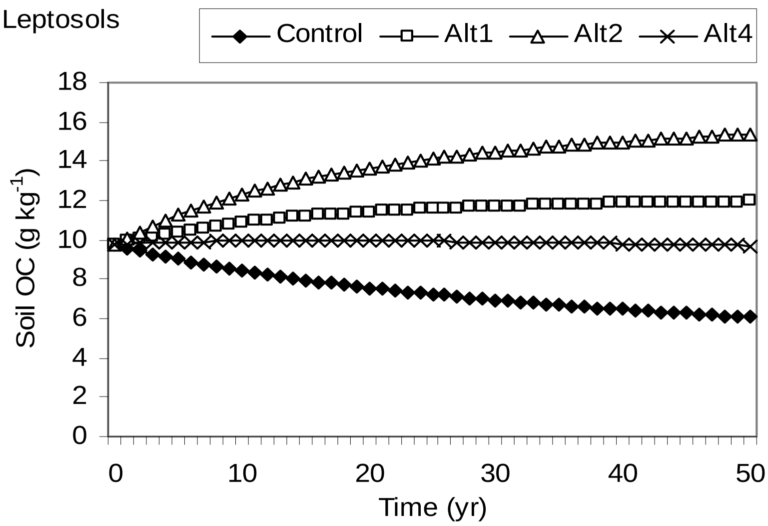


Figure 7. Simulated soil carbon dynamics in three soils of the Northern Highlands of Ethiopia (see text for explanation of farm management practices, Altx)

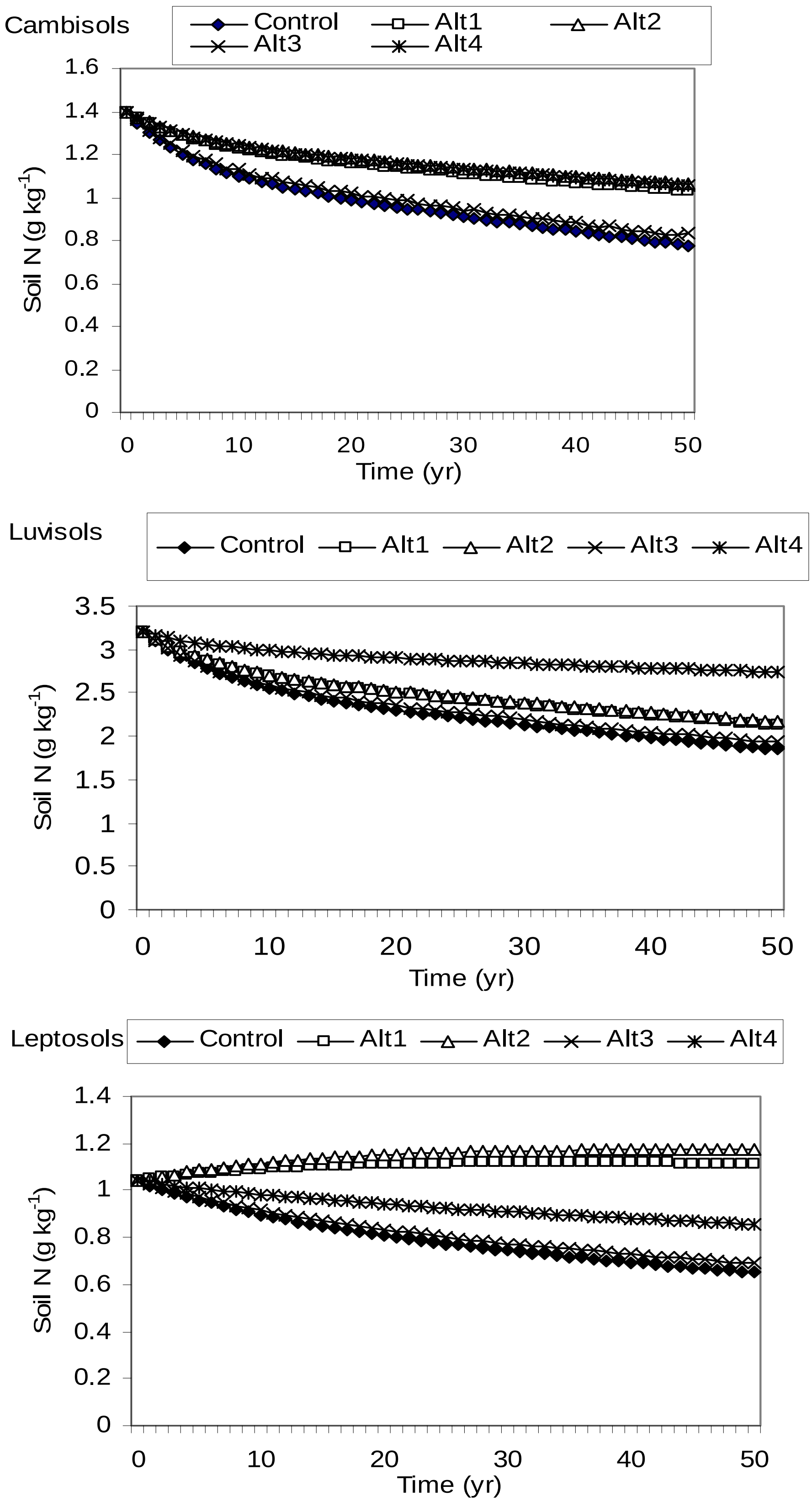


Figure 8. Simulated soil N dynamics in three soils of the Northern Highlands of Ethiopia (see text for explanation of farm management practices, Altx)

3.4.2 Soil P dynamics

Under the control and Alt2, total P content over 50 years decreases by 46 and 43% in Cambisols and 53 and 52% in Luvisols (Figure 9). As for OC and N, the depletion rates are highest (13% in Cambisols and 14% in Luvisols) in the first 10 years, albeit the rate of decline in total P is lower than those in OC and N. On the other hand, Alt1 will result in build-up of total soil P in Cambisols (69% higher after 50 years), but still to depletion (8%) in Luvisols. Under Alt4, maintaining soil P-levels requires, in addition to the organic P contribution from 5.3 (in Cambisols) and 15.0 (in Luvisols) Mg ha^{-1} yr^{-1} composted organic fertilizer (with P content = 0.00014), inorganic P-doses of 8 kg ha^{-1} yr^{-1} in Cambisols and 23 kg in Luvisols. Inputs above these levels result in build-up of total P and vice versa.

3.4.3 Crop-available N and P

In the simulations result (Figures 10 and 11) there is an 'artifact' in year 1, that is a sudden 'jump' in some of the alternatives, because in year 0 there was no application of fertilizers and/or organic amendments/biological N fixation while these managements start in year 1. Thus, changes are compared to the values in year 1 (considered as initial), not in 0. In crop available N under Alt3 shocks appeared due to biological N-fixation every three years. To avoid the shock moving averages are applied.

Under the control management, after 50 years, crop-available N is 87% (in both Cambisols and Luvisols) and 77% (in Leptosols) lower than initially (Figure 10). Under Alt1, crop-available N increases in Leptosols (14% higher than the initial value), whereas in Cambisols and Luvisols it decreases by 31 and 52%, respectively. Under Alt2, crop-available N decreases by 38 and 60% in Cambisols and Luvisols, respectively, whereas in Leptosols it increases by 35%. Under Alt3, crop-available N decreases by 81, 83 and 71% in Cambisols, Luvisols and Leptosols, respectively.

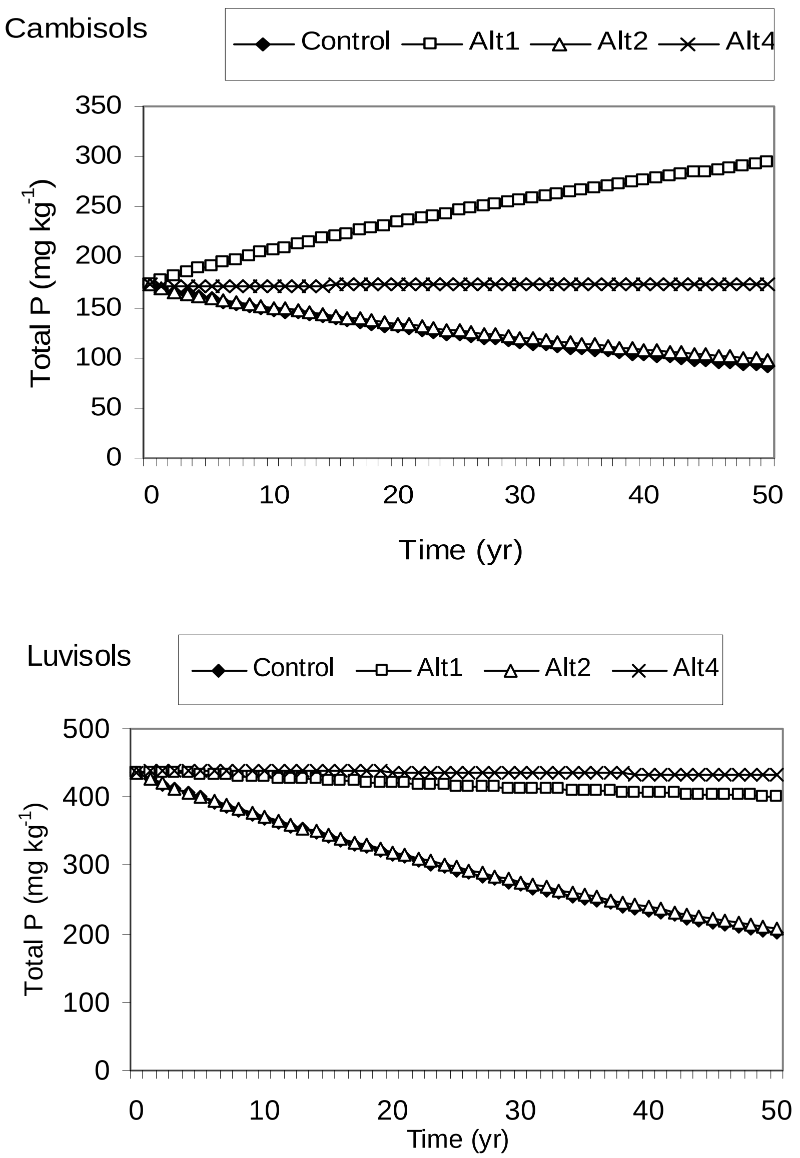


Figure 9. Simulated soil phosphorus dynamics in two soils of the Northern Highlands of Ethiopia (see text for explanation of farm management practices, Altx)

Under the control management, crop-available P after 50 years is 67% (in Cambisols) and 55% (in Luvisols) lower than the initial value (Figure 11). Alt1 results in 55 and 11% *higher* values in Cambisols and Luvisols, respectively. Under Alt2, crop-available P decreases by 54 and 52% for these two soils. Under Alt4, crop-available P increases by 7% in Cambisols and 20% in Luvisols.

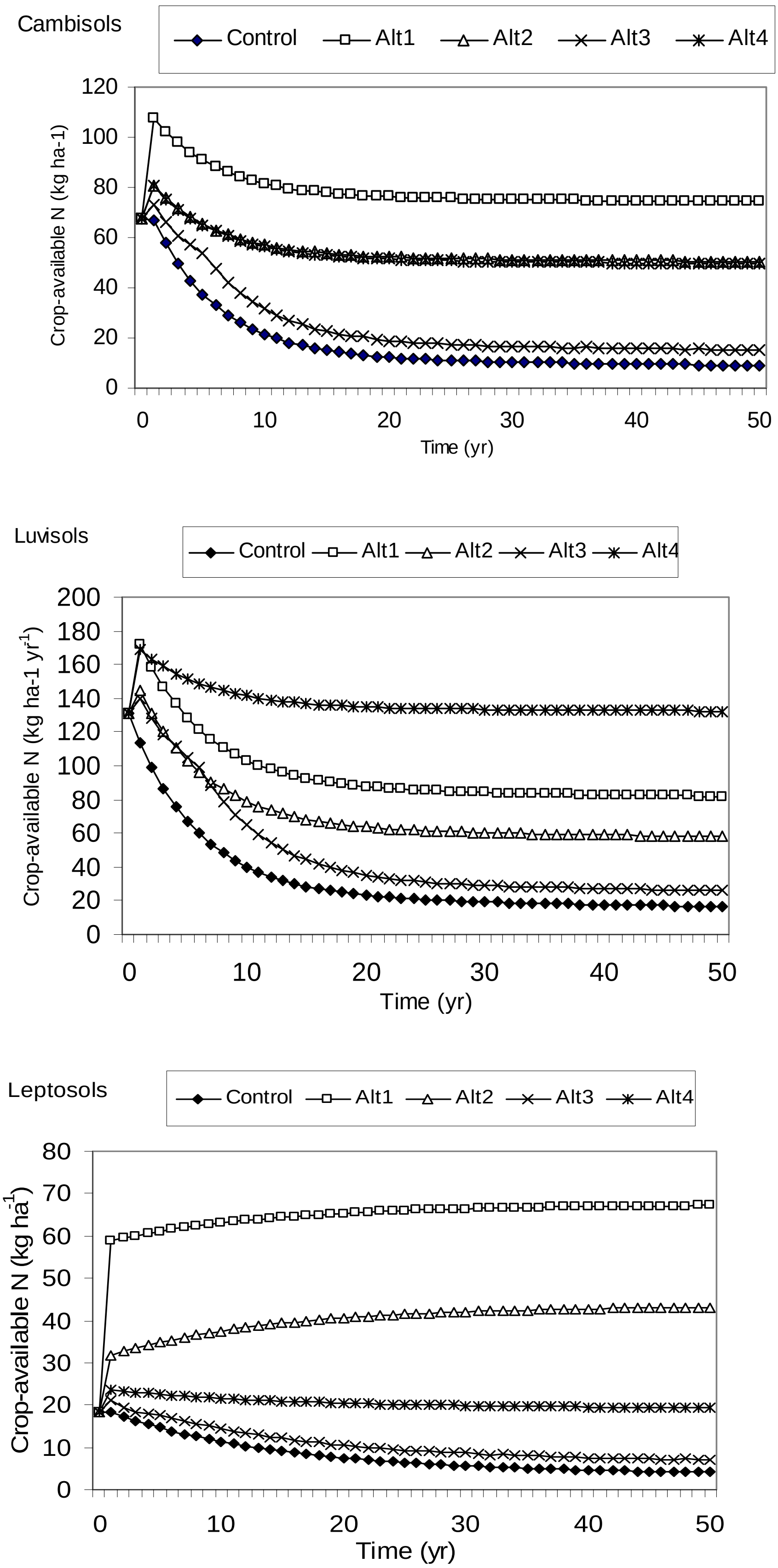


Figure 10. Simulated crop-available N dynamics in three soils of the Northern Highlands of Ethiopia (see text for explanation of farm management practices, Altx)

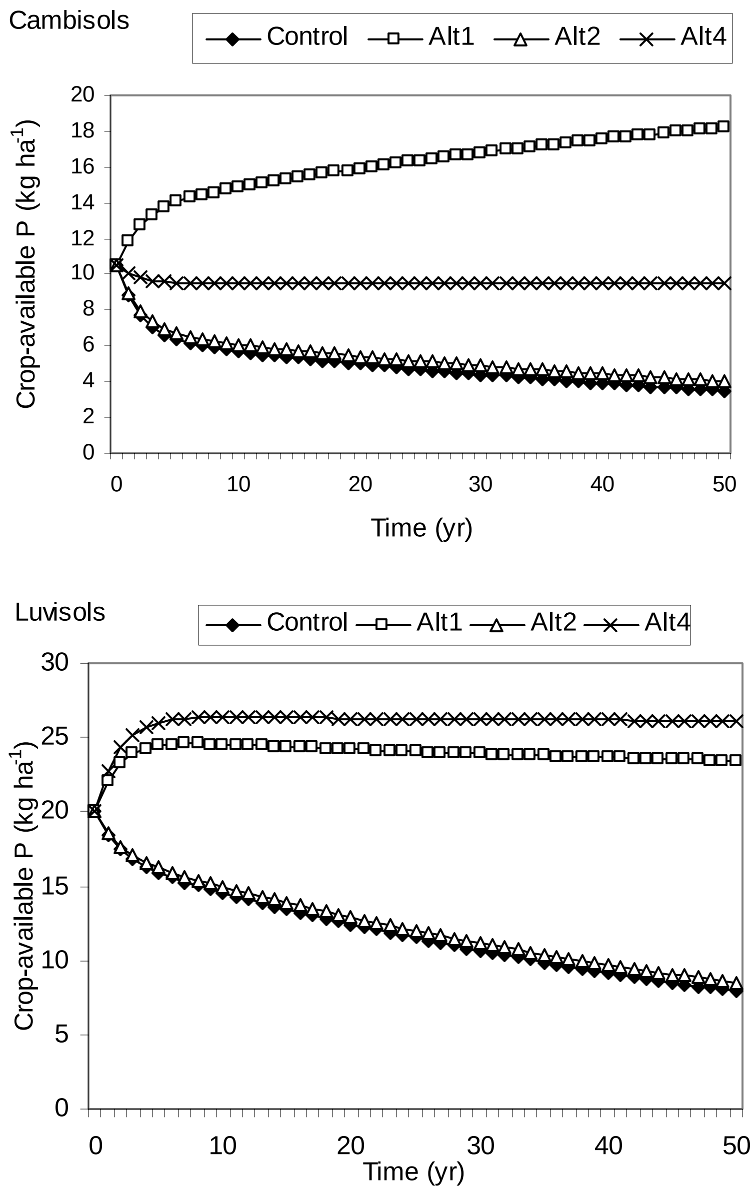


Figure 11. Simulated crop-available phosphorus dynamics in two soils of the Northern Highlands of Ethiopia (see text for explanation of farm management practices, Altx)

Changes in yield reflect the changes in crop-available N and P. For example, by applying the calibrated QUEFTS model, under the control management (unfertilized soil) ‘initial’ barley grain yield is estimated at 2.7 and 5.5 Mg ha^{-1} respectively in Cambisols and Luvisols (Assefa and van Keulen, Chapter 3). Assuming that supply of K is not limiting, barely yield declines to 0.5 Mg ha^{-1} [yield = {minimum (10 kg N x yield N diluted (52), (4 kg P x yield P diluted (365)}] in Cambisols and 0.9 Mg ha^{-1} [yield = {minimum (18 kg N x yield N diluted (52), (8 kg P x yield P diluted (365)}] in Luvisols after 50 years.

4 Conclusions

The purpose of our study was to explore the effects of farm management on long-term soil N, OC and P dynamics and the consequences for crop-available N and P and hence for crop yields, as crucial indicators for the sustainability of smallholder agriculture in the Northern Highlands of Ethiopia. Such explorations are useful tools in discussing the scope for improvements in the livelihoods of the smallholder farmers in the area. A simple modeling approach has been used that has the advantage that it is relatively easy to parameterize for specific situations, although it does not explicitly consider the effect of soil physical, chemical and microbiological processes nor within-season nutrient dynamics. It was shown that such a relatively simple model, though not suitable for explaining exactly the underlying processes, is able to reproduce the most important aspects of soil nutrient dynamics.

The simulation results indicate that, in terms of OC, only Alt2 in Cambisols and Alt1 and Alt2 in Leptosols and in terms of soil N, Alt1 and Alt2 in Leptosols are sustainable. In terms of total soil P, Alt1 (the recommended application rate of P) results in soil P accumulation in Cambisols and consequently increasing plant-available P. All other management regimes are not ‘sustainable’ in terms of soil N, OC and P, and lead to ‘soil mining’.

The model indicates that to maintain a dynamic equilibrium (Alt4) in OC and P different input levels are required, depending on current soil OC and P levels. To maintain soil OC and P at the current levels, annual required inputs increase with higher current nutrient contents. Under a given management regime in terms of (organic and inorganic) fertilizer application, the decline in soil nutrient contents is steeper the higher the initial soil nutrient content.

In general, current levels of organic fertilizer input are much lower than required to maintain a dynamic equilibrium. For example, in Luvisols, the required organic fertilizer input to maintain the current OC level is 4.4 times higher than the current level and 2.8 times higher than is available as organic resources from crop residues and pasture land. Thus, availability of organic inputs is a crucial constraint for attaining sustainability in terms of nutrient elements (de Ridder et al., 2004). Model results suggest that N and P supply to the crop in the non-fertilized situation is determined by soil fertility management regimes. In the control and low external input treatments, the risk of depleting soil nutrient stocks is high, with serious negative consequences for future agricultural production potentials.

The modeling approach applied in this study to explore the dynamics of soil OC, N and P and the consequences for crop-available N and P, can support the design of appropriate management practices that eventually would lead to improved soil fertility, higher crop-available N and P and thus as a basis for improved livelihoods.

It should be stressed, however, that in this study only attention has been paid to the bio-physical aspects of sustainability in terms of nutrient elements, while the major constraint for adoption of improved soil and crop management practices is formed by the (socio-) economic environment.

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Appendix A

Description of the long-term soil nutrient model

Organic carbon and nitrogen dynamics

The dynamics of stable organic N (NSP; kg ha^{-1}) are described as:

$$\mathbf{NSP_t = NSP_{t-1} + (NLPsp_t - NSPlp_t - NSPero_t) * \Delta t} \quad \mathbf{(1)}$$

where,

NSP_t	: size of the stable organic N pool at the end of year t
NSP_{t-1}	: size of the stable organic N pool at the end of the preceding year (kg ha^{-1})
$NLPsp_t$	: rate of N transfer from the labile organic pool to the stable organic pool (kg ha^{-1} yr^{-1})
$NSPlp_t$	: rate of N transfer from the stable organic pool to the labile organic pool (kg ha^{-1} yr^{-1})
$NSPero_t$	: rate of loss of stable organic N via erosion (kg ha^{-1} yr^{-1})
Δt	: time interval of integration (one year in this model)

$$\mathbf{NSPlp_t = NSP_t/tccsp} \quad \mathbf{(2)}$$

where,

tccsp	: time constant of conversion of stable organic N (yr)

$$\mathbf{tccsp = tcclp * 20} \quad \mathbf{(3)}$$

where,

tcclp	: time constant of conversion of labile organic N (yr)
20	: ratio of the time constants of conversion of stable and labile organic N (-)

$$\mathbf{tcclp = NLPin/(NMr/NMfcro)} \quad \mathbf{(4)}$$

where,

NLPin	: initial size of the labile organic N pool (kg ha^{-1})
NMr	: N-uptake by crop from unfertilized soil, assumed to originate from mineralization from labile organic N (kg ha^{-1} yr^{-1})
NMfcro	: fraction of mineralized N transferred to crop (-)

$$\mathbf{NLPsp_t = NLP_{t-1}/tcclp * NMfsp} \quad \mathbf{(5)}$$

where,

NLP_{t-1}	: size of the labile organic N pool at the end of the preceding year (kg ha^{-1} yr^{-1})
NMfsp	: fraction of N mineralized from the labile N pool transferred to the stable N pool (-)

$$\mathbf{NSPero_t = OCSPero_t/(CN_{sp})} \quad \mathbf{(6)}$$

where,

$OCSPero_t$: loss of stable organic carbon via erosion (kg ha^{-1} yr^{-1}) (Eqn. 14)
CN_{sp} : carbon to nitrogen ratio in stable organic pool (-)

The dynamics of labile organic N (NLP; kg ha^{-1}) are described as:

$$\mathbf{NLP_t = NLP_{t-1} + (NSPlp_t + Nrainlp_t + Nfixlp_t + Ninogflp_t + Norgflp_t - NLPsp_t - NLPcro_t - NLPloss_t - NLPero_t) * \Delta t} \quad \mathbf{(7)}$$

where,

NLP_t : size of the labile organic N pool at the end of year t
NLP_{t-1} : size of labile organic N pool at the end of the preceding year

$Nrainlp_t$, $Nfixlp_t$, $Ninogflp_t$ and $Norgflp_t$:
transfer of N from rain, fixation, inorganic fertilizer and organic fertilizer to the labile N pool (kg ha^{-1} yr^{-1})
$NLPcro_t$: transfer of N from the labile organic N pool to crop (kg ha^{-1} yr^{-1})
$NLPero_t$: loss of stable organic N via erosion (kg ha^{-1} yr^{-1})
$NLPloss_t$: loss of mineral N originating from the labile pool (NLPMloss) via leaching, volatilization and denitrification (kg ha^{-1} yr^{-1})

$$\mathbf{NLPero_t = OCLPero_t/(CN_{lp})} \quad \mathbf{(8)}$$

where,

$OCLPero_t$: loss of labile organic C via erosion (kg ha^{-1} yr^{-1}) (Eqn. 14)
CN_{lp} : carbon to nitrogen ratio of the labile organic pool (-)

Annual crop-available N ($Ncrop_t$, kg ha^{-1} yr^{-1}) is calculated as:

$$\mathbf{Ncrop_t = NLPcro_t + Norgfcro_t + Ninorfcro_t + Naincro_t + Nfixcro_t} \quad \mathbf{(9)}$$

Annual loss of N ($Nloss_t$, kg ha^{-1} yr^{-1}) is calculated as:

$$\mathbf{Nloss_t = NLPMloss_t + Norgfloss_t + Ninorfloss_t + Nrainloss_t + Nfixloss_t + NSPero_t + NLPero_t} \quad \mathbf{(10)}$$

The dynamics of stable organic C (OCSP; kg ha^{-1}) are described as:

$$\mathbf{OCSP_t = OCSP_{t-1} + (NLPsp_t * CN_{lp} - NSPlp_t * CN_{sp} - OCSPero_t) * \Delta t} \quad \mathbf{(11)}$$

where,

$OCSP_t$: size of the stable organic C pool at the end of year t
$OCSP_{t-1}$: size of the stable organic C pool at the end of the preceding year
$OCSPero_t$: loss of stable organic C via erosion (kg ha^{-1} yr^{-1})

The dynamics of labile organic C (OCLP; kg ha^{-1}) are described as:

$$\mathbf{OCLP_t = OCLP_{t-1} + (NSPlp_t * CN_{sp} + OCorgflp_t - NLPsp_t * CN_{lp} - NLPcro * CNlp - NLPloss_t * CN_{lp} - OCLPero_t) * \Delta t} \quad \mathbf{(12)}$$

where,

$OCLP_t$	: size of the labile organic C pool at the end of the end of year t
$OCLP_{t-1}$	: size of the labile organic C pool at the end of the preceding year
$OCLPero_t$	: loss of labile organic C via erosion (kg ha^{-1} yr^{-1})
$OCorgf_t$	: organic carbon transfer from organic fertilizer to the labile organic C pool (kg ha^{-1} yr^{-1})

$$\mathbf{OCorgflp_t = Norgflp_t * CN} \qquad \textbf{(13)}$$

The loss of organic C from the labile or the stable pool via erosion (OCero, kg ha^{-1} yr^{-1}) is calculated for the proportion of the upper 0.20 m of the soil that is lost through erosion, using an enrichment factor, by:

$$\mathbf{OCero = ENRICH * OC * 1000\ (Sloss/0.20 * 10000 * Bd)} \qquad \textbf{(14)}$$

where,

ENRICH	: enrichment factor, defined by 7.4 * (1000 * soil loss)$^{-0.2}$
OC	: total organic C in the upper 0.20 m soil (kg ha^{-1})
Sloss	: soil loss (Mg ha^{-1} yr^{-1})
Bd	: bulk density of the upper 0.20 m soil (kg m^{-3})

The annual rate of soil loss is calculated on the basis of annual rainfall, topography, crop cover, anti-erosion measures and soil erodibility factors (Renard and Ferreira, 1993; Roose, 1977):

$$\mathbf{Sloss = Frain * Ftopg * Fcrop * Fanter * Ferod} \qquad \textbf{(15)}$$

where,

Frain	: rainfall and runoff factor (-)
Ftopg	: topographic factor combining slope length and slope steepness (-)
Fcrop	: factor accounting for effect of crop cover (-)
Fanter	: factor accounting for effect of soil conservation measures (-)
Ferod	: soil erodibility factor (-)

$$\mathbf{Frain = 0.5 * rainfall\ (mm\ yr^{-1})\ (Roose, 1977)} \qquad \textbf{(16)}$$

The soil erodibility factor (Ferod) is set to 0.2726, valid for a medium erodibility class (Van Keulen, 1995).

The topographic factor is determined as (Roose, 1977):

$$\mathbf{Ftopog = (Fldslo^{1.5} + (fldleng/3)^{0.5})/100} \qquad \textbf{(17)}$$

where,

Fldslo	: slope of the field (degrees)
Fldleng	: length of fields (m)

The factor accounting for the effect of crop cover is set to 0.5 for barley, wheat and faba bean, equivalent to the factor for cotton set by Roose (1977).

The factor accounting for the effect of soil conservation measures (Fanter) is to 0.1 as defined by Roose (1977) for tied ridges. In the study area, extensive soil conservation measures, such as rock bunds or tied ridges are widely implemented.

Phosphorus dynamics

The initial size of the labile P pool (PLP_{in}, kg ha^{-1}) is estimated by:

$$\mathbf{PLP_{in} = PUuf_s/LPUF} \qquad \textbf{(18)}$$

where,

$PUuf_s$	: P uptake from unfertilized soil (kg ha^{-1})
LPUF	: fraction of P uptake from unfertilized soil originating from the labile P pool (-)

$$\mathbf{LPUF = Prf/PLf} \qquad \textbf{(19)}$$

where,

Prf	: first year uptake from fertilizer (kg ha^{-1})
PLf	: fertilizer P transferred to the labile P pool (kg ha^{-1})

$$\mathbf{Prf = PUfs - PUuf_s} \qquad \textbf{(20)}$$

where,

PUfs	: P uptake from fertilized soil (kg ha^{-1})

$$\mathbf{PLf = Fr * Pinorff} \qquad \textbf{(21)}$$

where,

Fr	: rate of inorganic fertilizer applied (kg ha^{-1})
Pinorff	: fraction of inorganic P fertilizer transferred to the labile P pool (= 0.8)

The initial size of the stable P pool (PSP_{in}, kg ha^{-1}) is calculated as

$$\mathbf{PSP_{in} = tccpsp * PSPlp} \qquad \textbf{(22)}$$

where,

tccpsp	: time constant of conversion of the stable P pool (= 30 yr)
PSPlp	: initial rate of transfer of the stable P pool to the labile P pool (kg ha^{-1} yr^{-1})

$$\mathbf{PSPlp = PUufs + PLPspin} \qquad \textbf{(23)}$$

where,

PLPspin	: initial rate of transfer of the labile P pool to the stable P pool (kg $ha^{-1}yr^{-1}$)

$$\mathbf{PLPspin = PLPin/tcclp} \qquad \textbf{(24)}$$

where,

tcclp : time constant of conversion of the labile P pool (= 5 yr)

The dynamics of the stable P pool (PSP, kg ha^{-1}) are described as:

$$\mathbf{PSP_t = PSP_{t-1} + (PLPsp_t + Pw - PSPlp_t - PSPero_t) * \Delta t} \quad \mathbf{(25)}$$

where,

PSP_t : size of the stable P pool at the end of year t

PSP_{t-1} : size of the stable P pool at the end of the preceding year (kg ha^{-1})

$PLPsp_t$: rate of P transfer from the labile P pool to the stable pool (kg ha^{-1} yr^{-1})

$PSPlp_t$: rate of P transfer from the stable P pool to the labile pool (kg ha^{-1} yr^{-1})

$PSPero_t$: rate of loss of stable P via erosion (kg ha^{-1} yr^{-1})

Pw : rate of mineral P transfer to the labile P pool from weathered parent material set to a fixed rate (1 kg ha^{-1} yr^{-1}, Van der Pol, 1992)

$$\mathbf{PSPlp_t = PSP_t/tccsp} \quad \mathbf{(26)}$$

where,

tccsp : time constant of conversion of the stable P pool (= 30 yr)

The loss of P from the labile or the stable P pool ($PSPero_t$, kg ha^{-1} yr^{-1}) is calculated for the proportion of the upper 0.20 m of the soil that is lost through erosion by:

$$\mathbf{PSPero_t = PSP_t * 1000\ (Sloss/0.20 * 10000 * Bd)} \quad \mathbf{(27)}$$

where,

PSP_t : quantity of P in the stabile P pool in the upper 0.20 m soil (kg ha^{-1})

$$\mathbf{PLPsp_t = PLP_t/tcclp} \quad \mathbf{(28)}$$

where,

PLP_t : size of the labile P pool (kg ha^{-1} yr^{-1})

tcclp : time constant of conversion of labile P (= 5 yr).

The dynamics of the labile P pool (PLP, kg ha^{-1}) are described as:

$$\mathbf{PLP_t = PLP_{t-1} + (PSPlp_t + Pinogf_t + Porgf_t - PLPsp_t - PLPcro_t - PLPloss_t) * \Delta t} \quad \mathbf{(29)}$$

where,

PLP_t : size of the labile P pool at the end of year t

PLP_{t-1} : size of the labile P pool at the end of the preceding year (kg ha^{-1})

$Pinogf_t$ and $Porgf_t$ are rates of P transfer to the labile pool via inorganic and organic fertilizer, respectively

$PLPcro_t$ and $PLPloss_t$ are rates of P transfer from the labile P pool to crop and loss, respectively

$$\mathbf{PLPcro_t = PLP_t * LPUF} \quad \mathbf{(30)}$$

$$\mathbf{PLPero_t = PLP_t * 1000\ (Sloss/0.2 * 10000 * Bd)} \quad \mathbf{(31)}$$

Chapter 7

General discussion

General discussion

1 Introduction[1]

Roughly 40 percent of the developing world's rural population live in less-favoured areas (LFAs), lands with limited agricultural potential, often environmentally sensitive, or with poor infrastructure and service support. Although they have escaped the environmental problems associated with the intensive use of external inputs (Conway and Barbier, 1990), they have nevertheless been ravaged by problems of their own. Fragile soils, unfavorable climatic conditions, growing population density, inadequate property rights, poor infrastructure and limited market access, and often neglect by policy makers and agricultural research and extension systems, have all contributed to agricultural and economic stagnation and aggravated poverty. As more and more people seek to make a living in these areas, they expand their cropland into forests and steep hillsides, farm their land in erosive ways and fail to replenish the soil nutrients that they remove.

Less-favoured areas are lands that have been neglected by man and/or nature. They include lands that are of low agricultural productivity, due to limited and uncertain rainfall, poor soils, steep slopes or other bio-physical constraints. They also include areas with higher agricultural potential that are presently in uses of low value due to limited access to infrastructure and markets, low population density or other socio-economic constraints. Due in part to their lower agricultural potential and/or remoteness, such areas are often politically marginalized, contributing to their neglect by policy makers.

Typically, LFAs have gained little from past agricultural successes as they have largely been bypassed by the modern farming revolution. Most of the population of these areas is in mountain and hillside regions (uplands or highlands), and in arid and semi-arid zones (drylands). Recent developments in technological progress for arable cropping and livestock systems tend to disregard the specific agro-ecological and socio-economic conditions that prevail in less-favoured areas, *e.g.*:

- low agricultural yields that impose constraints on labour productivity, making engagement in off/non-farm employment an important aspect of activity choice;

[1] This introduction is largely based on: Van Keulen, H., 2005. Heterogeneity and diversity in less-favoured regions. Guest editorial, Special Issue Agricultural Systems (in press)

- high risks in rainfed production that discourage farmers to specialise, leading to risk-aversion in input use and investment behavior;
- high incidence of serious degradation of the natural resource base due to deterioration of soil physical properties, soil erosion and nutrient depletion.

Poverty, low agricultural productivity, and natural resource degradation are strongly interrelated problems in less-favored areas of the tropics.

One of the reasons for the failure of many Integrated Rural Development Programmes was their top-down nature and limited recognition of the wide diversity and heterogeneity of farmers and fields as a prime characteristic of livelihoods and farming systems in LFAs. Biophysical conditions are highly *variable* among and within farms. Rural households are *diverse* in terms of resources, activities and access to markets and institutions. Rural communities are *heterogeneous* as far as assets, wealth and power are concerned. As a result, various development pathways, defined as a common pattern of change in livelihood strategies, will exist at different scales (Pender, et al. 1999). By carefully utilizing local comparative advantages, rural households linked to farms and firms, communities or regions will be able improve their level of living and natural resource management practices.

The overall objective of this study was to increase insight in the functioning of farming systems in the Northern Highlands of Ethiopia, one of the least-favored areas in East Africa, with special attention for the heterogeneity among farm households and farm fields, and the influence of farm management regimes on temporal dynamics of soil nutrients, taking into account the interactions among soil management and crop and livestock activities and their impacts on yields, as a basis for recommendations on modifications leading to increased farm productivity and improved quality of the agricultural resources.

2 The context

Agriculture is the basis of the Ethiopian economy, accounting for 46% of its GDP and 90% of its export earnings and employing 85% of the country's labour force (UNDP, 2002). About 95% of the agricultural output in Ethiopia is produced on integrated crop-livestock subsistence smallholder farms (ADF, 2002). Above all, the farm is the primary means of production used to generate a livelihood for the family and an asset for farmers to accumulate wealth (Nega et al., 2003). Moreover, Ethiopia's long-term economic development strategy, "Agricultural Development-Led-Industrialization" explicitly targets smallholders' private agricultural economy to maintain food security and contribute to economic growth. They are also supposed to initiate development of home industries, stimulate the service sectors and create additional purchasing power. These broad indicators underline the importance attached to agriculture in general and to smallholder farms in particular in the Ethiopian economy (Block, 1999). To achieve these targets, appropriate farm management for sustainable agricultural development is vital. However, most of the environmental problems facing the country are associated with subsistence agriculture-related activities (UNEP, 2002), resulting from inappropriate land management practices associated with low external nutrient inputs and population pressure (UN, 2002). With a continuously growing population, farm resource depletion is accelerating, resulting in widespread deforestation, overgrazing, biodiversity loss and soil fertility decline. Consequently, agricultural production declines and food deficits increase. What needs to be done to increase food production for the growing population and concurrently combat agricultural resource degradation remain unresolved questions and is on the agenda of the ongoing debate among economists, agriculturalists and policy makers (Keeley and Scoones, 2003).

3 Why farm management?

Farm management comprises a set of decisions and actions by the farmer with respect to his/her fields, animals and other resources through which he/she influences the way in which commodities are produced. The appropriateness of such practices should be evaluated on the basis of the degree to which the farm household can realize its objectives, without negatively affecting the quality of its natural resources. In the highlands of Ethiopia, farm management is characterized by the integrated management of crop and livestock components. In such mixed systems resources are cycled within the system, as nutrients and energy flow from crops to livestock and vice versa.

Thus, the specific objectives of the study were to describe the interactions between i) farm management and soil nutrient dynamics and ii) farm management and the availability and quality of feed and livestock production, as a basis for increasing insight in the functioning and performance of the current farming system. This insight should form the basis for the design of alternative farm management systems with their consequences for the long-term dynamics of soil organic carbon (OC), nitrogen (N) and phosphorus (P) and crop-available N and P, as crucial indicators of the sustainability of agricultural production systems. Quantification of the relation between current farm management practices and soil nutrient dynamics forms the basis for parameterization and calibration of models that are applied to explore effects of both current and alternative farm management practices.

In the ongoing debate, different alternatives have been suggested by different groups, such as: i) mass-mobilization schemes for conservation of natural resources are the only way to address the associated problems of soil erosion and insufficient food production, ii) increasing farmers' incentives to invest in their on land is more important than anything else, as a way of boosting food production and solving the recurrent food crises (Keeley and Scoones, 2003), iii) Nega et al. (2003) argue that the current tenure system is not encouraging sustainable farming practices, because it lacks ownership or even cultivation security and a commercial outlook, and hence the land tenure policy should be reformulated in targeting these issues, iv) Mintesinot et al. (2004) have suggested that maximizing the productivity of both land and water is important to achieve sustainable food security, v) Sonneveld (2002) has pointed out that a further growth of food production for the growing population in Ethiopia under the current technology and input levels would only be possible by increasing the cultivated area, although he does indicate that the scope for expansion of cultivated land is very limited. These various suggestions all highlight that attaining sustainable agricultural production systems combined with food security and economic growth is undoubtedly complex. Our study results, presented in the following sections, contribute to the ongoing discussion by tools and data that allow generation of explicit and quantitative information on the biophysical potentials and limits to agricultural production.

4 Soil nutrient balance

Many of the earlier studies on problems of farm management and low agricultural production in Ethiopia have dealt with physical soil erosion via run-off (Belay, 1992; Hurni, 1990; 1985; 1984; FAO, 1986; Constable, 1984; Hunting, 1976). Since the 1990s, export of nutrients in economic yield and crop residues from agricultural land and unavoidable losses through processes as leaching and volatilization have come to the fore as key mechanisms in soil nutrient mining (Harris, 1998; Bojo and Cassels, 1995; Stoorvogel and Smaling, 1990). Such studies in Ethiopia include those by Hengsdijk et al. (2005), Elias et al. (1998) and Stoorvogel and Smaling (1990). Although methodology and interpretation have been questioned (Scoones and Toulmin, 1998), cautious analysis of soil nutrient balances is an important tool to raise awareness of the local farming community and in the policy dialog, to alert policy makers to the need for measures that provide incentives for farmers to implement modifications in farm management systems (Janssen, 1999).

Thus, in Chapter 2, partial balances of the macronutrients (nitrogen (N), phosphorus (P) and potassium (K)) were studied at field and farm scales to evaluate the sustainability of current farming systems in terms of nutrient elements

Three farm groups (rich, medium and poor), selected through participatory techniques, were distinguished, based on farm size, capital assets and grain stocks. The balances of N, P and K for aggregated farm land resources (grazing lands plus cultivated lands) were negative for all three farm groups, with more negative values for the rich than for the medium and the poor groups. The values in this study suggest much higher rates of soil nutrient depletion than those reported by Stoorvogel and Smaling (1990) as averages for Ethiopia, Elias et al. (1998) for Kindo Koisha district in southern Ethiopia and Hengsdijk et al. (2005) for Gobo Deguat in the Northern Highlands of Ethiopia. Variation within farm groups was also significant.

The major causes of the high rates of nutrient mining are very limited external inputs, such as (chemical) fertilizers and concentrate feed, very small landholdings (average holdings of less than 2 ha per household, varying in size between 4 and 8 members), large herds compared to the available grazing lands and use of a major proportion of animal manure for household energy supply. All these characteristics lead to intensive exploitation of the agricultural resources without compensation for nutrients exported out of the system.

Population pressure in the study area exceeds the density of 13 persons per km^2 that supposedly can be supported at low external input levels (cf. Sonneveld, 2002). External chemical fertilizer inputs used are urea combined with diammonium phosphate (DAP), restricted to irrigated fields and at very low rates, i.e. on average less than 20 kg (N+P) ha^{-1} yr^{-1}, compared to a world-wide average input level of 97 kg ha^{-1} yr^{-1} (Pender et al., 1999). Consequently, N, P and K stocks in the soil are rapidly declining, with annual depletion rates higher for the rich group than for the poor group and the medium group taking an intermediate position. These differences are related to total biomass production and nutrient removal and soil nutrient status.

Chemical fertility of the soils of the rich farmers is generally higher than of those of the medium and poor farmers, leading to higher rates of nutrient export. These results confirm that farm management regimes characterized by low external input levels carry the risk of depleting soil nutrient reserves, seriously jeopardizing the long-term sustainability of agricultural production (Hengsdijk et al., 2005; Tellarini and

Caporali, 2000; Elias et al., 1998; Harris, 1998; Bojo and Cassels, 1995; Stoorvogel and Smaling, 1990).

Three major processes restrict the efficiency of nutrient cycling through manure in the systems in Teghane. First, a substantial proportion of the manure, both from the stable and from grazing lands is used for household fuel (equivalent to 26 to 52 kg N ha^{-1} yr^{-1}). Second, the poor physical state of the stables and poor manure management in the stable and compost pit lead to losses equivalent to 19-55 kg of NPK ha^{-1} yr^{-1} which is higher than the current external chemical fertilizer input. Third, compost is applied through surface spreading on the cultivated fields over an extended time period. As the compost is not immediately incorporated in the soil, some of the N will be lost through volatilization.

Moreover, as insufficient compost is available for all fields, some fields may not receive compost for 3 to 5 years. Enhancements in nutrient use efficiency from manure could be achieved through careful manure management. It must be carefully stored to minimize physical loss of manure and compost and its nutrients and it must be applied shortly before sowing. Introduction of energy-saving stoves could lead to reduction in the use of manure for household energy, thus increasing its availability as a fertilizer.

The low level of chemical fertilizer use is mainly due to two reasons: first it is expensive (Gezahegn Ayele and Tekalign Mamo, 1995) and secondly as a result of risk aversion (van Noordwijk et al., 1994). Conditions should be created to make application of external inorganic fertilizer more attractive (Breman and Debrah, 2003; Breman et al., 2001). This could lead to increased utilization in both irrigated and rainfed fields, combined with expansion of moisture harvesting for supplementary moisture supply.

5 Fertilizer management

Currently, in the Northern Highlands of Ethiopia use of animal manure for soil fertility management is very limited because of the increasing demand of this product for household energy supply (Chapter 2). Similarly, crop residues are almost completely used as cattle feed (Chapter 4). Moreover, the contribution of legumes in the rotation in the farming system, that could supply symbiotically fixed nitrogen, is limited. Fallowing, that could naturally regenerate soil fertility has been all but abandoned, because of the very small areas of cultivated land (0.43- 0.85 ha per household), on average less than the area required for minimum household food production for Tigray (0.93 ha, Nega et al., 2003), whereas the current average cultivated landholding for the region is 0.54 ha. Thus, to meet the food demand of the growing population, application of chemical fertilizer appears absolutely necessary (Breman, 1990). However, adoption and efficiency of chemical fertilizer use tend to be very low (Mulat Demeke et al., 1997), which may be associated with the fact that fertilizer application has been based on conventional blanket recommendations, without taking into account indigenous soil nutrient supply.

Identifying nutrient management practices that allow meeting the increasing demand for food, while minimizing environmental impact and being economically attractive for farmers is important (Ortiz-Monasterio, 2005). In current practice, the scope for using quantitative soil information (indigenous soil fertility) for fertilizer management is lacking. Hence, for formulation of more accurate fertilizer recommendations, a more generic nutrient balance method is required that considers indigenous soil nutrient supply, applied nutrients and their interactions. For that purpose, nutrient requirements of barley have been determined for three soils with different chemical properties, classified as Cambisol, Luvisol-1 and Luvisol-2, both experimentally and on the basis of the QUEFTS model (Chapter 3),.

Total nutrient uptake in aboveground dry matter varied with variation in indigenous soil nutrient supply. In Cambisol and Luvisol-2, indigenous exchangeable K was about 15 mmol kg^{-1} and TNU, TPU and TKU, and grain yield (GY) in treatments with K fertilization and no N and P were not different from those in the control treatments. In Luvisol-1, characterized by low exchangeable K, i.e. 2 mmol kg^{-1}, TNU, TKU and GY of similar treatments were significantly higher than those of the control treatments. In this soil, application of 25 and 50 kg K ha^{-1} resulted in an increase of about 50% in TNU and GY, compared to the average of the control treatments, whereas TNU, TPU and TKU in treatments receiving only N or P fertilizer were not different from those in the control, because the low level of K supply limits the uptake of other elements (Fitzpatrick, 1986). Consequently, the recovery fractions (fertilizer uptake in aboveground plant dry matter per unit fertilizer applied) of N and P fertilizers are lower in Luvisol-1 (Chapter 3).

Agronomic efficiencies (increase in grain yield per unit fertilizer applied) of applied nutrients varied with variations in indigenous soil nutrient supply and in applied NPK combinations. Average agronomic efficiency of N was highest on Cambisol and Luvisol-2, in which indigenous N, P and K supply are balanced, and lowest on

Luvisol-1 with low exchangeable K. Average agronomic efficiency of P was highest on Luvisol-2, which is characterized by high organic carbon (OC) content. Average agronomic efficiency of K was generally high on Luvisol-1, characterized by low exchangeable K.

Similarly, the best fertilizer combinations for attaining maximum yield appeared different for soils with different indigenous soil nutrient supplies. The results show that different rates of fertilizer application are required for different soils with different levels of indigenous soil nutrient supply for different objectives, i.e. either to attain maximum agronomic efficiency of a given nutrient or maximum yield or optimum economic returns. To allow generation of information in support of such decisions, the QUEFTS model (Janssen et al., 1990) has been calibrated for barley in the Northern Highlands of Ethiopia. This set of standard parameters allows estimation of indigenous supply of N, P and K from soil chemical characteristics (OC, exchangeable K and P-Olsen) and recovery of applied fertilizer nutrients, as the basis for formulation of balanced rates of fertilizer for barley.

6 Feed resources, livestock production and soil organic matter management

Increasing food demand associated with population increase in developing countries might at least partially be met by increasing livestock production (Delgado et al., 1999). However, in response to the population increase, good (common) pasture land is increasingly being converted into cropland, leaving increasingly marginal land for grazing.

Moreover, as rural population pressure increases, arable farmers need to intensify production. In the absence of external inputs (low external input agriculture, LEIA), arable farmers have to increase cereal production by expanding their cultivated area to maintain food self-sufficiency for their families. Introduction of animal traction helped to produce more grain by allowing cultivation of more land and maintaining labour productivity. Thus, many arable farmers became livestock owners themselves, their livestock grazed the crop residues and the contracting communal village pastures. Livestock owned by crop farmers changed the system dynamics by increasing the rate of processes, e.g. the turnover of nutrients. With continued increase in population pressure, soil fertility management also changed, to practices characterised by intensified internal recycling of nutrients. In these systems, crop residues are increasingly collected and transported to the homestead to feed animals that are kept in kraals and stables. This also creates the opportunity to collect the manure, that mixed with animal feed refusals and household waste, is applied to arable fields close to the homesteads, or as in the Northern Highlands is used to provide rural energy. Farmers owning less or no livestock use the technique of composting crop residues and household waste, returning the upgraded organic material to the fields.

In the Northern Highlands, the future possibilities for quality feed production are very limited, because the land holdings for grazing are very small, i.e., between 0.2 – 0.8 ha per household, with an associated herd size of between 2 - 9 Tropical Livestock Units (TLU). These stocking rates exceed the recommended 19-42 TLUs per km^2 for humid areas and 7-9 TLUs for semi-arid to arid areas (Jahnke, 1982), which thus represents a risky situation with respect to pasture degradation.

In the Northern Highlands, non-conventional feed resources and/or industrial by-products are not available as livestock feed. More than 30% of the total digestible organic matter (DOM) intake of the animals originates from crop residues, characterized by low metabolizable energy and low crude protein contents that provides sub-maintenance energy supplies, as voluntary intake and digestion of such feeds are generally low (Oosting, 1993).

Availability and quality of forage and hence live weight dynamics show a distinct seasonal pattern. In the late wet season, September to November, cattle graze natural pasture, and the high availability and quality of this feed resource is reflected in the observed high rates of live weight increase. Starting December, cattle graze aftermath in crop fields, and as the consequence of lower feed availability (in both quantity and quality), live weight gain decreases. From May to July, herbaceous feed resources are hardly available and the coping strategy consists of feeding leaves of prickly pear. From April onwards, animals loose live weight, with the maximum loss observed in August.

Average annual feed availabilities were below maintenance requirements for all three farm groups, and from the feed balances and observed live weight dynamics, the main conclusion in Chapter 4 is that meat and milk production are not the main objectives of livestock keeping for smallholders, but manure, draught power, progeny and capital asset are more important. Therefore, the main challenge is how to increase the livestock contribution to food security and economic growth. That could be attained via targeted feed resource use aimed at maximum livestock production (meat and milk) that would lead to higher system productivity, without jeopardizing environmental sustainability.

The results of the study on the relationships between available feed quantity and quality, feed use and livestock production (meat, milk, manure and draught) at village scale (Chapter 5), show that at small herd size (HS), individual animal productivity is high and decreases with increasing HS, whereas total annual live weight production (TLWP) and milk production (TMP) continue to increase with increasing HS up to the 'optimum' level of feed resource use. In that trajectory, the lower production per animal is more than compensated by the larger animal number. When more of the feed is used than the 'optimum' level, both, individual animal and herd productivity decrease, because more low quality feeds are included in the ration, and eventually a situation is reached characterized by losses of live weight. On the other hand, manure production increases with increasing HS. Total manure production and its application in the field varies with variations in the level of feed use. The soil C balance is negative at all levels of feed use, though the value is smaller at optimum feed use for TLWP and TMP than at 100% feed use.

A total herd size at village scale exceeding that leading to optimum feed use in terms of total live weight production, creates pressure on the environment and leads to resource degradation, such as soil compaction and overgrazing. It is also important to note that keeping large numbers of animals is associated with high risks of losses during periods of drought-induced feed shortage, a common phenomenon in the Northern Highlands of Ethiopia

Environmentally-friendly development of livestock production can be attained by increasing production per animal through reducing HS and not through increasing numbers. Thus, it is important to identify appropriate livestock husbandry practices that avoid negative environmental impacts but, at the same time, contribute to satisfying the still growing demand for livestock products (De Haan et al., 1997) and to improving the livelihoods of the rural population. This can be achieved by maintaining a HS that can be supported by the available good quality feed, and optimize feed use through appropriate storage and carry-over system.

For individual farmers, reducing herd size may conflict with other objectives, such as the functions of savings and capital asset and manure for fuel (Chapter 4). In the absence of functioning formal financial markets, livestock keeping appears a most interesting alternative (Slingerland, 2000). It is indicated in Chapter 5 that establishment of well-functioning savings and credit services, such as banking facilities, could alleviate (part of) the constraints preventing reduction in animal numbers, and introducing energy-saving stoves could reduce the demand for manure for fuel, so that feed resources can be used more efficiently for meat and milk production.

7 Long-term nutrient dynamics under alternative farm management

In the preceding analysis it has become clear that one of the major problems of the agricultural systems in the Northern Highlands of Ethiopia is the low soil fertility, the associated low levels of production of both food and forage crops, the low quality of the available feed resources for the animals and the use of organic resources for household energy. This represents a negative spiral of declining resource quality and poverty. To examine the options for halting or reversing this spiral, we developed a model describing the interactions between farm management, soil nutrient dynamics and agricultural production.

In Chapter 6, we present results of the model study, referring to cultivated Cambisol, Luvisol and Leptosol, on exploration of long-term dynamics of soil N, OC and P and crop-available N and P under five alternative farm management regimes, representing current and improved on-farm resource management and application of external inputs, i.e.

- i) Control: represents a farming system of continuous cereal crops with complete removal of crop residues and without external nutrient inputs,
- ii) Alternative 1 (Alt1): Cultivation of cereal crops with input of the current level of organic amendments and recommended chemical N and P fertilization doses.
- iii) Alternative 2 (Alt2): Composting all crop residues and all vegetation from pasture land, and applying the resulting compost to cultivated fields.
- iv) Alternative 3 (Alt3): Include leguminous crops in the rotation.
- v) Alternative 4 (Alt4): Applying required composted organic amendments and inorganic P fertilizer to maintain the current levels of soil C and P.

Initial soil C, N and P contents of the soils differed, as a consequence of differences in soil physical characteristics and in history of cultivation. Under the control management regime, after 50 years of cultivation, both soil C and N contents are reduced by 38% or more in all soils. Despite higher erosion rates in Leptosols, associated with steeper slopes, the rates decline in this soil are lower because of lower initial contents. In all three soils, depletion rates were highest in the first 10 years and gradually declined in the course of the period of cultivation. A given level of (nutrient) inputs in soils with different initial contents will result in different rates of depletion or build-up in the soil. Similar to OC and N, total P contents decline, albeit at lower rates than OC and N.

The current management regime (Alt1) results in the highest depletion rates in Luvisol, characterized by the highest C and N contents, followed by Cambisol, whereas in Leptosol, characterized by the lowest initial C and N contents, it leads to build-up of C and N. Total soil P contents in Cambisol increase by 70% over a 50-year cultivation period, whereas on Luvisol they decrease by 8%.

Under Alt4, the model generates dynamic equilibria of OC and P at different input rates, depending on the current soil OC and P levels. To maintain soil OC and P at the current levels, in combination with higher and more stable availability of N and P for crop growth, required annual inputs per unit area are higher, the higher current nutrient contents. However, at these rates of annual organic amendments, total soil N contents decrease, because of the higher C:N ratio of the organic inputs compared to the initial soil C:N ratios.

The current levels of organic inputs are much lower than the quantities required to maintain the current soil OC contents under continuous cultivation.
N and P supply to the crop is determined by soil fertility management regimes. In low external input systems, the risk of depleting soil nutrient stocks is high with serious threats for the sustainability of agricultural production.

The model developed in this study has the advantage that it is simple and can therefore be relatively easily parametrised for specific situations. It does not consider the effect of soil physical, chemical and microbiological processes and the short-term dynamics within the growing season, but is suitable for exploration of the long-term dynamics of soil OC, N and P and the consequence for crop-available N and P as affected by crop and soil management. It therefore can support the design of appropriate management practices that eventually would lead to improved soil fertility and higher crop-available N and P.

8 Agriculture for food security and economic growth?

A study by Sonneveld (2002) indicates that the Ethiopian population will double before 2030, despite a falling population growth rate from 3.2 to 2.2% annually (World Bank, 2001). As a consequence, food supply has to grow by 3.6% annually to attain self-sufficiency (Sonneveld, 2002).

The prospects for rural employment outside the agricultural sector in Ethiopia in general and in the Northern Highlands in particular are limited, because of various reasons, such as lack of investments, low levels of education and a persistent unstable political situation, that has formed a strong drain on the national resources that might have been used for socio-economic development programs of the country. As an alternative, Sonneveld (2002) has suggested that growth in food production in Ethiopia with current technologies and input levels would only be possible by expanding the cultivated area. However, the land use/cover data in this study indicate that, certainly in the Highlands, the scope for further expansion of cultivated land is limited.

In the last decades, considerable areas of degraded sloping lands have been reclaimed and in cultivated areas, extensive soil and water conservation structures, such as stone and earth bund terraces have been constructed (Beyene, 2003; Esser et al., 2002) to reduce run/off and associated soil loss and this program is still at the top of the agricultural development agenda. In addition, a variety of packages have been offered, such as a blanket fertilizer recommendations and micro-dam development for small-scale irrigation. However, achievements in terms of increased food production as part of the regional food security strategy are limited (Keeley and Scoones, 2003).

The model results on introduction of legumes in the rotation and low levels of organic fertilizer application (Chapter 6) and low chemical fertilizer application (Chapter 2; CSA, 1997) show that these practices can not compensate the current nutrient depletion rates, so that in the course of time, grain yields will significantly decrease as a consequence of the reduction in the supply of crop available N and P and soil OC.
To what extent farmers can be food-secure on the basis of the current production systems, given the low level of productivity and the small size of their holdings? As shown in Table 1, a very simple evaluation of food security in relation to cereal production indicates that currently, the rich farmers produce food grain slightly in excess of the minimum food requirements, whereas the medium and poor farmers produce 27 and 28% below the minimum requirements, respectively. The food deficit

is a result of both, the small size of the landholdings (which is not conducive to even small scale mechanization (FAO, 2001)) and the low level of productivity.

Current production at low levels of external inputs is below model yield estimates based on indigenous soil nutrient supply, suggesting that current production levels are lower than nutrient-limited yields. Yields of unfertilized treatments in on-farm experiments for barley (1.8, 2.6 and 5.3 Mg ha^{-1} on Luvisol-1, Cambisol and Luvisol-2, respectively (Chapter 3)) were much higher than those on farmer-managed fields (maximum grain yield on rich farms was 2.1 Mg ha^{-1} (Chapter 2)), whereas *with* fertilizer application the yield range was between 4.5 and 8.0 Mg ha^{-1} (Chapter 3). This would imply that other factors than nutrients limit current agricultural productivity. Note, however, that our experiments were *supplementary irrigated*.

In the study area in almost all crops, weed infestation resulted in up to 30% yield reduction (results not shown). Moreover, local orthodox Christian holidays take up a substantial proportion of the potential working time, i.e., about 62% of the annual days consists of non-working days (28% weekends and 34% local holidays during week days (Table 1)). Moreover, it has been observed that long-term external food grain aid may create a syndrome that affects the working culture of the people, so as not to go all-out for higher productivity.

These observations could indicate scope for increasing farm productivity and thus food security in the ***short-term***, because model-estimated yields at the currently recommended chemical fertilizer application rates result in per capita food grain production exceeding the minimum grain required for food security for all farm groups on the assumption that moisture is not a constraint and crops are free of weeds, pests and diseases (Table 1). It might thus be possible, provided that at least the water constraint can be removed in most cases through supplementary irrigation. It is, however, doubtful whether agriculture can serve as an engine for economic growth beyond food security, since 61% of the population in the study area is poor, owns small parcels of cultivated land, and the per capita surplus grain yield of 141 kg per year will hardly be enough to cover other expenses, such as school fees, medical costs, etc.. However, attaining the objective of production increase requires a fundamental change in the current developments, as between 1971 and 2000, the per capita agricultural production index in Ethiopia has steadily declined at 1.15% per year (FAO, 2001) and a further decline is expected with the increasing population.

On the other hand, the results of the soil organic matter model indicate that the quantities of external organic amendments required to maintain soil OC at the current level are much higher than the total biomass that can be produced in the area (Chapter 6). These results are in agreement with those of analyses that have been carried out for similar climatic conditions in W. Africa (cf. de Ridder et al., 2004). Hence, it is impossible to maintain sustainable agricultural development, even with the most efficient system of recycling of carbon and nutrients: thus there is no possibility for sustained development without external inputs (Breman, 1990).

The agricultural development problem in the Northern Highlands of Ethiopia not only has a biophysical dimension, but also, and probably equally important, a socio-economic dimension, and simple solutions are not available. These issues warrant further investigation as a basis for new policy formulation.

Thus, given the high rate of population increase and the small size of the agricultural holdings and the high demand for organic inputs into the soil to sustainably maintain soil quality and the associated crop yields, for ***long-term*** poverty reduction and economic growth a strategy is required that leads to sustainable increased land productivity, and transformation of the working culture of the population. Similarly, to enhance the contribution of livestock to food security and economic growth, its current roles (high manure production and savings and capital assets) have to be changed. All these changes, however, should be accompanied by a substantial expansion of the non-agricultural sectors that can provide gainful employment for a significant proportion of the rural population from the agricultural sector.

Table 1 Per capita food grain requirements and annual balances at different production scenarios for three farm groups*.

	Characteristic	Rich	Medium**	Poor**
Actual average grain yiel household^{-1} (kg) (2003)	Barley	1891	1016	641
	Wheat	300	153	190
	Faba bean	160	64	23
	Field pea	121	68	8
	Total per household	2472	1301	862
	Per capita food grain balance (supply/demand, fraction)	**1.05**	**0.73**	**0.72**
Estimated barley grain yield using QUEFTS model at different input levels	No external inputs			
	Barley grain (kg per household)	**5641**	**3086**	**1182**
	Barely per capita food grain balance (kg)	**402**	**211**	**-7.5**
	Current external input			
	Barley grain kg yr^{-1}	**5794**	**3203**	**1264**
	Per capita food grain balance (kg)	**421**	**230**	**13**
	External N fertilizer (kg ha^{-1} yr^{-1})	12.5	10.0	8.2
	External P fertilizer (kg ha^{-1} yr^{-1})	4.4	3.5	2.9
	Recommended external input			
	Barley grain kg yr^{-1}	**6257**	**3773**	**1777**
	Per capita food grain balance (kg)	**479**	**326**	**141**
	External N fertilizer (kg ha^{-1} yr^{-1})	64	64	64
	External P fertilizer (kg ha^{-1} yr^{-1})	21	21	21
Household characteristics				
	Average cultivated land (ha)	0.84	0.62	0.43
	Average household size (persons)	8	6	4
	Farm household barley grain requirement (kg yr^{-1})***	2424	1818	1212
Soil characteristics				
	OC g kg^{-1}	28.9	19.5	11.7
	P-Olsen mg kg^{-1}	26.0	19.3	9.1
	Exchangeable K mg kg^{-1}	10.4	7.7	6.4
Working and non-working days of the year				
	Working days of the year	138 (38%)		
	Weekends	104 (28%)		
	Local holidays in weekdays	123 (34%)		

*Of the total population of the study area, 2, 37 and 61% are classified as rich, medium and poor, respectively

**Actual average grain yields computed from data of Tables 1, 4 and 5 (Chapter 4), harvest index of 0.406, and 25% of the feed from crop residue in medium and poor farm groups, which includes weeds.

***Annual per capita barley grain requirement set to 303 kg; Daily per capita energy requirement set to 2500 kcal; 100 g raw barley = 301 kcal, wheat = 310, faba bean and field pea = 370 (Garrow et al., 2003)

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Summary

Farm management comprises a set of decisions and actions by the farmers with respect to fields, animals, crops and other resources through which they influence the way in which commodities are produced. The value of different practices within farm management should be evaluated on the basis of the degree to which they contribute to the realization of the farm household's objectives, but also on their effect on quality of natural resources. In the highlands of Ethiopia, farm management is characterized by a strong integration of crop and livestock components. In such mixed systems resources such as nutrients and energy flow from crops to livestock and vice versa.

The study was carried out in Teghane village, in Tigray regional state. Tigray is situated in the Northern Highlands of Ethiopia, stretching from 12^0 15' to 14^0 57'N and 36^0 27' to 39^0 59'E. Teghane is located in the eastern administrative zone of Tigray in the district "Atsbi-Wonberta". The main district town is Atsbi, about 70 km north of the capital of Tigray, Mekelle. Teghane micro-catchment is located 2 km north of Atsbi town. The catchment of Teghane is situated between 13^0 52' 53" and 13^0 53' 37" N and between 39^0 42' 05" and 39^0 43' 57" E, covering an area of 13.56 km^2. Its altitude ranges from 2710 to 2899 m above mean sea level.

The overall objective of this study was to increase insight in the functioning of farming systems in the Northern Highlands of Ethiopia, one of the least-favored areas in East Africa. Central issue was the dynamics of soil nutrients. The aim was to relate variation in dynamics of soil nutrients to wealth class (rich, medium and poor) differences between farm households and different farm management regimes and to differences between plots within farms. Interactions among soil management and crop and livestock activities and their impacts on yields were studied. Subsequently this was the basis for recommendations on modifications leading to increased farm productivity with optimal maintenance of quality of agricultural resources.

The first operational objective of this study was to monitor inflows and outflows of macronutrients (nitrogen (N), phosphorus (P) and potassium (K)) at plot and farm scales. The NUTMON-toolbox was used to assess current rates of nutrient losses for farm wealth classes (rich, medium and poor).

Thus, in Chapter 2 partial balances of macronutrients; N, P and K were described at field and farm scales. The results indicate that soil nutrient depletion proceeds at an alarming rate at both farm fields and plot scales. This so-called soil mining is associated with increasing population pressure, which has led to very small land holding sizes. Consequently, very intensive exploitation of the land is often the sole option for farmers to satisfy the household's food and fuel requirements and the livestock feed requirement as much as possible. Animal feed is extremely scarce and, hence, every piece of crop organic matter, including roots and weeds, is collected from the farm fields at harvesting time. Moreover, from immediately after harvest till first ploughing animals graze the cultivated land, so that hardly any plant remains are left in cultivated fields.

Nutrient depletion rates differ significantly among different farmer wealth groups. The highest rates were recorded for the rich farm group, followed by the medium and poor farm groups. These differences were associated with higher crop production by rich farm group as the result of two causes. First, chemical and physical soil fertility of the cultivated fields of the rich was generally higher. Secondly, they implement more frequently nutrient-saving techniques, such as soil and water conservation practices and apply more external and internal inputs. These farmers better prepare their land, seed on time, practice timely weeding. All these activities require higher labor inputs. On the other hand, the low rates of depletion in the poor farm group are partly associated with low crop production, due to low indigenous soil fertility, low input use and poor crop management.

Significant quantities of manure are used for household fuel supply, equivalent to 52.3, 21.9 and 26 kg N ha^{-1} yr^{-1} for rich, medium and poor farmers, respectively. In addition, due to inappropriate management of manure in the stable and the compost heap significant losses took place, averaging 25.3 kg N, 5.8 kg P and 23.8 kg K ha^{-1} $year^{-1}$ for the rich group, 25 kg N, 5.5 kg P and 33 kg K ha^{-1} $year^{-1}$ for the medium group, and 8.8 kg N, 2.4 kg P and 8 kg K ha^{-1} $year^{-1}$ for the poor group.

Nutrient use efficiency from manure could be improved through judicious manure management. Firstly, it should be carefully stored to minimize physical loss of manure/compost, and its nutrients and it must be applied to the appropriate crop with the appropriate method at the proper time. Secondly, introduction of energy-saving stoves so that more manure, now used for household fuel, can be applied to farming fields. On top of this, conditions should be created to make application of external inorganic fertilizer more attractive. This could lead to application of more external chemical fertilizer in both irrigated and rain-fed fields.

The second objective was to parameterize the indigenous soil nutrient supply and nutrient requirement of barley and to calibrate the QUEFTS (**QU**antitative **E**valuation of the **F**ertility of **T**ropical **S**oils) model for the management of applied fertilizer in the Northern Highlands of Ethiopia. Thus in Chapter 3, indigenous soil nutrient supply has been estimated from soil chemical properties of three soils identified as Cambisol, Luvisol-1 and Luvisol-2.

Soil organic carbon (OC) content of Luvisol-1 was 1.7 times that of Cambisol; total N uptake (TNU) of Luvisol-1 was only 67% of that of Cambisol, as a result of its substantially lower value of exchangeable K, which negatively affects the uptake of other elements. Similarly, the recovery fractions of applied N and P fertilizers were lower in Luvisol-1. In Cambisol and Luvisol-2 indigenous exchangeable K was about 15 mmol kg^{-1} and TNU, total P uptake (TPU) and total K uptake (TKU), and grain yield (GY) in treatments $N_0P_0K_{25}$ and $N_0P_0K_{50}$ were not different from those in the control treatments ($N_0P_0K_0$). On the other hand, in Luvisol-1, TNU, TKU and GY in treatments $N_0P_0K_{25}$ and $N_0P_0K_{50}$ were significantly higher than those in the control treatments. In this soil, application of 25 and 50 kg K ha^{-1} resulted in an increase of about 50% in TNU and GY compared to the average of the control treatments, whereas application of K fertilizer in Cambisol and Luvisol-2 gave no yield response. In Luvisol-1, TNU, TPU and TKU in treatments receiving only N or P fertilizer were not different from those in the control.

Agronomic efficiencies (GY kg^{-1} applied fertilizer) of applied fertilizers were different for different values of indigenous soil nutrient supply and different NPK combinations. Average agronomic efficiency of N was highest in Cambisol, in which indigenous N, P and K supply were balanced, and was lowest in Luvisol-1 with low exchangeable K. Average agronomic efficiency of P was highest in Luvisol-2, which is characterized by high OC contents. Average agronomic efficiency of K was generally high in Luvisol-1, characterized by low exchangeable K. Similarly, the best fertilizer combinations for maximum yield appeared different for different soils with different indigenous nutrient supplies.

The QUEFTS model was calibrated and can be used as a tool to quantify indigenous soil nutrient supply and to determine the best fertilizer combinations for targeted barley yields in the Northern Highlands of Ethiopia.

Knowledge of on-farm available feed resources and their quality is essential in exploring opportunities to increase farm productivity. Thus, in Chapter 4 the availability and quality of feed resources and their relationship with livestock performance in smallholder farms have been described.

In Teghane, in the medium and poor farm groups more than 40% of the total feed digestible organic matter (DOM) was derived from crop residues such as straw and stovers from barley, wheat, beans and peas. In the rich farm group crop-residues accounted for 30% of total DOM. All crop residues in the study area were characterized by a low metabolizable energy (ME) content (<8 MJ kg^{-1} dry matter (DM)) and low crude protein content (<7 g kg^{-1} DM).

Availability and quality of forage and hence live weight dynamics showed a distinct seasonal pattern. In the late wet season, September up to November, cattle graze natural pasture. The high availability and quality of this feed resource is reflected in the observed high rates of live weight increase. Starting December cattle graze aftermath in crop fields. As a consequence of lower feed availability (in both quantity and quality) daily live weight gain decreases then. From May to July herbaceous feed resources were hardly available and the coping strategy consists of feeding leaves of prickly pear. From April onwards, animals loose live weight with the maximum loss observed in August.

Smallholders sell surplus grain. They often do not have access to banking facilities. On the other hand, savings in cash create social pressure to share with or borrow to others. This problem is avoided by investing in animals, which the farmers consider a reliable and secure capital savings asset. An average rate of return above 22% has been observed (but involves high risk when feed is critically unavailable) which is considerably higher than the interest rate on most formal credits. Investing in sheep was thus worthwhile for smallholders.

From the feed balances we concluded that live weight gain and milk production are not the main objectives of livestock keeping for smallholders, but manure, draught power, progeny and capital asset are more important. Depending on the objective, the optimal pattern of use of the available feed resources is different, supporting different livestock numbers. If manure production was the sole objective, actual herd size in 2004 would be optimal. For optimization of other objectives such as meat or milk production, either HS should be reduced to the level that can be supported by the best quality feed or production of quality feed be increased. For instance, if the objective would be optimum milk production from the local Zebu cattle, i.e., 3 kg milk cow^{-1} d^{-1} for 6

months, only the good quality feed, i.e., native grass or hay would be used and hence herd size should be reduced by 25% for the rich, 60% for the medium and 75% for the poor farm group, compared to the values in 2004.

Restricted availability of feed that moreover was of low quality was a major constraint that needs to be tackled. Feed quality and quantity can be increased in two ways. First, about 43% of the currently cultivated land in the area was on Leptosols. These soils are generally located on sloping land, were very shallow, and crop production on these soils was extremely low. Discontinuing cultivation of this land, and using it in cut and carry feeding systems would significantly increase quality feed supply for livestock. Secondly, rainfall is monomodal and grass growth is thus restricted to one season (August to October). Much of the current pasture land is located in the valley bottom, where gravity irrigation is possible. Approximately in the middle of the valley bottom a micro-dam has been constructed to irrigate cultivated fields in the dry season for vegetable and cereal crop production. Not all the available water is being used. Thus, introducing proper water management would allow irrigation of pasture lands on the lower slope side of the dam in the dry season to increase quality and quantity of the feed supply.

The estimated annual feed balance was slightly negative for all farm groups while the observed live weight gain was slightly positive. The reason for the underestimation of feed balances is unknown, but could be in an overestimation of the maintenance requirements or an underestimation of the actual feed intake with regard to quality or to quantity. Feed balance as well as live weight gain was higher for animals in the rich farm group than in the other groups.

In Chapter 5 we have described the relationships between feed availability (quantity and quality) and feed intake on the one hand and live weight and milk production on the other to assess the best feed utilization pattern in view of various production objectives of farmers. Production objectives could be: live weight production (LWP), milk production, draught power and maintenance of soil carbon stock.

In the study area, over 70% of the annual feed dry matter supply is from crop residues, which are characterized by low ME content. Particularly wheat and barley straws were of low quality, with 23 and 34 g Crude Protein kg^{-1} DM.

Where many feeds are of low quality, maximum liveweight production and milk production can be obtained if either the farmer selectively uses the better feeds or the animals are allowed to select between and within feeds. This is on the (realistic) assumption that all feeds can be pooled and are available throughout the year.

Individual animal productivity decreases with increasing herd size (HS), because low quality feeds were included in the feed ration as the HS increases. Despite a high individual production at a smaller HS, annual total live weight production (TLWP) and total milk production (TMP) of the herd were smaller and increase with increasing HS up to the optimum level of feed resource use. Beyond that point, both individual animal and herd productivity decreased and eventually a situation characterized by losses of live weight was reached.

Actual HS in the study area (micro-catchment) was 1506 tropical livestock unit (TLU), which is lower than the HS that could be supported at maintenance when all feeds are pooled. The estimated optimum HS i) for maximum TLWP, TMP and soil C input and ii) for TLWP, manure and draught power was significantly lower than the actual HS, suggesting that in areas where most feeds are of low quality, optimum benefits from livestock can be obtained by selective utilization of quality feeds combined with proper storage and carry-over systems. Environmentally-friendly development of livestock production can be maintained by increasing production per ruminant for optimum HS and not through increased numbers. Alternatively, production of quality feed could be increased. For individual farmers, reducing herd size may conflict with other objectives such as savings and capital asset. This objective can be satisfied by facilitating savings and credit services. Technical and institutional arrangements, such as better banking facilities should be introduced, and farmers should be encouraged to use the banking facilities for their savings, on the one hand, and to get credits which might be directly related to the amount of their savings on the other hand. Under such conditions optimum feed resource use can be maintained for maximum meat and milk production.

In Chapter six the study results on long-term dynamics of soil C, N and P and the consequences for crop-available N and P under alternative farm management practices for 50 years was described.

The simulation results indicate that, in terms of OC, only Alt2[1] in Cambisol and Alt1[2] and Alt2 in Leptosols and in terms of soil N, Alt1 and Alt2 in Leptosols were sustainable. In terms of total soil P, Alt1 (the recommended application rate of P) results in soil P accumulation in Cambisol and consequently increasing plant-available P. All other management regimes were not 'sustainable' in terms of soil N, OC and P, and lead to 'soil mining'.

The model indicates that to maintain a dynamic equilibrium (Alt4[3]) in OC and P different input levels are required, depending on current soil OC and P levels. To maintain soil OC and P at the current levels, annual required inputs increase with higher current nutrient contents. Under a given management regime in terms of (organic and inorganic) fertilizer application, the decline in soil nutrient contents is steeper for the higher initial soil nutrient content.

In general, current levels of organic fertilizer input are much lower than required to maintain a dynamic equilibrium. Thus, availability of organic inputs is a crucial constraint for attaining sustainability in terms of nutrient elements. Model results suggest that N and P supply to the crop is determined by soil fertility management regimes. In the control and low external input treatments, the risk of depleting soil nutrient stocks is high, with serious negative consequences for future agricultural production potentials.

The modeling approach applied in this study to explore the dynamics of soil OC, N and P and the consequences for crop-available N and P, can support the design of appropriate management practices that eventually would lead to improved soil fertility, higher crop-available N and P and thus as a basis for improved livelihoods.

It should be stressed, however, that in this study only attention has been paid to the bio-physical aspects of sustainability in terms of nutrient elements, while the major constraint for adoption of improved soil and crop management practices is formed by the (socio-) economic environment.

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[1] Alternative 2 (Alt2): Composting all crop residues and all vegetation from pasture land, and applying the resulting compost to cultivated fields
[2] Alternative 1 (Alt1): Cultivation of cereal crops with input of the current level of organic amendments and recommended chemical N and P fertilization doses
[3] Alternative 4 (Alt4): Applying required composted organic amendments and inorganic P fertilizer to maintain the current levels of soil C and P.

In the general discussion section we have tried to evaluate the agricultural production system, to what extent farmers can be food-secure, given the low level of productivity and the small size of their holdings. A very simple evaluation of food security in relation to cereal production indicates that currently, the rich farmers produce food grain slightly in excess of the minimum food requirements, whereas the medium and poor farmers produce 27 and 28% below the minimum requirements, respectively. The food deficit was a result of both, the small size of the landholdings and the low level of productivity.

There is a scope for increasing farm productivity for food security in the ***short-term***, because model-estimated yields at the currently recommended chemical fertilizer application rates result in per capita food grain production exceeding the minimum grain required for food security for all farm groups. This is on the assumption that moisture is not a constraint and crops are free of weeds, pests and diseases. It is, however, doubtful whether agriculture can serve as an engine for economic growth beyond food security. Because, 61% of the population in the study area was poor, owns small parcels of cultivated land. The per capita surplus grain yield of 141 kg per year will hardly be enough to cover other expenses, such as school fees, medical costs, etc. Thus, for ***long-term*** poverty reduction and economic growth a strategy is required that leads to sustainable increased land productivity, and transformation of the working culture of the population. These changes, however, should be accompanied by a substantial expansion of the non-agricultural sectors that can provide gainful employment for a significant proportion of the rural population from the agricultural sector.

Samenvatting

Bedrijfsvoering omvat een verzameling van beslissingen en handelingen die de boer of boerin neemt en uitvoert met betrekking tot zijn of haar land, gewassen, dieren en andere hulpbronnen, waardoor hij of zij invloed uitoefent op de wijze waarop de productie tot stand komt. De waarde van de verschillende handelingen binnen de bedrijfsvoering zou geëvalueerd moeten worden op basis van de mate waarin ze bijdragen aan het halen van de doelstellingen van het boerengezin, maar ook op basis van hun effect op de kwaliteit van natuurlijke hulpbronnen. In de hooglanden van Ethiopië wordt de bedrijfsvoering gekarakteriseerd door een sterke integratie tussen gewassen en vee. In dergelijke gemengde systemen vinden interne stromen van hulpbronnen zoals nutriënten en energie plaats van gewas naar vee en andersom.

Het onderzoek werd uitgevoerd in het dorp Teghane, in de regio Tigray, in de Noordelijke Hooglanden van Ethiopie en strekt zich uit van 12^0 15’ tot 14^0 57’ Noorderbreedte en 36^0 27’ tot 39^0 59’Oosterlengte. Teghane ligt in de oostelijke administratieve zone van Tigray in het district Atsbi-Wonberta. De belangrijkste stad in dit district is Atsbi, dat ongeveer 70 km ten noorden van de hoofdstad van Tigray, Mekelle, ligt. Teghane (micro-stroomgebied) ligt 2 km ten noorden van Atsbi tussen 13^0 52' 53" en 13^0 53' 37" Noorderbreedte en tussen 39^0 42' 05" and 39^0 43' 57" Oosterlengte, en beslaat een gebied van 13.56 km^2. De hoogte varieert van 2710 tot 2899 m boven zeeniveau.

De doelstelling van deze studie was het verkrijgen van meer inzicht in het functioneren van bedrijfssystemen in de Noordelijke Hooglanden van Ethiopië, één van de minst bevoorrechte gebieden van Oost-Afrika. De dynamiek van bodemnutriënten stond hierbij centraal. Het doel was om variatie in dynamiek van bodemnutriënten te relateren aan verschillen in economische status (rijk, modaal en arm) en bedrijfsvoering tussen bedrijven en aan verschillen tussen percelen binnen bedrijven. Hiervoor dienden interacties tussen bodembeheer en gewas- en veehouderijactiviteiten en hun effecten op opbrengsten in kaart gebracht te worden. Dit inzicht in de dynamiek van bodemnutriënten was vervolgens de basis voor aanbevelingen voor veranderingen die kunnen leiden tot een verhoogde productiviteit met een zo goed mogelijk behoud van de kwaliteit van de landbouwkundige hulpbronnen.

De eerste operationele doelstelling van deze studie was het monitoren van de instroom en uitstroom van de macronutriënten stikstof (N), fosfor (P) en kalium (K) op de schaalniveaus perceel en bedrijf. Voor het vaststellen van de nutriëntenverliezen in de huidige bedrijfssystemen werd de NUTMON-benadering gebruikt.
In hoofdstuk 2 staan de partiële balansen (gebaseerd op de nutriëntenstromen over de dam van perceel of bedrijf) van de macronutriënten N, P en K beschreven op perceels- en bedrijfsniveau. De resultaten geven aan dat de nutriëntenuitputting van de bodem met een alarmerende snelheid plaatsvindt op beide schaalniveaus. Dit zogenaamde "uitboeren" is geassocieerd met een toenemende bevolkingsdruk, die geleid heeft tot erge kleine bedrijven. Dit laat de boeren slechts de mogelijkheid om hun land zeer intensief te gebruiken om in de voedselbehoefte van de familie en het vee, maar ook in de behoefte aan brandstof voor de huishouding zoveel mogelijk te voorzien. Diervoeder is enorm schaars en elk stukje organische stof uit gewassen, inclusief wortels en onkruiden wordt dan ook verzameld bij de oogst. Bovendien grazen de dieren de akkers af in de periode tussen oogst en de eerste maal ploegen, zodat er nauwelijks plantaardige resten op de akkers achterblijven. De snelheid van nutriëntenuitputting verschilde significant tussen bedrijven met verschillende economische status. De hoogste snelheden van uitputting werden gevonden voor de groep van rijke boeren, gevolgd door de modale en arme groep boeren. Deze verschillen zijn geassocieerd met een hogere gewasproductie bij rijke boeren. Hiervoor zijn twee oorzaken te noemen. In de eerste plaats is de chemische en fysische vruchtbaarheid van de akkerbouwpercelen van de rijke groep boeren over het algemeen beter. In de tweede plaats passen rijke boeren vaker technieken als bodem- en waterconservering toe en gebruiken zij vaker en meer externe en interne inputs. Rijke boeren bewerken hun land beter en zaaien en wieden op het juiste moment. Deze activiteiten vragen echter een hoge inzet van arbeid. De lagere snelheid van bodemuitputting bij de groep arme boeren is daarentegen deels geassocieerd met een lage gewasopbrengst als gevolg van de van nature lage bodemvruchtbaarheid, laag gebruik van inputs en slechte gewasverzorging.

Aanzienlijke hoeveelheden mest werden gebruikt voor de brandstofvoorziening van de huishoudens, equivalent aan 52.3, 21.9 en 26.0 kg N ha^{-1} $jaar^{-1}$ voor respectievelijk de rijke, modale en arme groep boeren. Daarnaast vonden er significante verliezen van nutriënten plaats als gevolg van suboptimaal management van mest in de stal en tijdens bewaring en compostering. Deze verliezen bedroegen gemiddeld 25.3 kg N, 5.8 kg P and 23.8 kg K ha^{-1} $jaar^{-1}$ voor de rijke groep, 25 kg N, 5.5 kg P and 33 kg K ha^{-1} $jaar^{-1}$ voor de modale groep en 8.8 kg N, 2.4 kg P and 8 kg K ha^{-1} $jaar^{-1}$ voor de arme groep boeren.

De efficiëntie van het gebruik van nutriënten uit mest kan verbeterd worden door verbetering van mestmanagement. In de eerste plaats moet de mest op de juiste manier opgeslagen worden om het fysieke verlies van drogestof en nutriënten te beperken en bij aanwending moet de mest op het juiste moment met de juiste methode aan het juiste gewas toegediend worden. Ook kunnen energiezuinige kookstellen geïntroduceerd worden zodat mest die nu voor brandstof gebruikt wordt, op het land aangewend kan worden. Bovendien zouden omstandigheden gecreëerd moeten worden waarin de toepassing van anorganische mest attractiever wordt. Dit zou kunnen leiden tot toepassing van meer kunstmest op zowel geïrrigeerde als niet-geïrrigeerde percelen.

De tweede doelstelling was om de nutriëntenvoorziening uit natuurlijke bronnen van de bodem en de nutriëntenbehoefte van gerst te kwantificeren en het QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils)-model te ijken als bemestingsadviessysteem voor de Noordelijke Hooglanden van Ethiopië. In Hoofdstuk 3 is de nutriëntenvoorziening uit natuurlijke bronnen van de bodem geschat op basis van chemische eigenschappen van de bodem voor drie bodemtypes, geclassificeerd als Cambisol, Luvisol-1 en Luvisol-2. Het organisch koolstofgehalte (OC) van Luvisol-1 was 1.7 maal zo hoog als dat van de Cambisol, terwijl de totale N opname in de onbemeste situatie (TNU) van Luvisol-1 slechts 67% was van die van de Cambisol. Dat is een gevolg van een aanzienlijk lagere waarde van uitwisselbaar K, die een negatief effect heeft op de opname van andere elementen. Ook de fracties van toegediende N- en P-meststoffen (‘uitbatingspercentage’) die in het gewas teruggevonden worden waren lager in Luvisol-1. In Cambisol en Luvisol-2 was het uitwisselbaar K in de onbemeste situatie ongeveer 15 mmol kg^{-1} en TNU, totale P-opname (TPU), totale K-opname (TKU) en graanopbrengsten (GY) waren voor de behandelingen $N_0P_0K_{25}$ en $N_0P_0K_{50}$ niet significant afwijkend van die in de controle-behandelingen ($N_0P_0K_0$). Anderzijds waren TNU, TKU en GY in Luvisol-1 in de behandelingen $N_0P_0K_{25}$ en $N_0P_0K_{50}$ significant hoger dan in de controlebehandeling. In deze bodem resulteerde het toedienen van 25 of 50 kg K ha^{-1} in een toename van ongeveer 50% in TNU en GY in vergelijking met het gemiddelde van de controlebehandelingen, terwijl toediening van K-bemesting in Cambisol en Luvisol-2 geen significante effecten op de opbrengst lieten zien.

Wanneer alleen N- of P-bemesting werd toegepast weken TNU, TPU en TKU in Luvisol-1 niet af van de controlebehandeling.

De landbouwkundige efficiëntie (toename in GY (kg) per kg toegediende nutriënt in de meststof) van toegediende bemesting was verschillend voor verschillende waarden van bodemnutriëntenvoorziening uit natuurlijke bronnen en verschillende NPK-combinaties. De gemiddelde landbouwkundige efficiëntie van N was het hoogst in de Cambisol, waarin de N-, P- en K-voorziening uit natuurlijke bronnen in balans zijn, en het laagst in Luvisol-1 met een laag gehalte aan uitwisselbaar K. De gemiddelde landbouwkundige efficiëntie van P was het hoogst in Luvisol-2, een bodem die gekarakteriseerd wordt door een hoog OC-gehalte. De gemiddelde landbouwkundige efficiëntie van K was over het algemeen hoog in Luvisol-1, de bodem met een laag uitwisselbaar K-gehalte. De beste combinatie van meststoffen voor het realiseren van de maximale opbrengst bleek derhalve te verschillen voor bodemtypes met een verschillende nutriëntenvoorziening uit natuurlijke bronnen.

Het QUEFTS-model werd geijkt en kan gebruikt worden als instrument om de nutriëntenvoorziening van de bodems uit natuurlijke bronnen te kwantificeren en om de beste combinatie van meststoffen vast te stellen voor het realiseren van een streefopbrengst van gerst in de Noordelijke Hooglanden van Ethiopië.

Kennis van de aard, beschikbaarheid in diverse seizoenen en kwaliteit van de op de boerderij gebruikte diervoeders is essentieel voor het verkennen van de mogelijkheden om de productiviteit van het bedrijf te verhogen. In Hoofdstuk 4 worden de beschikbaarheid en kwaliteit van diervoeders en de relatie met de prestaties van het vee op kleine boerenbedrijven beschreven.

Bij de modale en arme groep boeren in Teghane kwam meer dan 40% van de energie (uitgedrukt in verteerbare organische stof (DOM)) die aan dieren gevoerd werd uit gewasresten zoals stro van tarwe, gerst, bonen en erwten. Bij de rijke groep boeren was dit 30%. Gewasresten zijn laagwaardige voedermiddelen met een laag (< 8 MJ kg^{-1} drogestof (DM)) gehalte aan Metaboliseerbare Energie en een laag (< 7 g kg^{-1} DM) ruw eiwitgehalte.

De beschikbaarheid en kwaliteit van ruwvoer en daarmee het gewichtsverloop van de dieren liet een seizoensgebonden patroon zien. Tegen het einde van de regentijd (september tot en met november) graasden de koeien op de natuurlijke weiden. De hoge beschikbaarheid en goede kwaliteit van deze voederbron werden zichtbaar in de waargenomen snelle groei. Vanaf december graasden de koeien op de stoppel en hergroei van de akkers. Als gevolg van de lagere voederbeschikbaarheid en de lagere kwaliteit nam de groeisnelheid af. Van mei tot juli waren er nauwelijks kruidachtige gewassen aanwezig en de overlevingsstrategie bestond uit het voeren van de bladeren van prickly pear, een cactusachtige. Vanaf april daalde het lichaamsgewicht van de dieren met het grootste gewichtsverlies in augustus.

Kleine boeren verkopen hun overschot aan graan. Dikwijls hebben ze geen toegang tot bankfaciliteiten. Echter, spaargeld in contanten creëert sociale druk om het geld met anderen te delen of uit te lenen. Dergelijke problemen kunnen worden vermeden door het geld in dieren te investeren, wat door boeren als een betrouwbare en zekere belegging wordt beschouwd. Een gemiddeld rendement van boven de 22% is vastgesteld (maar wel met het nodige risico wanneer de voederbeschikbaarheid kritiek wordt), wat behoorlijk hoger is dan de rente op formele kredieten. Investeren in schapen is daarom de moeite waard voor kleine boeren.

Als we de energiebalansen beschouwen lijkt de conclusie gerechtvaardigd, dat voor de kleine boeren, groei en melkproductie niet de belangrijkste doelstellingen zijn voor het houden van vee . Mestproductie, trekkracht, aanwas en financiële functies waren van groter belang. Afhankelijk van de productiedoelstelling verschilt het optimale patroon van gebruik van de beschikbare voeders en daarmee varieert ook het aantal stuks vee dat gehouden (kan) word(t)(en). In het proefschrift is een model gebruikt waarmee de optimale veedichtheid kan worden berekend voor het realiseren van verschillende productiedoelstellingen. De resultaten van dat model lieten zien dat, wanneer bijvoorbeeld mestproductie de belangrijkste doelstelling is, de optimale kuddeomvang gelijk is aan de in 2004 in Teghane gevonden kuddegrootte. Als andere doelstellingen gemaximaliseerd werden, zoals vlees- of melkproductie, dan bleek de optimale kuddeomvang aanzienlijk kleiner, en de huidige kudde zou moeten worden ingekrompen tot een niveau dat onderhouden kan worden bij gebruik van alleen het beste deel van de beschikbare voeders of de kwaliteit van de beschikbare voeders zou verbeterd moeten worden. Als bijvoorbeeld de doelstelling zou zijn om de melkproductie van het locale Zebu-vee te optimaliseren (dit komt overeen met een productie van 3 kg melk koe^{-1} dag^{-1} gedurende 6 maanden), dan zou slechts de beste 30% van het beschikbare voer gebruikt moeten worden en dat is voornamelijk het verse gras en het hooi van de natuurlijk weiden. Dat zou betekenen dat de kuddeomvang ten opzichte van die in 2004 bij rijke boeren met 25% zou moeten afnemen, en met respectievelijk 60 en 75% bij de modale en arme groep boeren.

De beperkte beschikbaarheid van voer, met bovendien een lage kwaliteit, is een belangrijk probleem in de bedrijfsvoering dat aangepakt zou moeten worden. Hiervoor zijn twee mogelijkheden denkbaar. In de eerste plaats bestaat ongeveer 43% van het gecultiveerde land uit Leptosols. Deze bodems bevinden zich vooral op hellingen en zijn ondiep en de gewasopbrengsten op deze bodems zijn erg laag. Het omzetten van deze bodems in grasland met een maai- en stalvoederingssysteem zou de kwaliteit van het voor het vee beschikbare voer aanzienlijk kunnen verhogen. In de tweede plaats is de regenval monomodaal en gras groeit daarom slechts in één seizoen (augustus tot oktober). Veel van de huidige weiden bevinden zich in het midden van de vallei, waar zwaartekrachtirrigatie mogelijk is. Ongeveer in het midden van de vallei is een stuwdam gebouwd voor irrigatie van akkers voor groente- en graanproductie in de droge tijd. Niet al het beschikbare water wordt benut. Beter waterbeheer zou de mogelijkheid bieden voor irrigatie van weiland op de lagere hellingen in de droge tijd om daarmee de hoeveelheid voer en de kwaliteit te verhogen.

De berekende energiebalans over het gehele jaar was negatief, terwijl er een geringe gewichtstoename werd waargenomen. De reden voor deze discrepantie is onbekend, maar zou kunnen liggen in een overschatting van de onderhoudsbehoefte van de dieren of in een onderschatting van de werkelijke energieopname van de dieren. Zowel energiebalans als groei liet de hoogste waarde zien bij de groep rijke boeren.

In Hoofdstuk 5 wordt de relatie gemodelleerd tussen voerbeschikbaarheid en -kwaliteit en opname door de dieren enerzijds en productie anderzijds, om zo het beste voerbenuttingspatroon in relatie tot de productiedoelen van de boer vast te stellen. Productiedoelen kunnen zijn: melkproductie, vleesproductie, mest, trekkracht en behoud van de bodemvoorraad aan koolstof. In het studiegebied bestond meer dan 70% van het jaarlijkse voeraanbod uit gewasresten met een laag ME-gehalte. De belangrijkste gewasresten, tarwe- en gerstestro, zijn in het bijzonder van een lage kwaliteit wegens een laag ruweiwitgehalte (respectievelijk 23 en 34 g CP kg^{-1} DM).

Als het beschikbare voer in belangrijke mate van lage kwaliteit is kan de maximale productie van lichaamsgewicht of melk behaald worden als of de boer selectief de betere voeders gebruikt of de dieren zelf de kans krijgen om te selecteren tussen en binnen voeders. In de modelstudie werd aangenomen (en dit benadert de werkelijkheid) dat voer opgeslagen en bewaard kan worden, zodat een voer geproduceerd in één bepaald seizoen toch het hele jaar door gevoerd kan worden.
De individuele dierproductie van melk en vlees daalt met toenemende kuddegrootte, omdat bij toenemende kuddegrootte steeds meer laagwaardige voeders in het rantsoen opgenomen moeten worden. Bij een zeer kleine kuddegrootte is de individuele dierproductie hoog, maar de totale jaarlijkse kuddeproductie (totale productie van lichaamsgewicht, TLWP, of totale melkproductie, TMP) sub-optimaal. De kuddegrootte is optimaal daar waar de maximale TLWP of TMP wordt behaald. Bij een kuddegrootte die boven dat optimum uitstijgt, nemen TLWP en TMP af. TLWP kan zelfs negatief worden als er zoveel dieren zijn dat het gemiddelde rantsoen onvoldoende wordt om de onderhoudsbehoefte te dekken.

De werkelijke kuddegrootte in het studiegebied (micro-stroomgebied) was 1506 tropische vee-eenheden (TLU), een lager aantal dan op onderhoudsniveau gehouden zou kunnen worden als alle voeders gebruikt zouden worden. De geschatte optimale kuddegrootte voor i) maximale TLWP, TMP en koolstof-input in de bodem, ii) de combinatie TLWP, mest en trekkracht was beduidend lager dan de huidige kuddegrootte, wat aangeeft dat selectief gebruik van voer, waarbij goede opslagmogelijkheden om gebruik door het gehele jaar mogelijk te maken belangrijk is, kan resulteren in productieverhoging. De negatieve effecten op de hulpbronnen (bodemdegradatie) nemen eveneens af bij een hogere productie per dier in combinatie met een kleinere kuddegrootte. Het terugbrengen van de kuddegrootte zou voor een individuele boer kunnen conflicteren met andere functies van het vee, zoals de financiële functies. Deze laatste doelstellingen kunnen worden gerealiseerd wanneer goede spaar- en kredietinstellingen aanwezig zouden zijn. Technische en institutionele mogelijkheden, zoals betere bankfaciliteiten zouden gecreëerd moeten worden en boeren zouden gestimuleerd moeten worden om ook daadwerkelijk gebruik te maken van de bankfaciliteiten, aan de ene kant om te sparen, aan de andere kant om kredieten te krijgen. Onder dergelijke randvoorwaarden worden de mogelijkheden uitgebreid om de voervoorraad zo te gebruiken dat de maximale dierlijke productie kan worden gerealiseerd.

In Hoofdstuk 6 worden de effecten van enkele alternatieve vormen van bedrijfsvoering op de lange-termijn dynamiek van C, N en P beschreven, alsmede de effecten op N- en P-beschikbaarheid voor het gewas, zoals berekend met een simulatiemodel. De simulatie liet zien dat slechts Alt2 (composteren van alle gewasresten en alle vegetatie van de weiden en toediening van de compost aan de akkers) leidt tot duurzame bedrijfsvoering met betrekking tot OC in de Cambisol en Alt1 (verbouw van graangewassen met als inputs het huidige niveau aan organisch materiaal en de aanbevolen doses N- en P-kunstmest) en Alt2 in de Leptosols en ook, maar dan in termen van bodem-N, met Alt1 en Alt2 in de Leptosols. Alt 1 met P-bemesting volgens het advies resulteerde in P-accumulatie in de Cambisol en daarmee in toenemende P-beschikbaarheid voor het gewas. Andere situaties konden niet duurzaam genoemd worden, omdat met betrekking tot N, OC en P “soil mining” optrad.

De modelresultaten gaven aan dat wanneer de bemesting zodanig is dat zich in de bodem een dynamisch evenwicht instelt voor OC en P (en dat gebeurde in Alt4 met gecomposteerd organisch materiaal en anorganische P-kunstmest), verschillende bemestingsniveaus noodzakelijk zijn, afhankelijk van het huidige bodem-OC- en -P-niveau. Om OC en P in de bodem op het huidige niveau te handhaven, bleek de benodigde hoeveelheid nutriënten hoger bij een bodem met een hoger nutriëntengehalte. Bij een gegeven (lager) bemestingsniveau, liep het gehalte aan bodemnutriënten sneller terug in een bodem met een hoog nutriëntengehalte dan in één met een laag nutriëntengehalte.

In het algemeen bleek uit de modelresultaten dat het waargenomen organische bemestingsniveau ontoereikend was voor het bereiken van een dynamisch evenwicht. Voldoende beschikbaarheid van organische inputs is daarom een cruciale randvoorwaarde om duurzaamheid in termen van nutriënten te bereiken. In de ‘controlebehandeling’ en de ‘lage externe input behandeling’ was het risico van bodemnutriëntuitputting hoog. met negatieve consequenties voor de gewasopbrengsten.
De modelbenadering die in deze studie werd toegepast bleek geschikt om de lange-termijn dynamiek van bodem-OC, -N en -P en de gevolgen voor de beschikbaarheid van N en P voor het gewas te verkennen, en kan dus gebruikt worden om het ontwerp van geschikte bodem- en gewasbeheerssystemen te ondersteunen. Verbetering van de bodemvruchtbaarheid kan leiden tot een hogere N en P beschikbaarheid voor het gewas en daarmee tot hogere

opbrengsten, hetgeen uiteindelijk de basis moet vormen voor verbeterde levensomstandigheden.

Het dient benadrukt te worden dat in deze studie alleen aandacht is besteed aan de biofysische aspecten van duurzaamheid, terwijl de belangrijkste randvoorwaarden voor adoptie van verbeterde bodem- en gewasbeheerssystemen vooral sociaal-economisch van aard zijn.

In de algemene discussie hebben we getracht om het huidige landbouwsysteem te evalueren, met name met betrekking tot de mate waarin boeren voedselzekerheid kunnen realiseren bij de lage productiviteit van hun kleine bedrijven. Een simpele evaluatie van voedselzekerheid, gebaseerd op graanproductie, gaf aan dat de groep rijke boeren momenteel net iets meer produceert dan de minimum voedselbehoefte, terwijl de modale en arme boeren respectievelijk 27en 28% minder produceren dan zij nodig hebben. De lage productiviteit en de geringe bedrijfsomvang zijn hier debet aan.

Er zijn mogelijkheden voor een verhoging van de bedrijfsproductiviteit op korte termijn. Het model schat de potentiële graanopbrengsten per hoofd van de bevolking bij de huidige bemestingsadviezen hoger zijn dan de minimum graanbehoefte voor voedselzekerheid in alle bezitsklassen. De aanname was hierbij wel dat er geen vochttekorten optreden en ook dat de gewassen vrij waren van onkruiden, ziekten en plagen. Het is echter twijfelachtig of de landbouw kan fungeren als motor voor economische ontwikkeling boven voedselzekerheid, omdat 61% van de bevolking in het studiegebied erg arm is en slechts weinig land bezit en dat het berekende vermarktbare overschot aan graan slechts 141 kg per hoofd is, nauwelijks genoeg om noodzakelijke uitgaven zoals schoolgeld en medische kosten te dekken.

De hoge bevolkingsgroei, de geringe bedrijfsomvang en de hoge behoefte aan organische inputs voor de bodem om de bodemkwaliteit en de daarmee samenhangende gewasopbrengsten te handhaven, maken dat voor armoedebestrijding en economische groei op lange termijn een strategie nodig is die leidt tot verhoging van de bodemproductiviteit, en tegelijkertijd een verandering in de arbeidscultuur van de bevolking. En deze veranderingen dienen vergezeld te gaan van een substantiële uitbreiding van de niet-landbouwsectoren van de economie om werkgelegenheid te creëren voor een belangrijk deel van de rurale bevolking dat uit de landbouwsector moet uitstromen.

PE & RC PhD Education Statement Form

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 22 credits (= 32 ECTS = 22 weeks of activities)

Review of Literature (4 credits)

- Soil, plant/crop and livestock management and soil nutrient dynamics in the tropics (2001)

Writing of Project Proposal (5 credits)

- Farm management in mixed crop-livestock systems of the Northern Highlands of Ethiopia (2001)

Post-Graduate Courses (4 credits)

- Path ways for agricultural intensification (2001)
- Social science research methods (2001)
- Agro-ecological approaches for rural development (2002)

Deficiency, Refresh, Brush-up and General Courses (9 credits)

- Plant and animal production module of quantitative analysis of agro-ecosystem (2001)
- Case study: tropical animal production (2002)
- Quantitative evaluation of soil fertility and response to fertilizer (2002)

PhD Discussion Groups (4 credits)

- Plant-soil relationships (2001-2002)
- Sustainable agriculture with special emphasis on tropics (2001-2002)

PE & RC Annual Meetings, Seminars and Introduction Days (0.4 credits)

- PE&RC day: “Food Insecurity” (2001)
- PE&RC agriculture and nature (2001)

International Symposia, Workshops and Conferences (3 credits)

- Bio-economic and physical models for the analysis of sustainable land use (2003)
- Policies for improved land management and agricultural market development in the Ethiopian Highlands (2004)
- Integrated natural resources management: basis for achieving sustainable livelihoods in Ethiopia (2004)

Laboratory Training and Working Visits (2 credits)

- TSB/ICRAF (Nairobi), Resource flow mapping in tropical farming systems (2003)

Curriculum vitae

Assefa Abegaz yimer was born on 02 November 1961 in Ethiopia, South-Wello, Tehuladere district at a village known as Gobeya. In 1983 he obtained BA Degree in geography and then worked in comprehensive secondary high school as instructor for eight years. In 1991 he joined to the post graduate program of Addis Ababa university and graduated with Masters degree in physical geography (focusing on natural resources: soil, vegetation and water). He worked as a research fellowship in the soil and water conservation research Program (SCRP) for four years (research organization in Ethiopia, with collaboration of the Switzerland government and Bern University). Since 1998 he joined the Mekelle University as a full-time employee at the rank of lecture. During his stay in the university, besides to the teaching and research activities he worked as research and constancy officer of the faculty of Business and Economics and later as freshman program coordinator and continuing education program officer of Mekelle University. He also has served as head of the department of geography and environmental studies in the same university.

In September 2001 he started a ‘sandwich’ PhD program with the Plant Production Systems Group of Production Ecology and Resource Conservation Graduate School of Wageningen University under the framework of the RESPONSE PhD program (‘Regional food security policies for natural resource management and sustainable economies', jointly run by Wageningen University and IFPRI in collaboration with Mekelle University). Currently, he is working for Mekelle University as instructor and researcher. Assefa is married to Tigist Abate and have one son.

Regional Food Security
Policies for Natural
Resource Management
and Sustainable
Economies

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RESPONSE is one of the six multi-annual (2000-2004) research programmes of the INterdisciplinary Research and Education Fund (INREF) of WUR, launched in 2000, in which various Wageningen Graduate Schools, international and national research institutions in the South participate. In concerted action the research programmes are formulated and a coherent set of research projects formulated. The multi-annual research programmes focus on a variety of very complex issues which cannot be tackled in a mono- or multi-disciplinary manner.

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