I Introduction

1.1. Problem Analysis

1.1.1. Agroecosystem Sustainability: a Nutrient Balance Perspective

Nutrient cycling in all terrestrial ecosystems, whether they are natural (forests, rangelands, grasslands) or managed (agroecosystems, pastures, plantations), follows similar pathways. However the size of nutrient pools, fluxes and transformations in these systems may vary by several orders of magnitude (Hornung, 1990). Both natural and managed ecosystems are open systems i.e. nutrients can enter or leave the system (Binkley, 1986). The question, whether nutrient inputs and outputs are balanced or not, is closely related to the issue of sustainability (Smaling *et al.*, 1996). In natural ecosystems, processes that govern nutrient cycling like primary production, uptake and decomposition tend to be balanced (Saleem, 1998; Heal and Harrison, 1990). However, when ecosystems are managed, and food production is one of the major objectives, nutrient transfers are influenced not only by the conditions and process within the system, but also by circumstances and controlling forces outside the system (i.e. anthropogenic effects, Priess *et al.*, 2001). As a result, unequal transfers between nutrient pools may cause the system to accumulate or deplete nutrients. Many environmental problems like green house gas emissions, eutrophication of rivers and lakes and soil nutrient depletion are the results of such disproportionate transfers (Brady and Weil, 2002). Balanced nutrient input and output fluxes are a critical condition to reach sustainable ecosystem functioning and sustainable agricultural productivity (Dumanski *et al.*, 1991).

Evaluation of sustainability is complex because it can not be measured directly. Several approaches have been proposed (e.g. to use indicators) to evaluate sustainability. Apart from crop productivity and soil quality, nutrient balance has been used as one of the important indicators of sustainability (e.g. Nambiar *et al.*, 2001; Bell and Morse, 1999). To determine whether a nutrient flow is an input, output or whether it is an internal flow, one can place an 'imaginary box' around the ecosystem of interest (e.g. plot, farm, watershed, farming system etc.). Any nutrient flux crossing the 'walls' of the 'imaginary box' is an input or output flux and any flux staying inside the 'box' is considered an internal flow. The sum of nutrient inputs and outputs, defines whether the ecosystem is aggrading, sustaining or degrading (Smaling and Oenema, 1999). Any balance must be related to nutrient stocks in order to estimate the fraction of stock which is used per cropping cycle to offset potentially negative balances (Van den Bosch *et al.*, 1998).

Soil nutrients are among the least resilient elements of agroecosystem because disruption in one pool or path may affect the entire cycle. Therefore nutrient flux studies are of particular interest as an indicator of land quality for sustainable production. Already in 1841 the chemist Justus von Liebig realized that nutrients taken up from the soil by agricultural crops should be replenished (Smaling and Fresco, 1993; Smaling, 1993). Subsequently, in 1950s nutrient flux analyses became a major focus of systems ecology. More recently, nutrient balance is increasingly used to monitor and control levels of discharge in areas of high nitrate pollution (Brady and Weil, 2002).

Nutrient balance in agricultural system can be studied at different spatial and temporal scales. The spatial scales may range from plant and animal communities, via farming systems to the regional and global system level whereas temporal scales ranges from minutes to decades (Fresco *et al.*, 1990). Different approaches are used to estimate nutrient balances at different spatial and temporal scales. Soil nutrient balances are typically measured at the field level, whereas its aggregation yields farm level balances. Balances at higher spatial scales (e.g. region) can be estimated by aggregation of field level or aggregation of farms into land use types which can be aggregated into regional balances (Stoorvogel and Smaling, 1998).

1.1.2. Rationale for the Study

Nutrient balance studies as a tool to analyze African farming systems, have been used since about two decades. Quantitative N, P and K balance models that have been developed and applied at supra-national scale, show drastic net soil fertility losses (Stoorvogel and Smaling, 1990). In some regions, notably in the East African Highlands (e.g. Ethiopia and Kenya), depletion rates are very high (Henao and Baanante, 1999). Competitive uses for manure and crop residues (e.g. biofuel and animal feed) together with the break down of traditional soil fertility management practices (e.g. fallow) limited the application of organic inputs to replenish soil fertility. Application of inorganic fertilizer (mainly DAP and urea average less than 14 kg ha^{-1} yr^{-1}) is also low compared to other parts of the world (e.g. 70 kg ha^{-1} yr^{-1} in India, 260 kg ha^{-1} yr^{-1} in China and about 100 kg ha^{-1} yr^{-1} of world average; FAO, 1999; Nandwa and Bekunda, 1998).

Nutrient mining in Ethiopian agroecosystems is not exception: a national scale nutrient balance study (for the year 1983) indicated nutrient losses of 41 kg N ha^{-1} $yr,^{-1}$ 6 kg P ha^{-1} yr^{-1} and 26 kg K ha^{-1} yr^{-1}. This was about twice as much as the average depletion rates for sub Saharan Africa (22 kg N ha^{-1} yr^{-1}, 2.5 kg P ha^{-1} yr^{-1} and 15 kg K ha^{-1} $yr,^{-1}$ (Stoorvogel and Smaling, 1990)) and illustrates the magnitude of soil degradation and nutrients mining in Ethiopia. Agricultural production in Ethiopia can only be maintained in the long run if sustainable land use practices are introduced and large degraded areas will be restored. A successful, implementation of sustainable practices depends however on: our understanding how soil fertility management decisions in different farming systems and social classes affect nutrient mining at different spatial scales. In this context spatial scales range from plots to farming system, while the corresponding social unit range from a household to regional and national administrations. As interactions occur between different scales, integration is essential to plan a comprehensive soil fertility management strategy.

1.2. Objectives of the Study

The overall goal of this study was to examine soil fertility management and sustainability of smallholders' mixed farming systems in Ethiopia at different spatial scales using nutrient balances as indicator. More specifically, the objectives were:

1. To identify and quantify 'hot spots' of nutrients depletion and accumulation in different cropping systems of Ethiopia (at regional and zonal scales);
2. To identify and quantify important fluxes contributing to accumulation or depletion of nutrients in agroecosystems at different scales;
3. To examine how smallholders' soil nutrient management practices are affected by natural soil nutrient gradients and wealth status of smallholders in typical highland mixed farming systems;
4. To examine states of nutrient balances, zones of nutrient depletion and accumulations at field and farm scales in two contrasting altitudinal belts in Central Highlands of Ethiopia;
5. To determine, how processes of nutrient depletion and accumulation at lower spatial scales feedback to nutrient balances at higher scales.

1.3. Organization of the Thesis

Despite their significances to raise awareness of soil nutrient mining, aggregated national scale nutrient balances do not provide information on the spatial distribution of the problem. Furthermore, studies at plot, farms and landscape scales are scarce. The present study reports the results of soil fertility management and nutrient flux analysis at decreasing spatial scales ranging from *national* via *region*, *zone*, *farming system*, *landscape*, *and farms* to *fields*.

Following motivation and objectives of the research in this introduction, the second and the third chapters assess nutrient depletion at national and regional scales (for Ethiopia; Chapter 2) and zonal scales (for different zones of Oromiya; Chapter 3) using aggregated balances by cropping systems. Chapter 4 deals with a case study on soil nutrient management and agroecosystem sustainability in enset and teff based farming systems (in two watersheds in Central Highlands of Ethiopia). After a description of the enset and teff farming systems and methodologies used in nutrient fluxes calculation, results on soil fertility gradients; management diversity and agroecosystems sustainability are presented. Chapter 5 presents a case study of ten farms (in two contrasting altitude belts) on nutrient fluxes and zones of nutrient depletion and accumulation at field and farm scales. In this chapter, smallholders' accesses to resources and implications for nutrient fluxes are discussed. Nutrient fluxes between different fields and landscape positions are compared and the results at different spatial scales are integrated. Finally, in the 6th and the 7th chapters, interactions between nutrient fluxes and balances at different spatial scales are discussed and general conclusions and summary of the entire works are presented.

II Assessment of Soil Nutrient Depletion on Smallholders' Mixed Farming Systems in Ethiopia Using Partial versus Full Balance

2.1. Introduction

Soil nutrient depletion is rarely directly linked to food shortage, as it is a gradual process unlike natural calamities (e.g. drought, flooding and etc.). Nevertheless, several studies have revealed that a lack of plant nutrients is one of the principal causes for low agricultural productivity and food insecurity in Africa (e.g. Nandwa and Bekunda, 1998; Sanchez, 2002 Smaling, 1993). This is illustrated by small increases in crop productivity, even in years with adequate rainfall. As a result, more intensive land use (e.g. by fertilizer application) has become necessary to reverse the trend of declining per capita food production. Agriculture in Ethiopia is no exception: more soil nutrients are exported compared to natural and anthropogenic inputs (Elias *et al.,* 1998; Okumu, 2000). In 1983, Stoorvogel and Smaling (1990) predicted for Ethiopia that the national nutrient balances would be on average: -47 kg N ha^{-1}, - 15 kg P_20_5 ha^{-1} and - 38 kg K_2O ha^{-1} for the year 2000. This prediction was twice as high as the average value for sub Saharan Africa and indicates the severity of nutrient depletion in Ethiopia.

Nutrient depletion in Ethiopia has several causes. Application of organic fertilizer like crop residues and manure is limited because of competitive uses (e.g. animal feed and biofuel). Also problems in the fertilizer sector have restricted the wider use of inorganic fertilizers. Fertilizer subsidies were eliminated since 1997 (fertilizer subsidies were 15% in 1993, 20% in 1994, 30% in 1995, 20% in 1996, 0% in 1997) and consequently costs of fertilizer went up. At the same time, low grain prices on the market probably discouraged farmers from using fertilizer (Demeke *et al.,* 1998). Additionally inadequate soil conservation practices and reduced fallow periods contributed to the problem (Wood, 1990).

Previous efforts to quantify nutrient balances were at sub-continental and national scales without addressing the large spatial variability of nutrient balances within the country. Our objectives were to illustrate the regional differences in nutrient depletion in Ethiopia and to identify regional ‘hot spots’ of nutrient depletion. Furthermore we wanted to identify cropping systems which are either favorable for nutrient conservation or which are responsible for high nutrient losses under current management practices. This kind of information is critical for decision makers to plan and implement integrated nutrient management policies and strategies at a regional level.

2.2. Materials and Methods

2.2.1. The Study Region

Ethiopia covers an area of 1.1 million km^2 and has a considerable variation of climate due to the wide range of altitudes. The lowlands are arid to semiarid, with annual temperatures more than 20^0C. The plateaus have a temperate climate with annual temperature ranging between 10^0C and 20^0C, while the high mountains have cold, alpine climate with temperature between 10^0C and 16^0C. Rainfall increases from 200 mm yr^{-1} in the east to over 2000 mm yr^{-1} in the southwest (FAO, 1982; FAO, 1983).

The wide ranges of topographic, climatic factors, parent material and land use have resulted in extreme variability of soils in Ethiopia. In different parts of the country, different soil forming factors have played a major role. According to FAO (1986) and FAO (1984) the big proportion of the country’s landmass is covered by Lithosols (14.7%), Nitosols (13.5%), Cambisols (11.1%), Regosols (12%) and Vertisols (10.5%). Ethiopian soils are largely of volcanic origin. Assessments of nutrient status of Ethiopian soils indicate ranges of 0.9 – 2.9 g N kg^{-1} and 0.4 - 1.10 g P kg^{-1} soil. Data on exchangeable K are inadequate; those existing indicate values ranging between 0.53 to 5.79 $cmol_c$ kg^{-1} (Murphy, 1968).

Farming systems in Ethiopia can be divided into mixed farming and agro-pastoralism /pastoralism (Assefa, 1986). Mixed farming systems which integrate both crops and livestock (animals used for traction, meat, milk etc.) are becoming increasingly important in Ethiopia (Tsegaye, 2001). Combination of crop and livestock production on the same farm has evolved as a result of regional differences in climate, population density, diseases, economic opportunities and cultural practices (Stangel, 1993). In mixed farming systems, livestock and crop production are complementary in that livestock is used for nutrient recycling while crop production provides residues for animal feed. But at the same time livestock and crop production compete for space. Information on such interactions is important for sustainable agroecosystem management planning.

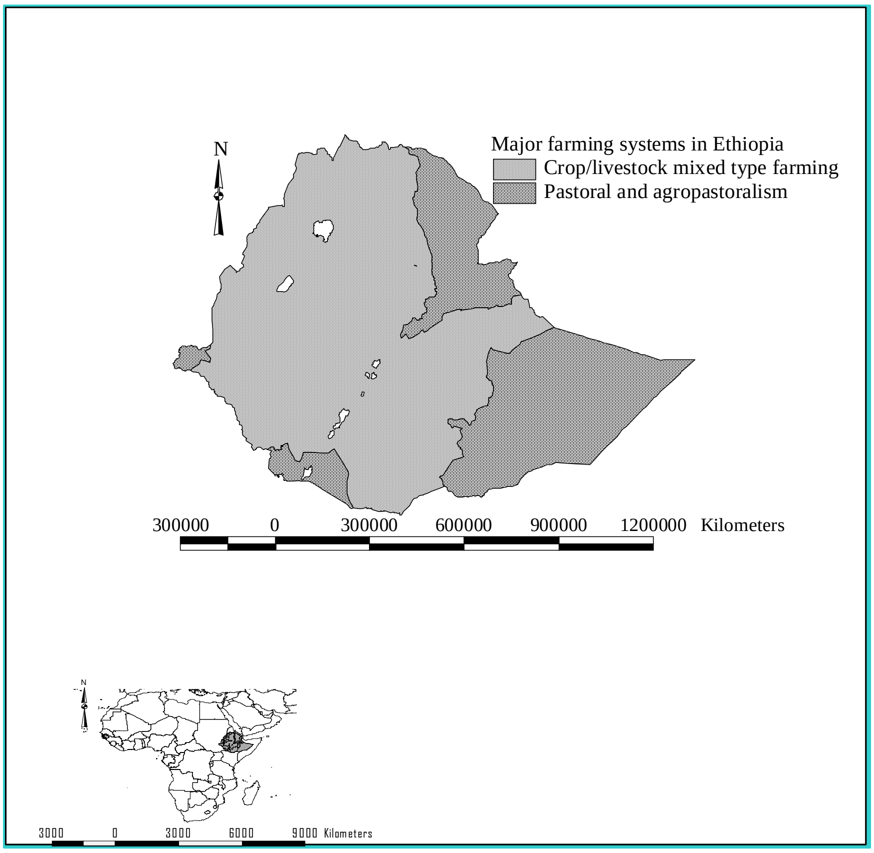

Figure 2.1. Major farming systems in Ethiopia (FAO, 1998a)

Mixed farming systems are well developed in the moderately warm to cool mid highlands and highlands of Ethiopia, but are poorly developed in hot to warm sub-humid lowlands (e.g. parts of Gambella regions) due to animal and plant pests and diseases. They are also weakly developed in hot to warm arid and semiarid lowland plains (e.g. parts of Afar and Somali regions) because of the short growing seasons (Engda, 2000). Crop production is negligible (except some agro-pasture) in major parts of the hot to warm sub-humid lowlands and hot to warm arid and semiarid lowland plains (Figure 2.1). The majority of smallholders involved in mixed farming systems are sedentary. Thus the focus in this chapter is sedentary farmers, because the available census data does not include information on non sedentary farmers (CSA, 2000).

2.2.2. Quantification of Nutrient Fluxes

To quantify the nutrient balance, five output and five input fluxes were used and internal nutrient flows were not taken into account (Table 2.1). The net nutrient balance is the total of nutrient inputs minus nutrient outputs expressed in kilogram nutrients ha^{-1} yr^{-1}. Positive balances indicate that nutrients are accumulating in the soil and negative balances indicate that the soil is being mined for nutrients (Nandwa and Bekunda, 1998).

Table 2.1. Input and output fluxes of a nutrient balance (Smaling and Fresco, 1993; De Jager *et al.*, 1998)

In flows		Out flows	
IN_1	Mineral fertilizer	OUT_1	Harvested products
IN_2	Organic inputs	OUT_2	Residues removed
IN_3	Atmospheric deposition	OUT_3	Leaching losses
IN_4	Nitrogen fixation		
IN_{4a}	Symbiotic N fixation	OUT_4	Gaseous losses
IN_{4b}	Non- symbiotic N fixation		
IN_5	Sedimentation		
IN_{5a}	Irrigation	OUT_5	Erosion
IN_{5b}	Eroded sediments deposition		