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ORIGINAL PAPER

Smallholders' soil fertility management in the Central Highlands of Ethiopia: implications for nutrient stocks, balances and sustainability of agroecosystems

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Abstract Low agricultural productivity caused by soil degradation is a serious problem in the Ethiopian Highlands. Here, we report how differences in soil fertility management between farming systems, based either on enset (*Ensete ventricosum*) or on teff (*Eragrostis tef*) as the major crops, affect the extent of nutrient stocks, balances and ecosystem sustainability. We collected information on farmers' resources and nutrient management practices from stratified randomly selected households in two watersheds in the Central Highlands of Ethiopia. In addition, we collected soil samples from each land use and calculated nutrient stocks, partial and full nutrient balances (N, P and K) for one cropping season. Our results show that farmers in the two farming systems manage their soils differently and that nutrient inputs were positively related to farmers' wealth status. The watershed with the enset-based system had higher soil N and K stocks than the watershed with the teff-based system, while P stocks were not different. Management related N and K fluxes were more negative in the teff-based system (−28 kg N ha^{-1} yr^{-1} and −34 kg K ha^{-1} yr^{-1}) than in the enset-based system (−6 kg N ha^{-1} yr^{-1} and −14 kg K ha^{-1} yr^{-1}) while P fluxes were almost neutral or slightly positive. Within the enset-based system, a strong redistribution of N, P and K took place from the meadows and cereals (negative balance) to enset (positive balances). Although in the teff-based system, N, P and K were redistributed from meadows, small cereals and pulses to maize, the latter still showed a negative nutrient balance. In contrast to nutrient balances at land use level, nutrient balances at the watershed scale masked contrasting areas within the system where nutrient oversupply and deficiencies occurred.

Keywords East Africa · Ethnopedology · Highland farming system · Nutrient stocks and fluxes · Watershed · Wealth distribution

This paper is dedicated to the 75th birthday of Prof. Dr. H. Fölster to honour his contributions to soil science.

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Introduction

Soil fertility management is continuously modified and adapted as conditions change in time. A classic example is the intensification of soil fertility management, when population pressure increases and suitable land becomes scarce (Fournier 1989; Boesen and Hansen 2001). Soil fertility management is also adapted to variations within a landscape (e.g. in parent material (Chuma et al. 2000; Wezel et al. 2002; Emmerling and Udelhoven 2002)). Especially in areas where farmers cannot afford to invest heavily in farming in terms of capital, they adapt their management to the locally prevailing natural conditions and substitute capital by other input factors like available labor or additional land, or they choose to produce off-farm income (Lamers and Feil 1995; Elias et al. 1998; Shepherd and Soule 1998).

In Ethiopia, the highlands (>1500 m elevation) occupy 44% of the area of the country and are home to 90% of the human population and to 75% of livestock. Soil nutrient depletion and related low agricultural productivity are serious problems (Tilahun et al. 2001). In a study on soil nutrients balances at national and regional level, Haileslassie et al. (2005) reported large variations in the nutrient balances of different cropping systems, ranging from nutrient accumulating systems (e.g. enset, *Ensete ventricosum*) to cropping systems including most cereals (e.g. teff, *Eragrostis tef*) with strongly negative nutrient balances. In the present study we focused on two typical highland farming systems with strongly contrasting nutrient balances as reported from the regional scale analyses.

Our main objectives were to examine differences in soil fertility management between the two farming systems and to evaluate the extent of nutrient gains and losses and ecosystem sustainability by elaborating nutrient balances. Furthermore, we assessed to which degree smallholders' nutrient management strategies depend on socio-economic conditions (e.g. access to resources, wealth of households). To answer these questions we collected information on farmers' resources and nutrient management by conducting interviews in stratified randomly selected households. We combined this information with data on soil nutrient stocks and fluxes from each of the different land use types in the watersheds.

Materials and methods

Study areas

Galesa (enset[1]- based farming) and Gare (teff[2]-based farming) watersheds are situated on the Western escarpment of the Rift Valley in the Central Highlands of Ethiopia (Fig. 1). Galesa watershed (elevation 2880–3095 m.a.s.l.) is located in the cool highlands ('*Dega*') while Gare watershed (elevation 2320–2620 m.a.s.l.) is located in the warm-to-cool mid-highlands *'Woina-dega'* (FAO 1983; Ethiopian Mapping Agency 1980). Rainfall data from Ginchi (~12 km Southwest of Gare) shows mean annual rainfall of 1117 mm. Both study areas have a bimodal rainfall pattern, with the long rainy season extending from June to September and the short rainy season from February to April. Topography at Galesa is mostly flat to rolling (0–16% slope; 78% of total area) followed by hilly (16–30% slope; 18% of total area) and steeply dissected (>30% slope; 4% of total areas). Gare watershed has a higher fraction of hilly and steep area, with 55% flat to rolling, followed by hilly (24%) and steeply dissected area (21%). Soils at Galesa are well drained; reddish brown; friable clay to clay loams and developed on volcanic rocks (Luvisols). Soils at Gare also originated from volcanic rocks, but are poorly drained, dark cracking clays on the lower slopes (Vertisols), while on the steeper mid- and upper slopes, soils are stony and shallow; brownish; friable clay loams (Leptosols).

Enset-based farming systems in Ethiopia can be divided into four major subsystems based on the extent to which people depend on the plant as a staple food (Westphal 1975). In the subsystem

[1] Enset (*Ensete ventricosum*), is a long-leaved, banana like perennial plant used for food, fodder and fiber production in parts of the Central Highlands and major parts of southern Ethiopia.

[2] Teff (*Eragrostis tef*) is a fine stemmed tufted annual grass. Grains are used as main ingredient in Ethiopian traditional flat bread called *injera*.

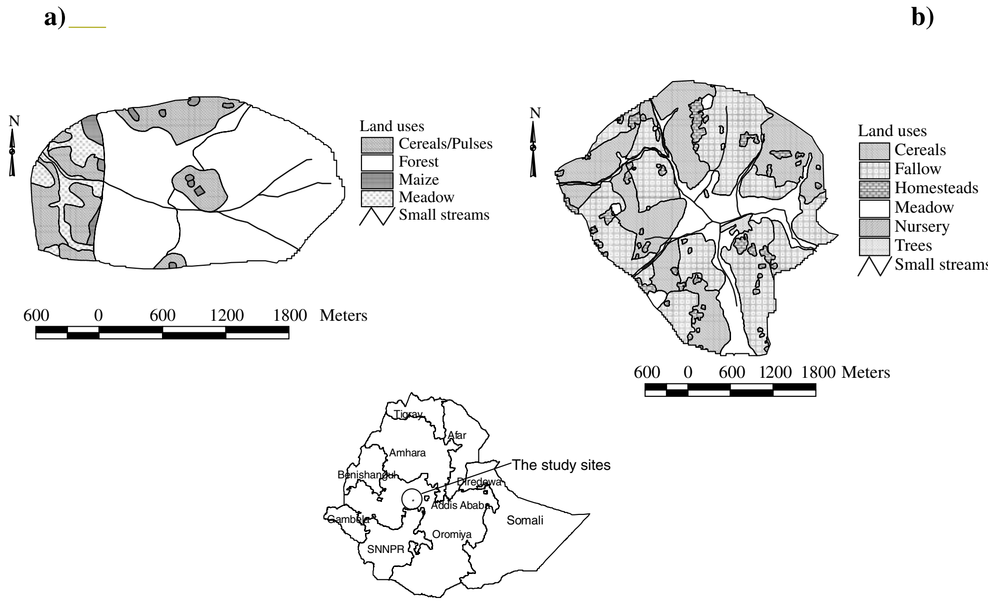

Fig. 1 Location and land uses of Gare (**a**) and Galesa (**b**) watersheds

practised at Galesa, cereals serve as principal crop with enset and potato of secondary importance. In the 2002/2003 cropping season, Galesa watershed (in the cool highland zone) was covered by 40% cereals, 36% fallow, 16% meadow, and (6%) enset and potato. More than 92% of the cereal land is planted with barley (*Hordeum vulgare*). Minor crops cultivated are wheat (*Triticum durum* and *Triticum aestivum*) and some vegetables like onion (*Allium cepa*). Crop rotation is limited because of high risk of frost damage on crops other than barley.

In Gare watershed in the mid-highland zone, a cereal-based farming system is practised, in which teff covers 50% of the cereal land. Furthermore, barley, wheat, maize (*Zea mays*), chickpea (*Cicer arietinum*) and faba bean (*Vicia faba*) are major crops grown in Gare. Recently, enset was introduced in some parts of Gare, mainly due to its ecological adaptability and multiple uses. The major fraction of Gare watershed is covered by forest (68%, *the Chilimo National Forest Priority Area*) which is mainly located on the hilly and steeply dissected topographic units (Fig. 1). The cropping area comprises cereals and pulses (22%), meadow (7%) and homesteads (3%). In both watersheds, livestock plays an important role in the crop production systems (e.g. draught powers, income generation, manure supply, etc).

Household survey

We identified 184 farm households in Galesa and 24 in Gare. Using a participatory wealth ranking method, we stratified the households into three wealth groups (Table 1). The major criteria used

Table 1 Characteristics of wealth groups in enset- and teff-based farming systems

Farming systems	Wealth classes	Samples size	Land holding* (ha)	Livestock* (TLU)	Oxen * (TLU)
Enset system	Rich	10	3.3	12.3	2.4
	Medium	20	2.3	6.7	1.5
	Poor	20	1.6	2.3	0.5
Teff system	Rich	5	2.3	6.2	1.4
	Medium	7	1.6	3.5	1
	Poor	4	1.3	2.5	0.5

Tropical Livestock Unit (TLU): conversion factors for cattle = 0.7, horses = 1, mules = 0.7, sheep = 0.1 and goats = 0.1 are used; * mean values for wealth classes for stratification were the number of oxen and other livestock owned by the farmers, followed by the criterion farm size. At Galesa, we randomly selected 50 farm households proportionally distributed between the wealth groups. At Gare, we did the same with 16 households. We used semi-structured questionnaires to collect information related to farmers' resources and nutrient management practices. In addition, in each of the watersheds, we intensively monitored farm activities of five randomly selected households.

Land use mapping and soil sampling

We mapped land uses using air photos in combination with a Geographic Positioning System (GPS). In June 2003, we collected three composite soil samples (0–30 cm depth, each sample consisting of five sub samples) for each land use. Additionally, we collected five undisturbed soil samples from each land use to analyze bulk density. All soil samples were air-dried, passed through a 2-mm sieve and analyzed in the laboratory of the International Livestock Research Institute (ILRI), Addis Ababa. Soil pH was determined in 1:2.5 soil water ratio, texture was measured by applying the hydrometer method (Bouyoucus 1951) and soil organic carbon was determined by the wet oxidation method (Walkley and Black 1934). Available P was determined with the Bray method (Bray and Kurtz 1945), while total N was determined by Kjeldahl digestion, distillation and titration. Exchangeable K was analyzed using an atomic absorption spectrophotometer following an ammonium acetate extraction. Cation Exchange Capacity (CEC) was determined at pH 7 using ammonium acetate as exchanger cation. Soil nutrient stocks in the top 0–30 cm were calculated from soil nutrient concentrations and bulk densities.

Statistical analysis

Data sets from the household survey and soil laboratory results were analysed using one-way analysis of variance (ANOVA) and Tukey's HSD test (0.95 confidence interval) to separate means of significantly different parameters (for land use and wealth group data). The Kolmogorov Smirnov two samples test (0.95 and 0.99 confidence interval) was used to test significant differences between soil parameters of the two farming systems. Pearson's product moment correlations were used to relate selected soil parameters and nutrient management practices. All statistical analyses were performed with STATISTICA 6.0.

Nutrient balances

We considered five types of major input and output fluxes to calculate N, P and K balances (Smaling and Fresco 1993; De Jager et al. 1998), which we address as $IN_{1–5}$ and $OUT_{1–5}$ throughout the paper. Fluxes, which are directly related to farm management, like inorganic fertilizer input (IN_1), organic fertilizer input (IN_2), harvested products (OUT_1) and residues removed (OUT_2), were estimated from the household survey. Wet deposition (IN_3) was estimated (in kg ha^{-1} yr^{-1}) as a function of mean annual rainfall using coefficients of 0.14, 0.023 and 0.092 for N, P and K, respectively (Smaling and Fresco 1993). We estimated symbiotic nitrogen fixation (IN_{4a}) assuming that legumes fix 60% of total N uptake symbiotically (Smaling and Fresco 1993), while nitrogen fixation by free-living bacteria (IN_{4b}) was estimated using the regression model of FAO (2005). As irrigation of crops is not practiced in the region, the deposition of nutrients from irrigation (IN_{5a}) was zero. Leaching (OUT_3) and gaseous losses (OUT_4) are important pathways of nutrient losses (Snyder 1995). To estimate the amount of N leached, we used the regression equation developed by De Willigen (2000), which includes rooting depth of crops; annual precipitation (mm); clay content (percent); mineral and organic fertilizer nitrogen (kg N ha^{-1}); mineralization rate (assumed 1.5% yr^{-1}), the amount of N in soil organic matter (kg N ha^{-1}) and N uptake by crops. We calculated K leaching as a function of the clay content of soils and mean annual rainfall (Van den Bosch et al. 1998; Smaling and Fresco 1993).

We estimated gaseous losses using the regression model developed by FAO (2005). The model consists of two parts: one regression model for N_2O and NO_x losses through denitrification, and a direct loss factor for volatilization of NH_3. We estimated soil erosion and deposition (OUT_5 and IN_{5b}) using the Landscape Process Modelling at Multi-Dimensions and Scales (LAPSUS (Schoorl et al. 2002)).

Results

Smallholders' soil fertility management: ethnopedological approach

Smallholders in both study areas are well aware of soil fertility differences. They use indigenous soil classification methods as basis for soil nutrient management practices, i.e. crops are grown depending on the quality of the site and nutrient inputs are adjusted accordingly. Crop yields, soil depth, soil color, drainage and workability are the basis for the local soil classification. Farmers in the Galesa watershed practicing the enset-based farming system recognize four types of soils (*Diimilee, Magaalee, Gurraacha and Boorilee*), while those at Gare, engaged in teff-based farming identify three soil types (*Magaalee, Kossii and Kooticha*; Table 2). *Boorilee* (brownish-grey) and *Diimilee* (reddish-brown) soils in enset-based farming are shallow soils located on upper and mid slope positions. They cover a major part of the Galesa watershed. According to farmers, these soils have a low inherent fertility, which is why fertilizer inputs and fallowing are considered as essential means to maintain/increase productivity. In contrast, *Gurraacha* (dark-brown) soils are considered very fertile soils located on some foot slopes adjacent to meadows. Most often farmers do not apply fertilizer to these soils but rotate barley and wheat, which according to local knowledge is an adequate measure to maintain crop yield levels. In the teff-based farming system, *Kooticha* (dark-grey) soils cover the major fraction of the Gare watershed (mainly the lower landscape positions). Its poor drainage limits cultivation of crops to teff and pulses. On the mid and upper slopes *Magaalee* (shallow and well-drained) soils dominate. Most often farmers plant barley and wheat on these soils. *Kossii* soils (located at homesteads) are dark brown soils with high organic matter content as a direct result of regular manure and organic waste application. *Kossii* can be characterized as a man-made soil. The results from soil analyses are in reasonably good agreement with the classification system of local farmers (Table 2). For example *Gurraacha* (enset-based system) and *Kossii* (teff-based system) soils, described as very fertile in the local system, had the highest base saturation, CEC, available P, N, and a favourable pH. In some cases, soil quality is defined only on the basis of depth and vulnerability to erosion (e.g. *Magaalee*). Farmers' perception of fertility also depends

Table 2 Farmers' soil classification and fertility perception in the Central Highlands of Ethiopia (data on soil properties were provided by Mekonen et al. personal communication)

Local name	Farmers' fertility perception	Soil properties								
		Clay (%)	pH (1:2.5 soil water)	Total C (%)	Total N (%)	Available P-Bray (ppm)	Exchangeable K (cmol$_c$ kg^{-1})	% Base saturation	CEC (cmol$_c$ kg^{-1})	Farming system
Diimilee	Moderately-poor	68	5.0	0.2	0.1	2.4	0.2	19	29	Enset-based
Magaalee	Moderately fertile	38	4.1	6.1	0.5	4.0	1.1	18	34	Enset-based
Gurraacha	Very fertile	48	6.2	11.1	0.7	7.4	4.3	67	59	Enset-based
Borelie	Poor soil	30	5.5	0.4	0.0	3.2	0.2	26	38	Enset-based
Kooticha	Moderately fertile	55	5.1	2.3	0.2	1.2	0.7	54	58	Teff-based
Magaalee	Moderately-poor	20	5.5	2.2	0.2	192	1.0	63	62	Teff-based
Kossii	Very fertile	9	6.5	7.3	0.4	992	15.0	95	58	Teff-based

on local conditions, i.e. a moderately fertile *Megaalee* soil at Galesa watershed is described as moderately poor soil by farmers in Gare watershed (Table 2).

In the enset-based system, soil nutrient management consists of fallowing (1 year, only for barley areas) and application of manure and household waste to homestead land. Nitrogen-fixing legumes are not included in the system. In contrast, in the teff-based system, farmers plant legumes and rotate with cereals (*pulses—teff—-wheat* or *barley—pulses*). In some cases other crops like niger seed (*Guizotia abyssinica*) are included in the rotation. Most farmers reported that rotation including pulses and cereals improves crop productivity more than rotation based on cereals only.

In the enset-based system farms had significantly larger size (2.2 ha) and included more livestock (6.15 TLU, Tropical Livestock Unit) compared to the farms of teff-based farming (4.1 TLU). TLU correlated positively with farm size ($r = 0.56$; $P = 0.00$) and with manure application ($r = 0.60$; $P = 0.00$). During months of feed shortage (July–September) fallow land is used for grazing and animal droppings on fallow plots are incorporated into the soil.

Effects of niche management on some soil properties within the two farming system was remarkable. In the enset-based farming system, land use types closer to residences (enset and potato) had significantly higher pH, available P, P stock, exchangeable K and CEC (Table 3). Meadows (particularly in enset-based farming) also showed significantly higher mean values for available P, pH, total N and N stocks. In teff-based farming, maize plots (close to homesteads) showed no higher values for pH, N stock, CEC, while C, total N, available P, P stock and exchangeable K were significantly higher than under other land uses. Soil parameters (pH, organic matter, available P, total N, total P, total K, exchangeable K and CEC) of fallow and cereal lands showed no statistically significant differences. However, positive effects of fallowing on soil properties could be observed (Table 3).

Organic and inorganic inputs and relation to wealth status

Crops are harvested by uprooting (e.g. pulses, enset, and potato) or mowing close to the surface (e.g. cereals). Crop residues like maize straw are used as biofuels for cooking and heating, while fine

Table 3 Soil parameters (0–30 cm) under different types of land use in two farming systems of the Central Highlands of Ethiopia

Soil parameters	Farming systems							
	Enset-based system					Teff-based system		
	Fallow	Enset	Potato	Cereals	Meadow	Cereals	Maize	Meadow
Bulk density (g cm^{3-1})	1.16c	0.83b	0.99a	1.03a	0.97a	0.94b	1.11a	1.04b
Clay (%)	35.4a	29.4ab	26.7b	34.7a	26.7b	50.7	34.7	44.1
Silt (%)	47.9	49.9	45.9	39.3	37.3	28.6	39.3	32.6
Sand (%)	16.6b	20.7b	27.3a	26.0a	36.0a	20.7	26.0	23.3
pH (1:2.5 soil water ratio)	5.1a	5.9b	5.9b	4.9a	5.1a	5.8	6.4	5.9
Organic C (%)	3.3a	4.1ab	4.4ab	2.9a	5.3b	2.5a	4.3b	3.0a
Total N (%)	0.3a	0.4a	0.4a	0.3a	0.6b	0.2a	0.4b	0.3ab
C:N	10.5	10.4	10.3	10.0	9.1	11.8	12.2	11.7
N stock (mg ha^{-1})	9.8a	12.6ab	13.4ab	9.5a	15.6b	5.5	10.5	8.2
Available P-Bray (ppm)	0.4a	8.6b	13.5c	0.5a	0.9a	5.9a	37.2b	3.6a
P stock (mg ha^{-1})	2.3a	4.3b	5.2b	2.3a	2.1a	1.2a	3.8b	1.5a
CEC ($cmol_c$ kg^{-1})	27.0ac	36.1b	33.7ab	24.4c	32.0abc	37.0	38.1	39.8
Exchangeable K ($cmol_c$ kg^{-1})	1.0a	4.1b	5.2b	0.4a	0.4a	0.8a	4.4b	0.9a
K stock (mg ha^{-1})	48.0	47.0	37.5	44.2	33.3	30.8	44.1	32.7

Soil parameters under different land use types are compared within each farming system; comparison is based on one way ANOVA (Tukey's HSD test; 0.95 confidence); values followed by the same letter are not significantly different; triplicate samples for each land use type sized residues (teff, wheat, barley, pulses) are used as animal feed with priority given to lactating cows, oxen and calves. Enset leaves are used as animal feed in years of extended dry season, but most often they are incorporated into the soil. In both study areas farmers did not apply fresh manure to their plots. Night droppings of livestock were collected daily, piled in the front yard (for 8–12 months) and spread at the beginning of the rainy season. In dry seasons, dung (only from cattle) was collected and dried (dung cake) to be used for household energy during the rainy season.

Urea and DAP were the only mineral fertilizers applied to cereals. In enset-based systems, farmers mix DAP and urea (2:1 ratio) before application. Normally fertilizer is broadcasted during seeding and incorporated into the soils with oxen drawn plows. In contrast, in the teff-based farming systems, farmers apply fertilizer 5–7 days after planting, under the waterlogged conditions of *Kooticha* soils (Vertisols). Farmers in the enset-based system applied higher quantities of organic and mineral fertilizers (Table 4). The analysis of the household survey shows that a much smaller fraction of farmers classified as poor (16%) were applying DAP and urea, while the majority of households classified as 'rich' (86%) did use mineral fertilizer (Table 5). Application of manure showed a similar trend (Table 5). Soil fertility management methods requiring only land and labor (regardless of size) were applied similarly in all wealth groups. Examples of such fertility management include the application of household waste (Table 5), fallowing and plowing along contour lines to decrease soil erosion. More than 90% of respondents in all wealth categories reported that they observed declining soil fertility on their fields.

Table 4 Organic and inorganic fertilizers applied by farm households in enset- and teff-based farming systems

Inputs	Enset-based System (n = 50)	Teff-based System (n = 16)	*P*
Manure (mg ha^{-1} yr^{-1})	2.3	0.5	*
Waste (mg ha^{-1} yr^{-1})	0.2	0.04	*
DAP and UREA (kg ha^{-1} yr^{-1})	74.2	18.3	*

Kolmogorov–Simirnov two samples test at 0.95 confidence interval; n = sample size

* indicates significant difference

Nutrient balances, stocks and flux rates

Balances

Full nutrient balances indicate a considerable P accumulation in enset-based farming systems (Table 6). In contrast, in teff-based systems, P was under slight depletion. The latter also had negative N and K balances, i.e. a five-fold higher depletion rate of N and a two-fold higher depletion of K than the enset-based farming system. The partial (management related) nutrient balances revealed that in enset-based farming P was accumulating, while N and K revealed slightly negative balances (Table 7). In teff-based farming, partial balances for N and K were clearly negative.

Table 5 Organic and inorganic fertilizers applied by farm households of different wealth classes in enset- and teff-based farming systems

Farming system	Wealth classes	Sample size:	Types of fertilizer		
			DAP and UREA (kg ha^{-1} yr^{-1})	Manure (mg ha^{-1} yr^{-1})	Waste fv(Mt ha^{-1} yr^{-1})
Enset-based	Rich	20	113.9a	3.6a	0.1a
	Medium	20	62.5b	1.8b	0.1a
	Poor	10	71.8b	1.1c	0.2a
Teff-based	Rich	5	46.2a	0.5a	0.1a
	Medium	7	52.1a	0.4a	0.03b
	Poor	4	7.5c	0.1b	0.02b

Tukey's HSD test at 0.95 confidence intervals; a, b and c indicate significantly different means; comparisons are made between wealth classes within the same farming system

Table 6 Nutrient stocks, fluxes and full nutrient balances of enset- and teff-based farming systems

Stocks and fluxes	Enset-based system						Teff-based system				
	Cereals	Potato	Enset	Fallow	Meadow	All	All	Cereals	Pulses	Maize	Meadow
N-stock (mg ha^{-1})	9.5	13.4	12.6	9.5	15.6	11.4	6.6	5.5	5.5	10.5	8.2
N-flow (kg ha^{-1} yr^{-1})	−10.0	−23.0	+28.0	−19.0	0.0	−12.0	−52.0	−38.0	−60.0	−43.0	−92.0
N-flow (% of stock yr^{-1})	0.1	0.2	0.2	0.2	0.0	0.1	0.8	0.7	1.1	0.4	1.1
P-stock (mg ha^{-1})	2.3	5.2	4.3	2.3	2.1	3.0	1.6	1.2	1.2	3.8	1.5
P-flow (kg ha^{-1} yr^{-1})	+34.0	−2.0	+20.0	−1.0	+2	+12.0	−3.0	+2.0	−10.0	−15.0	−10.0
P-flow (% of stock yr^{-1})	1.5	0.0	0.5	0.0	0.1	0.4	0.2	0.3	0.8	0.4	0.7
K-stock (mg ha^{-1})	44.2	47.8	47.6	48.0	33.3	44.2	33.0	30.8	30.8	44.1	32.7
K-flow (kg ha^{-1} yr^{-1})	−43.0	−82.0	−20.0	−27.0	+52.0	−20.0	−87.0	−69.0	−112.0	−142.0	−110.0
K-flow (% of stock yr^{-1})	0.1	0.2	0.0	0.1	0.2	0.1	0.3	0.2	0.4	0.3	0.3

Table 7 Crop-specific partial nutrient balances in enset- and teff-based farming systems in the Central Highlands of Ethiopia (in kg ha^{-1} yr^{-1})

Farming systems	Land use types	Inorganic and organic Fertilizer ($IN_1 + IN_2$)			Crop yields and crop residues ($OUT_1 + OUT_2$)			Balances		
		N	P	K	N	P	K	N	P	K
Enset system	Barley	23	42	63	16	9	44	7	33	−41
	Wheat	72	60	34	60	11	55	49	55	12
	Oat	0	0	0	4	3	8	−4	−3	−8
	Potato	113	13	129	114	12	140	−1	1	−11
	Enset	149	32	169	97	13	153	53	19	17
	Fallow	50	12	65	52	9	48	−2	2	17
	Meadow	31	7	36	81	13	79	−51	−6	−44
	Enset system	43	22	45	50	10	59	−6	11	−14
Teff system	Barley	1	3	0	30	17	87	−28	−14	−87
	Wheat	4	4	0	14	3	14	−21	0	−23
	Teff	9	11	0	18	3	11	−9	8	−11
	Faba bean	0	0	0	71	9	81	−71	−9	−81
	Vetch	0	0	0	75	10	61	−75	−10	−60
	Meadow	31	15	36	91	15	90	−60	−8	−54
	Maize	15	13	14	26	13	60	−11	−10	−51
	Teff system	13	7	9	38	8	41	−28	−1	−34

Within farming systems, large differences between land use types were observed (Tables 6 and 7). Balances of N and P in enset farming systems were positive for major land uses with the exception of oats, potatoes and meadows. On meadows (enset-based farming) the full nutrient balance was less negative than the partial nutrient balance, a finding that can be explained by the sedimentation of eroded material at the foot slopes, where the meadows are located.

Stocks

Potatoes, enset and meadows (in enset-based farming) had the highest stocks of soil N followed by maize (in teff-based farming; Table 3). P stocks on potato, enset and maize fields were higher than on all other plots. The lowest mean P stock was recorded on teff areas (1.2 mg ha^{-1}), while the highest was found on potato (5.2 mg ha^{-1}). Highest mean value of K stock was measured on fallow land followed by enset and potato (Table 3).

Table 8 Areas of different land use types affected by erosion and sedimentation

Farming system	Land use	Area (%) under different erosion severity (mg ha^{-1} yr^{-1})				Area (%) under different sedimentation intensity (mg ha^{-1} yr^{-1})			
		>15	15–10	10–5	5–0	0–5	5–10	10–15	>15
Enset-based	Cereals	1.6	0.9	3.2	93.2	0.5	0.0	0.0	0.5
	Homesteads	0.0	1.5	8.5	90.0	0.0	0.0	0.0	0.0
	Fallow	1.6	1.4	3.7	92.6	0.3	0.1	0.1	0.3
	Meadow	7.9	2.6	6.4	69.6	4.6	1.1	1.1	5.8
	Enset system	4.1	1.8	4.7	83.8	2.0	0.5	0.5	2.6
Teff-based	Cereals	2.4	0.2	8.3	89.0	0.0	0.0	0.0	0.0
	Homesteads	0.0	0.0	4.7	95.3	0.0	0.0	0.0	0.0
	Meadow	0.0	8.8	6.5	84.7	0.0	0.0	0.0	0.0
	Teff system	4.2	0.1	7.8	87.9	0.0	0.0	0.0	0.0

Flux rates

Annual depletion of N stocks was strong under meadows and pulses in teff-based farming, while N accumulated on enset plots (0.22% of N stock; Table 6). When aggregated at farming system/watershed level, annual N-depletion was small (0.12% in enset and 0.71% in teff-based farming systems). Soil erosion and deposition are major fluxes in both farming systems. Fractions of land affected by erosion and sedimentation are presented in Table 8.

Table 9 Comparison of soil parameters (0–30 cm) under different farming systems in the Central Highlands of Ethiopia

Soil parameters	Farming systems		P
	Enset-system[a]	Teff-system[b]	
Bulk density (g cm^{-3})	0.99 ± 0.02	1.0 ± 0.02	NS
Clay (%)	30.6 ± 2.1	43.2 ± 1.9	**
Silt (%)	44.1 ± 1.9	33.5 ± 1.7	**
Sand (%)	25.3 ± 2.0	23.3 ± 1.8	NS
pH	5.4 ± 0.1	6.0 ± 0.1	**
Organic C (%)	4.2 ± 0.3	3.4 ± 0.2	*
Total N (%)	0.4 ± 0.03	0.3 ± 0.02	**
C:N	10.1 ± 0.2	11.9 ± 0.2	**
N stock (mg ha^{-1})	12.3 ± 0.8	8.1 ± 0.7	**
Available P-Bray (ppm)	4.8 ± 3.3	15.6 ± 3.0	NS
P stock (mg ha^{-1})	3.2 ± 0.4	2.2 ± 0.3	NS
CEC (cmol$_c$ kg^{-1})	30.6 ± 1.3	38.3 ± 1.2	**
Exchangeable K (cmol$_c$ kg^{-1})	2.2 ± 0.6	2.0 ± 0.5	NS
K stock (mg ha^{-1})	44.2 ± 2.5	35.9 ± 2.3	*
% Base saturation	32.3 ± 10.5	70.7 ± 8.6	*

Probability is based on Kolmogorov Smirnov two samples (group) tests

NS: indicates no significant differences

** indicates $P \geq 0.99$

* indicates $P \geq 0.95$

[a] n = 25 for bulk density and 15 for all other parameters

[b] n = 15 for bulk density and 9 for all other parameters

Discussion

Soil nutrient management in relation to soil fertility and income

Soil parameters with strong influence on nutrient availability differed between the two farming systems investigated (Table 9). In the teff system, the higher clay content and related CEC in combination with a higher pH and base saturation are favorable soil fertility parameters, contributing to the relatively high K stocks, and also serving as an indicator of plant nutrients related to the mineral fraction of the soil (Brady and Weil 2002). In contrast, organic matter related parameters like N and P contents were higher in the enset-based system, which may be the result of management, which includes higher inputs of organic residues than in the teff-based system. However, we are aware that differences in elevation (influencing the carbon cycle) and parent material also contribute to the pedogenetic differences between the farming systems.

Differences in soil properties encountered within a watershed were assumed to be related to terrain factors and to land use and management practices. Our results clearly indicate that some differences in soil parameters are related to landscape position and were influenced by the redistribution of soil material. Other differences in soil parameters were more likely caused by agricultural management (Table 3). For example the low organic matter content in soils of fields planted with cereals in both farming systems was probably caused by the combined effects of plowing, which lowers organic matter content (Davidson and Ackerman 1993), and a low return of organic residues. In contrast to this finding, in both farming systems soils close to homesteads had a higher organic matter content than other soils (potato in the enset-based farming and maize in the teff-based farming). These results illustrate the importance of niche management by which farmers deliberately enrich certain fields to increase production (Chuma et al. 2000; Elias 2000; Hilhorst et al. 2000). However, there are risks related to this land use strategy, as nutrient enrichment in one place often brings about nutrient impoverishment elsewhere.

In general, farmers in the teff-based farming system adapted their land use strategy to the soils distinguished in the local classification system (e.g. they grow mainly maize on *Kossii*, barley and wheat on *Magaalee*, teff and pulses on *Kooticha*; see Table 2 for soil properties and classification). In contrast, farmers in the enset-based farming system did not choose to grow their crops on selected soil types, but used all four soil types which are distinguished in the local system to grow barley. However, they did not ignore different levels of soil fertility and adapted their management strategies accordingly. For example *Gurraacha* soils are considered to be fertile soils and therefore they are not fertilized. Thus, the farmers' management strategies are directed towards minimizing the risk and producing a reasonable harvest on all soils, instead of maximizing the harvest on the fertile fields.

Wealth and off-farm income had contrasting influences on nutrient management. The rich farmers applied more fertilizer and manure than the poor farmers (Table 5), while farmers with a relatively high off-farm income tend to invest less in nutrient management. For example access to off-farm income, as reported from the teff-based farming system, on average reduced a farmer's incentive to invest in nutrient inputs: a decision, which explains the more rapid nutrient depletion as compared to the enset-based system. Our results confirm the findings of Pender et al. (2001) and Wijnhoud et al. (2003), who reported that soil fertility management can be affected by the livelihood strategies being pursued.

Nutrient balances and sustainability of agroecosystems

In general, the partial (management-related) nutrient balances of both farming systems do not appear to be dramatically negative, neither for N nor for K. For P the partial nutrient balance in the teff system was neutral and for the enset system it was even slightly positive (Table 7). Both watershed areas loose plant nutrients, but these losses make up only a small fraction of overall nutrient stocks (Table 6), and will probably not endanger agricultural land use in the near future. However, the image of sustainable land use changes quite dramatically if we analyze the nutrient balances of individual land use types or crops that are components of the farming systems (see Table 6: full balance). In the enset system some land use types have clearly negative nutrient balances (e.g. meadows), while other components of the system accumulate nutrients (e.g. enset grown on homesteads). These findings illustrate that although the net losses of the watershed seem to be limited, the considerable redistribution of soil and nutrients within the watershed cause decreasing crop yields as reported by farmers.

Our results illustrate a general scaling problem when looking at nutrient balances: while many studies at supranational or national scales invariably show strongly negative nutrient balances (e.g. Stoorvogel and Smaling 1998; Haileslassie et al. 2005), this does not necessarily mean that the entire amount of nutrients leave the system since a significant quantity of nutrients removed from arable land can be deposited on adjacent ecosystems (e.g. meadows), processes which are usually ignored in the aggregated perspective of higher spatial scale studies. For example the strongly negative partial nutrient balances for meadows, in the enset system, was clearly less negative if the full balance was considered. This was caused by the inclusion of erosion and especially deposition, which partly compensated for the negative partial fluxes.

In contrast to the partial nutrient balances, full nutrient balances have been used as an indicator of sustainability with respect to soil fertility (Whitbread et al. 2003; Nambiar et al. 2001; Bouma 2002; Dechert et al. 2004). However, the utility of full nutrient balances is greatly increased, when they are related to soil nutrient stocks (Van den Bosch et al. 1998). Using nutrient balances and stocks implicitly assumes that the methods used to quantify nutrient stocks actually quantify stocks of available nutrients. However, major nutrient fluxes like erosion and sedimentation, do not only affect the stock of available nutrients, but they also affect e.g. primary minerals, which have not been weathered yet. For this reason we compare our fluxes to *total* N, P and K stocks.

If however, we are interested in the effects of nutrient mining on crop yields, we should only consider stocks of *available* nutrients. While exchangeable K gives a reasonable estimate of available K, for N it is widely accepted that only a small part of soil organic nitrogen is actively cycling, and total N is therefore not a good measure of 'available' N stocks. A better estimate of available N stocks may be the amount of N lost following cultivation, which has been found to be in the order of 30% (Davidson and Ackerman 1993). Taking this into account, the percentage of annual loss of N stocks in both study areas can exceed 3.5%. This is in agreement with earlier studies arguing that more than 1% removal or enrichment of total N stocks indicate unsustainable agroecosystems (Hilhorst et al. 2000). For the P stocks the estimate is even more difficult, but also here using total P is clearly a large overestimate of P that may become available for agricultural use.

In conclusion, it is evident that soil fertility managements associated with the distinct farming systems account for inter-system variations in stocks and fluxes of N and P. The discrepancies between different land uses (within the watersheds) are caused by niche management and differences in magnitude of erosion and sedimentation. Farmers tend to give more weight to specific land use than sustainability of the whole system, which is revealed through uneven transfer of nutrients between different fields. Indeed, prevalence of such nutrient oversupply and depletion in different land uses implies that sustainability is threatened and nutrients are not optimally used. While these problem areas account for the largest fraction of cereals and meadows, they should be the focus of future interventions promoting optimal nutrient redistribution and inputs.

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