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ORIGINAL ARTICLE

Soil nutrient balances under diverse agro-ecological settings in Ethiopia

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Abstract Soil fertility is one of the main constraints to agricultural intensification in Ethiopia. Like in many East African countries, nutrient depletion rates are exacerbated in Ethiopia by high erosion rates, biomass and animal manure removal from farm plots and limited application of mineral and organic fertilizers. In this paper, soil nutrient balances at plot level were calculated for 350 farms spread across the high potential highlands of Ethiopia. The nutrient input flows and output flows were monitored over a period of 3 years (2012–2014) using the monitoring for quality improvement toolbox. Average nitrogen (N), phosphorus (P) and potassium (K) balances were -23 ± 73, 9 ± 29 and -7 ± 64 kg ha^{-1}, respectively. The situation was most severe for N, where average depletion rate was 0.2 % of the soil total N stock per year, which equals about 4.2 % of the available soil N pool. Depletion rates were highest in the relative intensive farming systems in mountainous areas located in the central and southern parts of Ethiopia. Nutrient depletion rates increased in time with 13, 3 and 10 kg ha^{-1} year^{-1}, respectively for N, P and K during the monitoring period. The Ethiopian government responds to the on-going, and worsening, soil nutrient depletion by stimulating the use of mineral fertilizers. We conclude that the current efforts on increased inputs of mineral fertilizers are a step in the good direction, but to really halt and reverse soil fertility decline, organic fertilizer application and soil and water conservation should be an integral part of the intervention strategy.

Keywords Fertilizer · Composting · Ethiopia · Farming systems · MonQI · Nutrient balance

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Introduction

Soil fertility is a key production factor for most farmers in Sub-Sahara Africa. Low intrinsic soil fertility, limited replenishment of removed nutrients and high erosion rates in mountainous areas cause soil fertility decline to become a major threat to current and future food production (Gachimbi et al. 2005; AGRA 2014). Many farming systems still rely on natural release of nutrients from the soil through mineralization and de Jager et al. (2001) estimated that approximately 60–80 % of the farm income was obtained at the expense of soil nutrient depletion, i.e. through unreplenished nutrient uptake in marketable crops. Soil nutrient mining cannot be visualized easily and, therefore, indicators are often used to facilitate discussions on soil fertility management. Soil nutrient balances are a commonly used indicator and are defined as the difference between the sum of nutrient input flows and the sum of nutrient output flows within a specific system (field, farm, nation) over a certain period (season or year). Soil nutrient balances reflect the net change in soil fertility and indicate trends in time, but do not necessarily determine the current state of soil fertility. To determine the severity of the depletion rate, nutrient balances can be related to the soil nutrient stocks, where typically a depletion rate of more than 2 % per year of the soil nutrient stock is considered unsustainable (Elias 2002).

Ethiopia is considered as one of the most vulnerable countries in sub-Sahara Africa (SSA) with regard to soil fertility depletion because of its mountainous topography and intensive farming systems based on small cereals. Indeed, national averages of nutrient balances were estimated at −41 kg N, −6 kg P and −26 kg K per ha per year, which is among the highest nutrient depletion rates for sub-Saharan Africa (Stoorvogel and Smaling 1993). Yet, soil nutrient balances can differ considerably between different crops, farming systems and agro-ecological zones (Sommer et al. 2014). Restoring soil fertility is, therefore, a key priority of the Government of Ethiopia (GoE). The Agricultural Growth Plan (AGP) is the flagship programme of the Ethiopian government designed to achieve the Growth and Transformation Plan (GTP) which was running from 2011 to 2015 and is currently extended with a second phase until 2019. One of the objectives of the GTP is to double agricultural production by scaling up of existing best practices and introducing new promising innovations (World Bank 2010). It is increasingly realized that it could be difficult to achieve GTP/AGP objectives with the current levels of nutrient mining. To this effect, more balanced and site-specific fertilizer recommendations and improved management practices have been proposed and are being implemented by different projects including Ethiopian Soil Information System (EthioSIS) and Capacity building for Scaling up of Evidence-based best Practices for increased Production in Ethiopia (CASCAPE).

In this paper, soil nutrient balances and nutrient flows were analysed at field level in six areas of Ethiopia. Soil nutrient depletion rates were related to soil nutrient stocks to evaluate the longer term sustainability of the agro-ecosystem.

Materials and methods

Selected sites

The results described in this paper are part of the results of the broader study of the CASCAPE project (www.cascape.info). This project operates in 30 AGP *woredas* (districts) of five main agricultural production areas. The *woredas* represent different farming systems, agro-ecological zones and soil types. Table 1 summarizes the general features of the selected *woredas* and Fig. 1 presents the geographical distribution of the *woredas* included in this study. The *woredas* are located in the eastern part of Tigray National Regional State, western part of Amhara National Regional State and some parts of Southern Nations Nationalities and Peoples Regional State. Given the spread of the Oromiya National Regional State, three sites were selected in its central, eastern and western highlands. In each area local teams collected and analysed data from selected *woredas*. *Woredas* managed by one team were termed clusters and covered 4 or 5 *woredas*. In each cluster, soil nutrient balances were determined for approximately 60 farms, comprising more than 500 fields for 3 years (2012–2014).

Soil characterization

In each *kebele* (a *kebele* being the lowest administrative unit) of the *woredas*, soil profile studies were performed. A total of 706 soil samples were taken for

Table 1 Balance entries for soil nutrient balances at field level as used in the MonQI toolbox

IN			OUT		
Balance entry		Method of determination	Balance entry		Method of determination
IN1	Mineral fertilizer	Farm survey + secondary data	OUT1	Harvested products	Farm survey + secondary data
IN2	Organic inputs	Farm survey + secondary data	OUT2	Harvested crop residues	Farm survey + secondary data
IN3	Atmospheric deposition	Pedo-transfer function	OUT3	Leaching	Pedo-transfer function
IN4	Biological N fixation	Pedo-transfer function	OUT4	Gaseous losses	Pedo-transfer function
			OUT5	Erosion	Pedo-transfer function based on USLE equation

Details about methods of determinations are described in Lesschen et al. (2007)

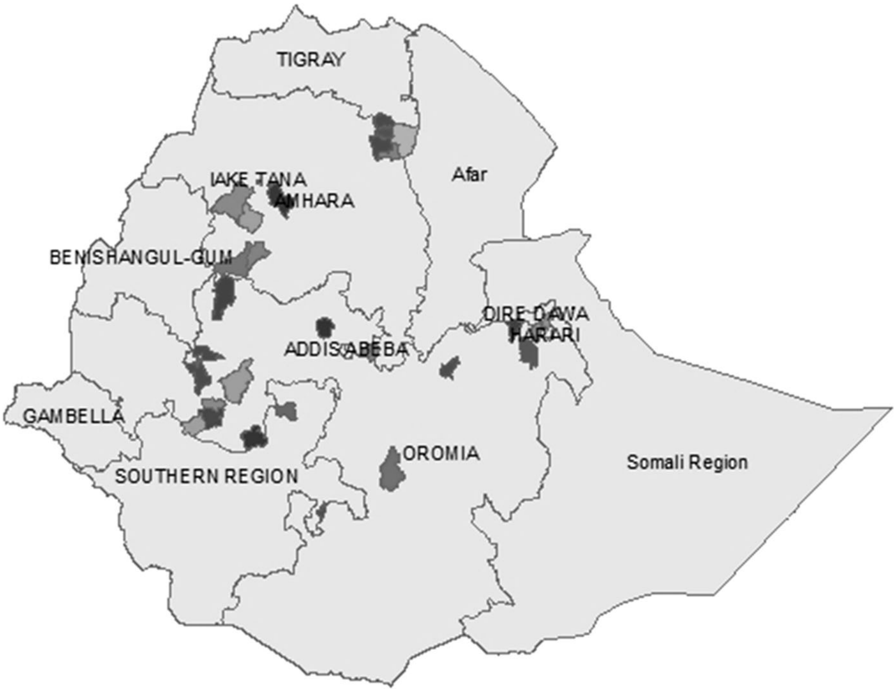


Fig. 1 Locations of the intervention *woredas*

soil analysis to the Soil Fertility Laboratory of the Federal Water Works Design and Supervision Enterprise of Ethiopia. Amongst others, samples were analyzed for pH-H_2O, in 1:2.5 soil:water solution, organic carbon content (%), total N content (%), available P content (mg/kg), cation exchange capacity [CEC cmolc (+)/kg] and exchangeable K (cmolc/kg). The analyses were carried out following the soil laboratory procedures as outlined in Van Reeuwijk (2002). Soil organic carbon was analyzed using the Walkley and Black method (Nelson and Sommers 1996) and total nitrogen according to the Macro-Kjeldahal method that involves digestion of the sample and a wet-oxidation procedure (Bremner and Mulvaney 1982). Available phosphorus content was determined using the Olsen sodium bicarbonate

Table 2 Characterization of the farming systems of the different *woreda*

Region/ university	*Woreda*	Agro-climatic condition	Soil types	Main farming systems
Gray/ Mekelle	Alaje	Cold sub-moist highland	Eutric cambisols with eutric regosols/ lithosols	Livestock/sheep-wheat/barley-faba bean system. High potential for temperate fruits (apple, pear) and dairy development
	Endamehoni	Cool sub-moist to most mid-highland (1800–3250 masl)	Chromic vertisols with eutric cambisols	Livestock-wheat-barley-faba bean system. Most dominant livestock are sheep in the higher altitudes
	Ofla	Cold sub-moist mid-highland	Pellic vertisols with eutric nitisols/cambisols/ regosols	Livestock-wheat/barley-faba bean/field pea system. High potential for dairy and commercial sheep farming
	Raya-Alamata	Hot semi-arid lowland	Chromic vertisols with eutric cambisols	Livestock-cereal system (sorghum, maize, teff); irrigated fruit production (papaya, mango, avocado)
	Raya-Azebo	Hot sub-moist lowland	Chromic vertisols with eutric regosols	Livestock-cereal system (sorghum, teff, maize and chickpea as catch crop); irrigated vegetable production (potato, onion, sweet potato)
Amhara/ Bahir Dar	Bure	Tepid moist mid highlands	Nitosol cambisols and acrisols	Mixed crop-livestock farming system, maize, tef, wheat, finger millet, hot pepper, barley and potato
	Debub Achefer	Tepid moist mid highlands	Nitosol and vertisol	Crop-livestock mixed farming system. The major crops grown in the area are maize, finger millet and tef. Vegetables like cabbage, potato, coffee and sugar cane are grown under irrigation
	Jabi Tehnan	Tepid moist mid highlands	Nitosol and Cambisols	Crop-livestock mixed farming system. Maize; finger millet, pepper, teff, wheat, hot pepper, faba bean, potato and barley are the major crops grown in the *woreda*
	Mecha	Tepid moist mid highlands	Nitosol dominated	Crop-livestock mixed farming system. The major crops grown in the area are maize, finger millet and tef
	Dera	Tepid moist mid highlands	Nitosols, vertisols, gleysols, luvisols and cambisols	Crop-livestock mixed farming system. Tef, finger millet, maize, rice, wheat and barley, among cereals; chick pea and grass pea among pulses are the major crops grown
Oromia (East)/ Haramaya	Haramaya	Tepid sub-moist mid highland	Cambisol dominated	Vegetable based mixed farming system. Vegetable based mixed farming system. Rain-fed and irrigated production of potato, and other vegetables (cabbage, carrot beetroot and shallot), khat and rain-fed cereal (maize and sorghum) production
	Kombolcha	Tepid moist mid highland	Luvisol dominated	Vegetable based mixed farming system. Rain-fed and irrigated production of potato, and other vegetables (cabbage, carrot beetroot and shallot), khat and rain-fed cereal (maize and sorghum) production
	Habro	Tepid sub-moist mid highland	Vertisol dominated	Cereal-livestock mixed farming system. Rain-fed cereal (maize, teff and sorghum) and haricot bean production. Livestock (cattle, goat and sheep) with zero grazing and tethering practices

Table 2 continued

Region/ university	*Woreda*	Agro-climatic condition	Soil types	Main farming systems
	Gurawa	Tepid sub-moist mid	Nitosol dominated	Cereal-livestock mixed farming system. Rain-fed cereal (maize, wheat, barley, sorghum and teff), potato and haricot bean production. Livestock (cattle, goat and sheep) with zero grazing and tethering practices
	Meta	Tepid sub-humid mid highland	Cambisol dominated	Cereal-livestock mixed farming system. Rain-fed cereal (maize, sorghum, wheat and barley) and potato production. Livestock (cattle, goat and sheep) with zero grazing and tethering practices
Oromia (West)/ Jimma	Bedelle	Warm sub-humid lowlands	Nitosol (redsoil), vertisol (brown)	Maize dominated crop livestock mixed farming system (maize, sorghum, teff, finger millet, wheat)
	Dhidhessa	Warm sub-humid lowlands	Dominant soil type is nitosols	Maize dominated crop livestock mixed farming system (maize, teff, sorghum, wheat) are the major cereal crops produced
	Limu Seka	Warm sub-humid lowlands	Dominated by nitosol and some vertisol	Crop-livestock based farming system(maize, sorghum, teff and coffee)
	Gera	Tepid sub-humid mid-highlands	Fluvisols and cambisols are dominant soil types	Coffee dominated crop livestock mixed farming system (coffee, avocado, mango, teff and maize) and fattening of livestock are practiced
	Omonada	Very cold sub-humid sub-afro-alpine to afro-alpine	Dominated by leptosols and nitosols	Cereal dominated crop livestock mixed farming system (maize, sorghum, Teff and pepper) are the major crops produced
Oromia/ Addis Ababa	Munessa	Cold humid, sub afro to afro alpine	Dominated by fluvisol soil with some vertisol soils	Wheat dominated crop livestock mixed farming system
	Gimbichu	Cold sub humid sub afro alpine to afro alpine	Dominated by vertisol soil with some cambisol soil	Chick pea-teff and livestock mixed farming system
	Girar Jarso	Very cold sub humid sub afro to afro alphine	Vertisol and cambisol soils are dominant	Livestock based farming system
	Bako Tibe	Warm sub humid low land	Dominated by reddish brown nitosol soil	Maize dominated crop livestock mixed farming system
	Becho	Tepid sub humid mid highland	Dominated by vertisol soil	Tef dominated crop livestock mixed farming system
SNNPR/ Hawassa	Misrak Azernet	Tepid per-humid mid highlands and cool sub-humid mid highlands	Pelic vertisols; etric fluvisols and dystric nitosols	Cereal—livestock mixed farming system
	Bulle	Tepid per-humid mid highlands and cool sub-humid mid highlands	Dystric nitosols	Agro forestry and crop-livestock system with coffee and enset
	Enamore na ener	Tepid per-humid mid highlands and cool sub-humid mid highlands	Eutric nitosols and pelic vertisols	Crop livestock mixed farming system where (enset, barley, wheat, pea, bean and potato, cabbage, oats, khat and teff)
	Melga	Tepid per-humid mid highlands and cool sub-humid mid highlands	Etric fluvisols	Khat, coffee and enset livestock mixed farming system

masl meters above sea level

Table 3 Number of farms surveyed using the MonQI toolbox per cluster per year

Clusters	Year		
	2012	2013	2014
Addis Ababa	nd	72	60
Bahir Dar	52	nd	57
Haramaya	80	100	95
Hawassa	80	74	79
Jimma	44	92	66
Mekelle	100	nd	102

nd no data collected

extraction solution (pH 8.5) method as described by Van Reeuwijk (2002) whereby the amount of phosphate was determined by spectrophotometer at 882 nm. Exchangeable basic cations and the cation exchange capacity (CEC) of the soils were determined by using the 1 M ammonium acetate (pH 7) method according to the percolation tube procedure (Van Reeuwijk 2002) whereby exchangeable K was determined by flame photometer. The soil data were used in the background database of the MonQI software to estimate hard to quantify flows through pedo-transfer functions (Lesschen et al. 2007) and to calculate soil nutrient depletion rates, defined as the nutrient balance divided by the relevant soil nutrient pool.

Nutrient balances

Soil nutrient balances were calculated as the net differences of nutrient inputs and outputs flows taking the soil as “black box” (Smaling and Stoorvogel 1990). Input flows include farmer managed flows like applications of fertilizer and seeds and natural processes like atmospheric deposition and biological N fixation. Output flows include removal of nutrients from soil by harvests, leaching, volatilization and soil erosion by water. The different balance entries were assessed through farm surveys (farmer managed nutrient flows) and transfer functions (naturally occurring nutrient flows) as shown in Table 2. Nutrient balances were estimated using the monitoring for quality improvement (MonQI) toolbox. The MonQI toolbox is a method for monitoring management and performance of small scale farming systems worldwide. MonQI has been used in the Tropics for over 30 years (www.monqi.org; Smaling et al. 2013; Vlaming et al. 2012). Basically, farmers provide information about their farm management and farm activities using standardized questionnaires. The questionnaire consists of different sections related to the main farm activities (livestock activities, crop activities, household activities, redistribution activities and storage activities). Data analysis is automated and combined with background data on e.g. nutrient contents of products, soil data and conversion factors from farmer used units (e.g. headloads) to SI units.

The software produces a wide range of farm management and farm performance indicators like NPK balances and gross margins at plot, activity, and farm level. Data collection started in 2012 for all *woredas* except those in the Addis Ababa cluster (Table 3) who joined the project only after 2012. Table 3 gives an overview of the number of surveyed farms per cluster and per year. Participating farmers were beneficiaries of the CASCAPE project and were selected on the basis of representativeness for their region. The soil data were used in the background database of the MonQI software to estimate hard to quantify flows through pedo-transfer functions (Lesschen et al. 2007) and to calculate soil nutrient depletion rates, defined as the nutrient balance divided by the relevant soil nutrient pool. Hard to quantify flows included atmospheric deposition, biological N fixation, leaching, gaseous losses and erosion. Hard to quantify flows, as the term suggests, are extremely difficult to quantify, both by physical measurements as by simulation modelling. This is especially true for soil erosion which is the results of many, highly variable factors (Hessel et al. 2006). In MonQI soil erosion is estimated using the modified USLE equation which was considered as the best compromise

Table 4 Average soil data of upper 30 cm and standard deviations (n = 4–10), nutrient balances and depletion rates per *woreda*

Woreda	Soil data							Nutrient balance (kg ha^{-1} $year^{-1}$)^a			Annual depletion rate^{-1}		
	N (%)	K (meq/100 g)	Bulk density (kg m^{-3})	pH-H_2O	P-available	CEC	Org. C	N	P	K	N	P	K
Addis Abeba													
Bako Tibe	2.10 ± 0.59	1.25 ± 0.20	1.20 ± 0.03	5.87 ± 0.36	12.3 ± 6.64	44.4 ± 4.28	20.7 ± 7.11	−79	3	−18	−0.46	1.29	−0.38
Becho	1.22 ± 0.43	1.07 ± 0.23	1.18 ± 0.03	6.44 ± 0.51	12.1 ± 3.19	53.0 ± 10.4	13.1 ± 6.59	−40	6	−13	−0.23	3.02	−0.27
Gimbichu	1.23 ± 0.41	1.22 ± 0.42	1.27 ± 0.05	7.66 ± 0.41	12.1 ± 4.95	55.4 ± 6.47	11.4 ± 3.32	−105	10	−16	−0.62	4.79	−0.34
GirarJarso	1.26 ± 0.34	0.70 ± 0.28	1.26 ± 0.04	6.26 ± 1.05	15.4 ± 3.62	46.2 ± 10.3	12.8 ± 2.87	−87	−1	−12	−0.51	−0.33	−0.26
Munessa	2.31 ± 0.47	0.93 ± 0.34	1.12 ± 0.07	5.75 ± 0.51	10.0 ± 4.55	46.4 ± 9.07	26.8 ± 5.09	−100	7	−18	−0.59	3.05	−0.38
Bahir Dar													
Burie	1.95 ± 0.53	0.17 ± 0.09	1.19 ± 0.04	5.30 ± 0.26	3.09 ± 1.78	44.6 ± 5.72	23.2 ± 5.15	−18	19	−2	−0.09	24.66	−0.17
Dera	2.02 ± 0.37	0.62 ± 0.80	1.21 ± 0.05	5.17 ± 0.26	1.98 ± 1.29	45.3 ± 6.48	18.5 ± 6.09	−21	12	−6	−0.11	21.43	−0.30
Jabi Tehnan	1.48 ± 0.41	0.49 ± 0.39	1.20 ± 0.21	5.70 ± 0.99	2.49 ± 1.33	46.2 ± 13.5	23.5 ± 8.89	−15	20	−2	−0.11	40.74	−0.15
South Achefer	1.99 ± 0.56	0.28 ± 0.11	1.16 ± 0.04	5.05 ± 0.22	1.59 ± 0.90	40.3 ± 6.85	22.3 ± 2.85	−20	18	−7	−0.11	50.08	−0.64
Haramaya													
Gurawa	1.64 ± 0.64	0.60 ± 0.33	1.23 ± 0.07	6.23 ± 0.75	12.0 ± 3.73	45.1 ± 6.88	15.3 ± 5.63	−15	4	−2	−0.11	1.95	−0.09
Habro	1.92 ± 0.40	0.64 ± 0.44	1.30 ± 0.12	6.54 ± 0.48	12.2 ± 5.62	47.3 ± 13.3	17.4 ± 3.44	−18	2	−7	−0.09	0.92	−0.22
Haramaya	1.27 ± 0.29	0.68 ± 0.28	1.25 ± 0.08	7.45 ± 0.63	11.7 ± 4.96	39.7 ± 9.46	11.7 ± 2.03	9	10	3	0.08	5.16	0.12
Kombolcha	1.13 ± 0.36	0.66 ± 0.19	1.21 ± 0.06	6.72 ± 0.59	7.22 ± 2.37	46.7 ± 4.06	11.3 ± 2.79	−3	4	4	−0.02	2.77	0.14
Hawassa													
Bulle	2.72 ± 0.72	0.50 ± 0.30	1.09 ± 0.07	5.40 ± 0.48	9.85 ± 2.79	32.4 ± 2.43	27.9 ± 10.2	−4	12	0	−0.02	7.25	0.00
Cheha	2.16 ± 0.68	0.78 ± 0.50	1.01 ± 0.10	5.21 ± 0.68	8.87 ± 2.11	36.9 ± 6.83	23.9 ± 8.91	−38	1	−38	−0.30	0.79	−0.18
Enemor Ener	2.63 ± 0.69	0.65 ± 0.33	1.00 ± 0.01	5.26 ± 0.35	10.8 ± 2.23	32.8 ± 3.69	29.5 ± 9.73	−19	9	−35	−0.11	5.96	−0.15
Malga	2.08 ± 0.50	0.89 ± 0.70	1.10 ± 0.03	5.69 ± 0.61	10.9 ± 2.32	32.8 ± 2.51	23.0 ± 6.94	−1	13	−14	−0.01	8.06	−0.05
Mesrak Azernet Berber	1.71 ± 0.60	0.77 ± 0.30	1.09 ± 0.08	5.12 ± 0.39	7.20 ± 2.08	30.1 ± 2.22	18.2 ± 5.13	−22	12	−18	−0.18	9.78	−0.07
Jimma													
Bedele	2.08 ± 0.25	0.66 ± 0.46	1.07 ± 0.04	4.81 ± 0.56	4.43 ± 1.23	44.2 ± 10.8	19.5 ± 4.37	−4	9	−4	−0.03	8.08	−0.02
Didessa	2.56 ± 1.04	0.66 ± 0.39	1.04 ± 0.04	4.91 ± 0.31	3.91 ± 2.06	44.9 ± 5.75	25.3 ± 10.4	−45	5	1	−0.23	4.60	0.01
Gera	2.30 ± 0.47	1.15 ± 0.95	1.05 ± 0.04	5.10 ± 0.51	3.78 ± 3.28	42.6 ± 6.82	22.0 ± 4.66	−37	7	0	−0.24	8.38	0.00
Limu Saka	1.89 ± 0.31	0.68 ± 0.42	1.09 ± 0.05	5.05 ± 0.42	2.69 ± 0.91	37.3 ± 5.07	17.5 ± 2.36	−45	6	−7	−0.27	6.36	−0.03
Omo Nada	1.57 ± 0.59	1.36 ± 0.71	1.07 ± 0.04	5.42 ± 0.19	2.53 ± 1.57	41.0 ± 7.38	16.0 ± 5.64	−53	5	−3	−0.43	8.44	−0.01

Table 4 continued

Woreda	Soil data							Nutrient balance (kg ha^{-1} year^{-1})[a]			Annual depletion rate^{-1}		
	N (%)	K (meq/100 g)	Bulk density (kg m^{-3})	pH-H$_2$O	P-available	CEC	Org. C	N	P	K	N	P	K
Mekelle													
Alaje	1.64 ± 0.40	0.35 ± 0.14	1.30 ± 0.06	8.01 ± 0.10	12.7 ± 4.85	38.4 ± 1.72	13.8 ± 2.59	−49	5	−1	−0.36	2.60	0.00
EndaMokhoni	1.27 ± 0.32	0.74 ± 0.75	1.27 ± 0.09	7.23 ± 0.45	9.80 ± 4.72	45.8 ± 5.09	10.7 ± 2.97	−53	3	−4	−0.30	1.80	−0.01
Ofla	1.60 ± 0.41	0.46 ± 0.19	1.27 ± 0.04	7.14 ± 0.25	10.0 ± 1.38	46.8 ± 6.90	13.5 ± 3.54	−42	8	−2	−0.24	3.12	0.00
Raya Alamata	1.66 ± 0.42	0.19 ± 0.10	1.28 ± 0.24	6.87 ± 0.48	15.4 ± 9.20	40.0 ± 4.47	13.0 ± 2.97	−9	17	6	−0.05	7.35	0.01
Raya Azebo	2.07 ± 0.67	0.32 ± 0.19	1.24 ± 0.08	7.64 ± 0.27	15.3 ± 6.49	47.0 ± 7.70	18.4 ± 6.49	−9	13	−6	−0.04	5.84	−0.02

[a] See Table 5 for more detail

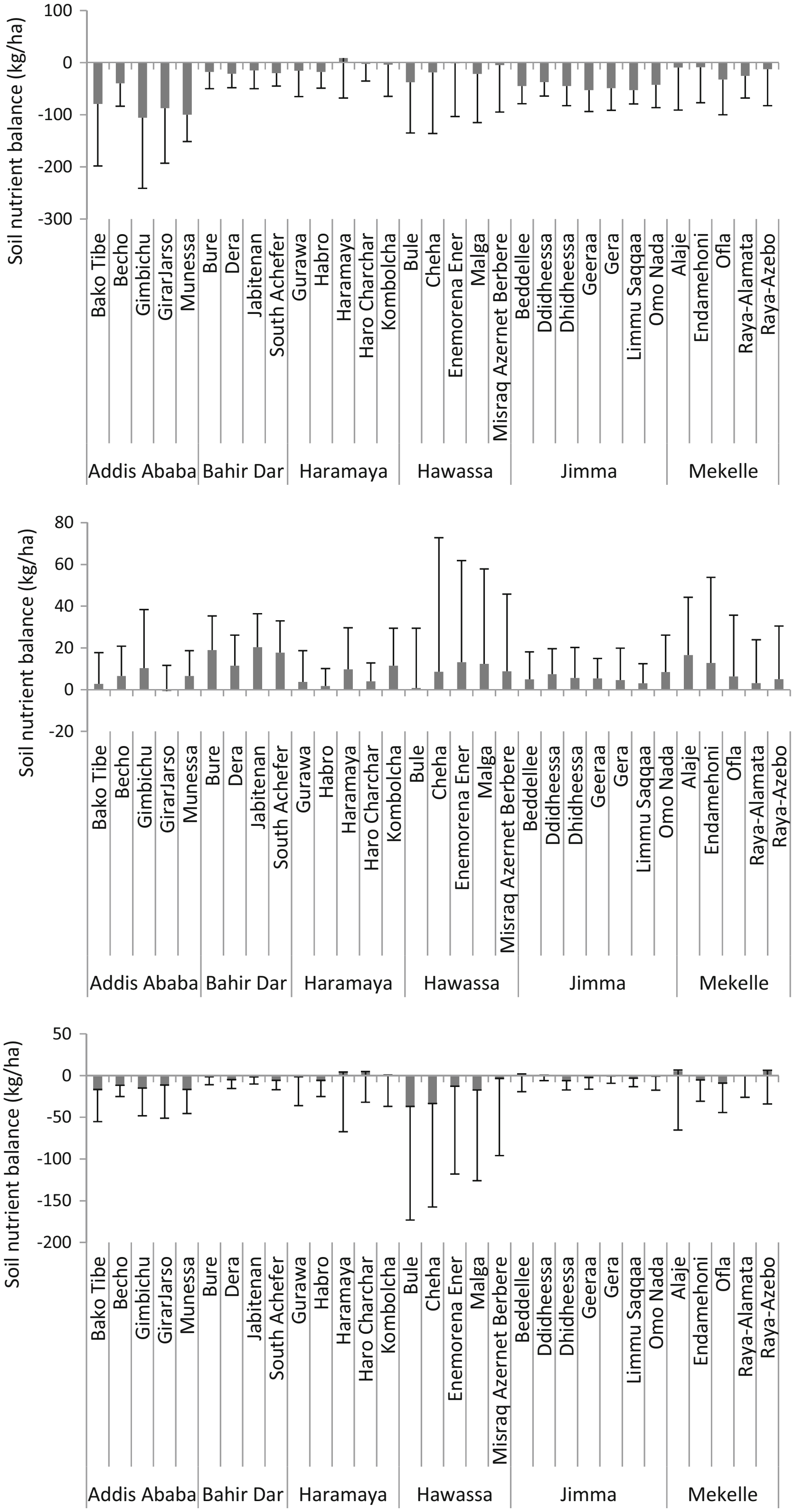
Fig. 2 Average nutrient balances (kg ha^{-1} year^{-1}) per *woreda* ▶ for N (*top*), P (*middle*) and K (*bottom*). *Error bars* show standard deviations

between accuracy and data requirements, though the results should be interpreted with care (Sonneveld et al. 2011). Briefly, soil loss by erosion was estimated by multiplying site specific parameters on rainfall, soil erodibility, slope, slope length, protection by crops and protection by management factors (i.e. anti-erosion measures). The estimated soil loss was subsequently corrected for enrichment of nutrients in the topsoil and soil formation (i.e. weathering of nutrients in newly accessible soil layers).

Data analysis

The current state of the soil fertility was assessed using soil fertility thresholds of 0.15 %, 10 ppm and 1.0 cmol kg^{-1} for N, P and K respectively (Hazelton and Murphy 2007). Soil nutrient depletion rates were calculated by dividing soil nutrient balances by relevant *woreda* average soil nutrient pools, using soil properties of the upper 30 cm. We used average *woreda* soil data because the soil sampling was part of a different project and selected sites were in close proximity, but did not exactly coincide with MonQI survey sites.

Data was subject to an extensive data cleaning process. Data was checked for consistency, completeness and correctness. Consistency checking included systematic reviewing of similarities of sources and destinations of flows. E.g. maize harvest could only originate from a maize plot or a plot with maize intercropping, but not from plots with a different crop. Completeness checking was the systematic reviewing of input and output flows. E.g. plots with only output data (harvests) were double checked when inputs were missing. In some cases, especially for leguminous crops used for home consumption, this turned out to be correct, and no inputs were provided. Outlier checking was done for income and nutrient balances. Outliers were defined as fields with N balances smaller than −500 kg N/ha and higher than 500 kg N/ha. Typically these outliers were found on small fields (less than 100 m^2) where small flaws in original data were exacerbated when data was normalized to hectares. These outliers were often due to difficulties of farmers to estimate inputs (especially organic inputs), land


Soil nutrient balance (kg/ha)
100
0
-100
-200
-300
Bako Tibe
Becho
Gimbichu
GirarJarso
Munessa
Bure
Dera
Jabitenan
South Achefer
Gurawa
Habro
Haramaya
Haro Charchar
Kombolcha
Bule
Cheha
Enemorena Ener
Malga
Misraq Azernet Berbere
Beddellee
Ddidheessa
Dhidheessa
Geeraa
Gera
Limmu Saqqaa
Omo Nada
Alaje
Endamehoni
Ofla
Raya-Alamata
Raya-Azebo
Addis Ababa
Bahir Dar
Haramaya
Hawassa
Jimma
Mekelle
Soil nutrient balance (kg/ha)
80
60
40
20
0
-20
Bako Tibe
Becho
Gimbichu
GirarJarso
Munessa
Bure
Dera
Jabitenan
South Achefer
Gurawa
Habro
Haramaya
Haro Charchar
Kombolcha
Bule
Cheha
Enemorena Ener
Malga
Misraq Azernet Berbere
Beddellee
Ddidheessa
Dhidheessa
Geeraa
Gera
Limmu Saqqaa
Omo Nada
Alaje
Endamehoni
Ofla
Raya-Alamata
Raya-Azebo
Addis Ababa
Bahir Dar
Haramaya
Hawassa
Jimma
Mekelle
Soil nutrient balance (kg/ha)
50
0
-50
-100
-150
-200
Bako Tibe
Becho
Gimbichu
GirarJarso
Munessa
Bure
Dera
Jabitenan
South Achefer
Gurawa
Habro
Haramaya
Haro Charchar
Kombolcha
Bule
Cheha
Enemorena Ener
Malga
Misraq Azernet Berbere
Beddellee
Ddidheessa
Dhidheessa
Geeraa
Gera
Limmu Saqqaa
Omo Nada
Alaje
Endamehoni
Ofla
Raya-Alamata
Raya-Azebo
Addis Ababa
Bahir Dar
Haramaya
Hawassa
Jimma
Mekelle

sizes and, sometimes, typing errors. Several data cleaning sessions were organized and suspicious data were corrected or removed from the dataset.

Results

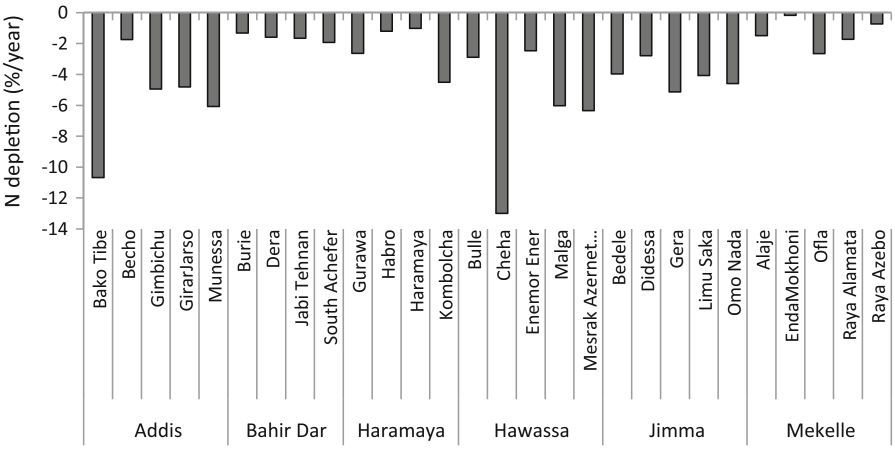
Soil data

Table 4 presents the chemical soil fertility data per *woreda*. In general, soil fertility was low to medium for most sites; soil N contents were below the thresholds for sufficient soil fertility in 68 % of the sites. For P and K these numbers were respectively 11 % and 89 %. In 2 *woredas* (out of 28, namely Girar Jarso and Munessa) all macro nutrients were below the threshold values. For P, relatively high values were found for the *woredas* in the Mekelle cluster. For N and K, no regional differences were observed. Variabilities were high for soil P and soil K contents with standard errors of 0.43 and 0.51, respectively. For soil N contents the standard error was 0.21.

Nutrient balances

Balance entries per *woreda* are shown in Table 5 for N. For P and K comparable patterns were found, but with less balance entries (because biological fixation, atmospheric deposition and gaseous losses mainly refer to N). The differences between the inputs and the outputs are the soil nutrient balances, which are shown in Fig. 2. Soil nutrient balances varied considerably between *woredas* and on average equalled −23 ± 73, 9 ± 29 and −7 ± 64 kg ha^{-1} year^{-1} for N, P and K, respectively. Whereas some sites showed negative P balances, most sites showed P-accumulation (Fig. 2). Average soil N depletion rates were 0.2 % per year when calculated as percentage of the total soil N stock. Typically, only 5 % of the total soil N pool is available for crop uptake (Havlin et al. 2014). When N depletion was expressed as percentage of available N, depletion rates were on average 4.2 % which was considered as severe. For K, average depletion rate was 0.1 % year^{-1}, with higher values in South Achefer and Ofla (Fig. 3). On average, soil nutrient balances decreased with 20, 3 and 12 kg ha^{-1} year^{-1} for N, P and K, respectively during the monitoring time (2012–2014) (Fig. 4). These values equal accelerated soil nutrient depletion of 33, 14 and 41 % for N, P and K, respectively each year. The soil nutrient balances are the net result of various balance entries as listed in Table 1. Mineral inputs were the main nutrient inputs and predominantly consisted of mineral fertilizers. Erosion, leaching and harvests were main nutrient output processes (Fig. 5). Figure 6 shows the inputs of N per *woreda*, which predominantly consisted of urea. For P more than 95 % of the total inputs originated from DAP and for K hardly any inputs were given. Soil erosion was a key loss pathway of nutrients (Fig. 5). Estimated erosion rates were most often moderate or moderate to high according to the classification of Beskow et al. (2009), but especially in the Addis

Fig. 3 Nitrogen depletion rates per *woreda* (% year^{-1})



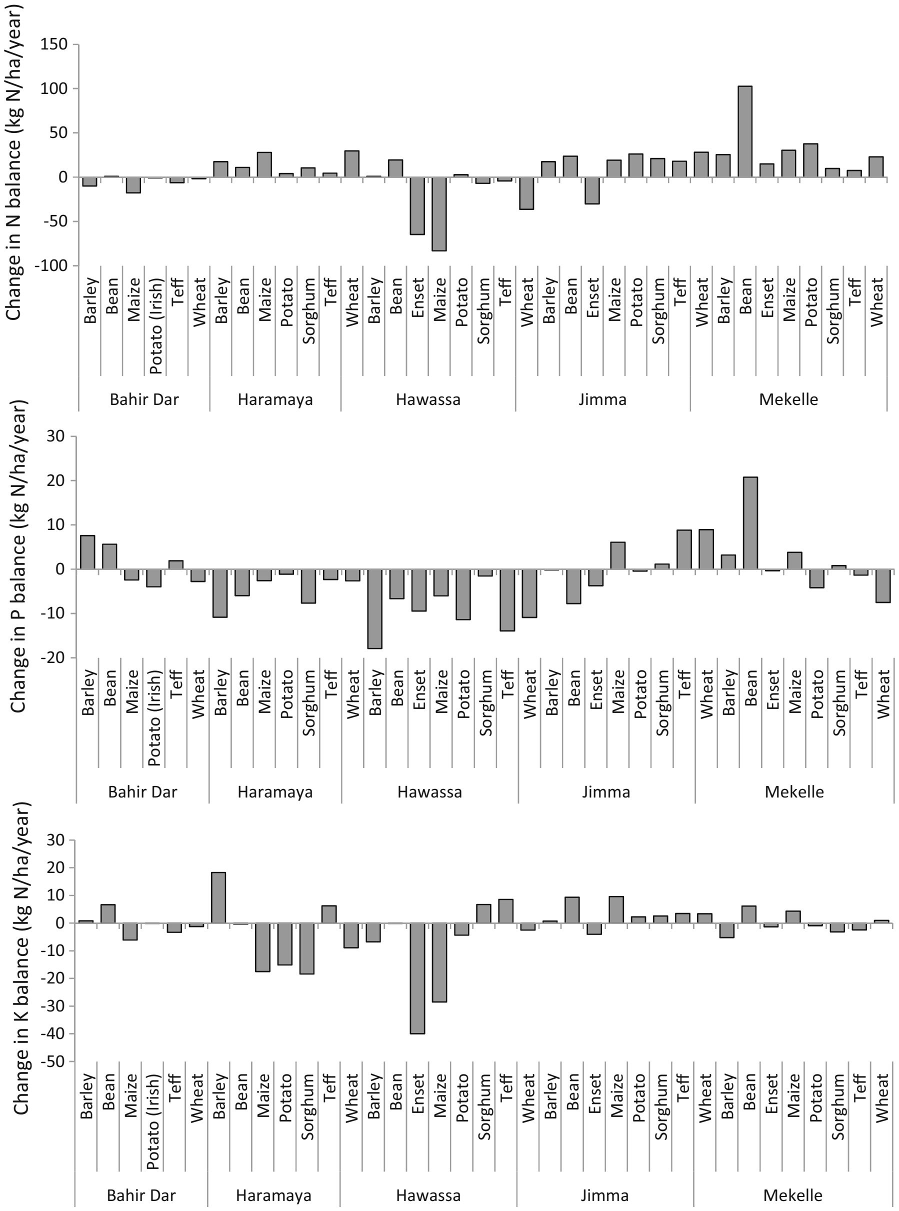


Fig. 4 Average changes in soil N (*above*), P (*middle*) and K (*below*) balances (kg ha^{-1} $year^{-1}$) for main crops between 2012 and 2014

Abeba cluster erosion rates could be very high (Fig. 7).

Standard deviations of the nutrient balance entries were in the order of 100–300 % (Fig. 2; Table 5) and were due to the high diversity of agro-ecological conditions and farming systems. For reasons of readability of the graph, no standard errors were added in Fig. 5. Soil nutrient balances found in this study compared reasonably well to results found by others as shown in Table 6.

Nutrient balances and crop yields

Figure 4 shows soil N balances and yield levels for the major crops, namely maize, wheat, barley and teff. On average, soil N balances were negatively correlated to yield level, indicating that for every kg of yield increment, soil N depletion increased, i.e. became more negative (Fig. 8). On average, i.e. averaged for all crops, years and sites, yield induced depletion was

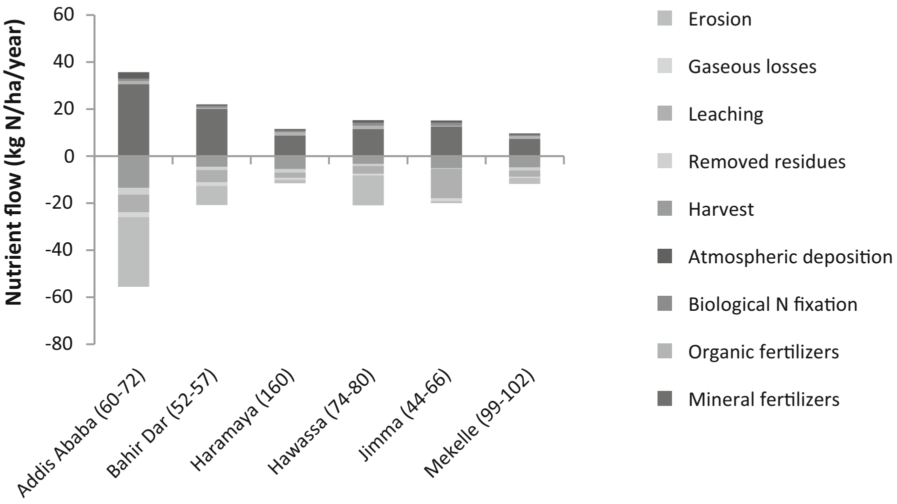


Fig. 5 Average soil N balance entries per cluster (kg ha^{-1} year^{-1})

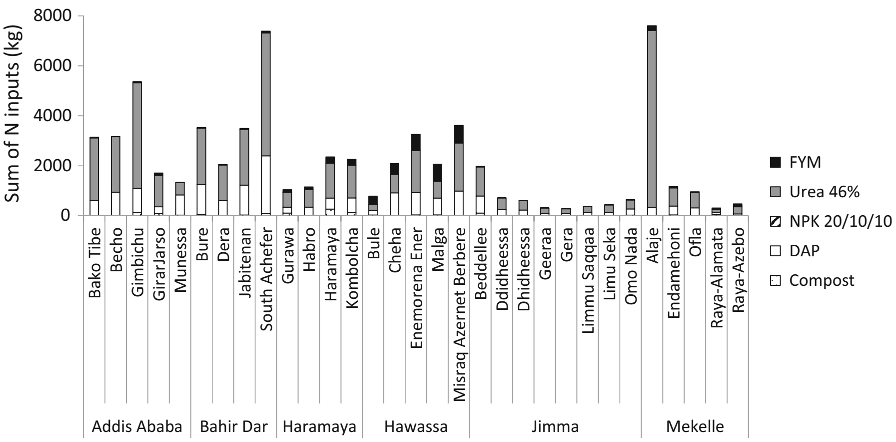


Fig. 6 Sources of N inputs per *woreda*

about 18 g N per kg of yield. For P and K, no relations between yields and soil nutrient balances were found.

Discussion

Soil fertility and agricultural development in Ethiopia

Ethiopia's agriculture is on the rise. Projects like CASCAPE demonstrate that yields can be doubled or tripled by the combination of good seeds, sound nutrient supply and proper management practices. Indeed production levels in Ethiopia have been rising for the last decade (Simons et al. 2014) mainly because of an effective extension mechanism in combination with market reforms. Yet, on average fertilizer strategies, to compensate for the increased withdrawal of nutrient in the harvested products and crop residue removals, did keep pace with the yield increments (e.g. Fig. 8). As a result, soils of Ethiopia are now, more than ever, under threat for soil nutrient depletion. Soil nutrient depletion is often regarded as a precursor of soil fertility loss which in its turn can eventually lead to abandonment of land (Sanchez 2002). This is confirmed by the current study which shows that

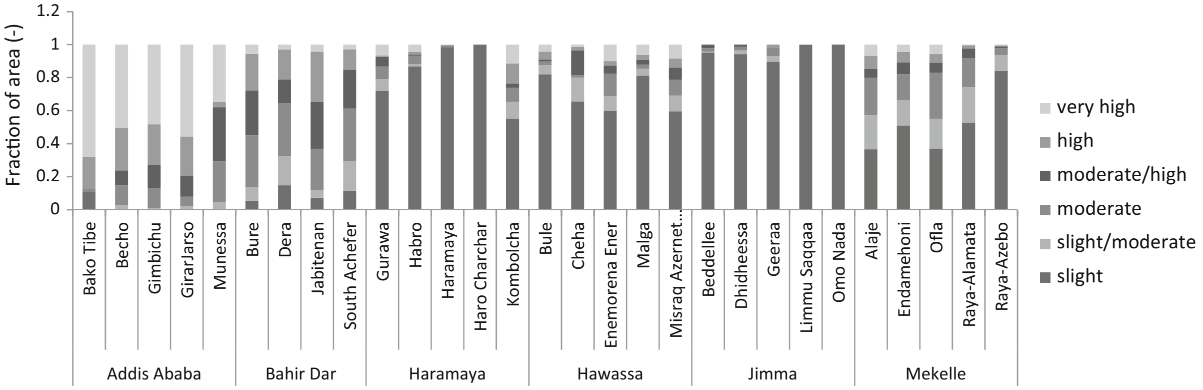


Fig. 7 Relative share of land within erosion classes: slight (<2.5 tonne/year), slight/moderate (2.5–5.0 tonne/year), moderate (5.0–10 tonne/year), moderate/high (10–15 tonne/year), high (15–25 tonne/year) and very high (>25 tonne/year)

nutrient depletion has increased over time as well as with yield levels (Fig. 8). The Ethiopian government is aware of this and responded with massive soil sampling campaigns to detect deficient nutrients though the EthioSIS project. This effort culminated in the establishment of fertilizer blending plants in the country to produce specific fertilizer blends targeted at the observed deficient nutrients. Notwithstanding the success of the EthioSIS project, this study showed that soil erosion accounted for about 50 % of the nutrient losses (Fig. 5). Hence, it is possible to argue that an effective soil restoration campaign should include soil and water conservation measures to combat erosion, improve on-farm nutrient use efficiency by promoting composting and mulching (and reduce competing claims for crop residues) in combination with targeted fertilizer recommendations that at least compensate for nutrient removal. Without such measures, soil nutrient depletion will continue and eventually soils will become exhausted.

Interpretation of soil nutrient balances and erosion rates

The nutrient depletion rates found in this study are commonly interpreted as 'mild'. However, even 'mild' depletion may become serious when prolonged over time. The classification of 'mild' is based on the comparison with previous studies (Table 6). Moreover, the results of this study showed that nutrient depletion increased over time and worsened with increasing crop yields. Consequently, the results are alarming and call for structural improvement of soil nutrient management practices in the highlands of Ethiopia. In general, previous studies performed at national level showed more negative soil nutrient balances compared to the results found in this study. To some extend these differences can be related to differences in spatial scales, i.e. system boundaries. Nutrient balances increase with increasing spatial scales, because losses remain within system boundaries when assessed at higher spatial scale. For instance, erosion is a major loss item at field level, but not at regional scale when the sediments remain within system boundaries.

Soil erosion equalled 8.3 ± 16.1 tonne ha^{-1} year^{-1}. This average can be interpreted as 'moderate' according to the classification of Beskow et al. (2009). Figure 7 shows the distribution of the estimated erosion rates over the different classes for each *woreda*. The vast majority (59 %) of the *woreda* average erosion rates was classified as 'moderate' with an estimated erosion rate between 5 and 10 tonnes per hectare per year. However, variability was high and severe erosion rates of more than 25 tonnes year^{-1} occurred, especially in the *woredas* within the Addis Ababa cluster (Fig. 7).

Data variability

Variabilities within the dataset were high, with standard errors often exceeding 100 % (Fig. 2). Partly, this is caused by the nature of topic; diverse agro-ecological conditions, socio-economic conditions and

Table 5 Input and outputs of N per balance entry per *woreda* (kg/ha/year) and standard deviations (n = 51–570)

Cluster	*Woreda*	Mineral fertilizer	Organic fertilizer	Biological fixation	Atmospheric deposition	Harvest	Removed crop residues	Leaching	Gaseous losses	Erosion
Addis Ababa	Bako Tibe	87.15 ± 86.55	6.865 ± 29.20	3.713 ± 1.200	3.273 ± 1.769	47.92 ± 54.67	1.657 ± 3.349	22.76 ± 17.19	11.23 ± 10.52	96.37 ± 81.02
	Becho	39.38 ± 39.31	1.650 ± 5.292	2.357 ± 0.916	5.865 ± 10.19	26.25 ± 22.47	2.851 ± 7.275	9.554 ± 8.554	3.504 ± 3.181	46.85 ± 25.56
	Gimbichu	90.53 ± 97.10	5.865 ± 12.49	2.980 ± 0.904	12.78 ± 32.87	52.55 ± 40.79	16.09 ± 23.03	30.61 ± 22.50	8.290 ± 7.519	110.0 ± 69.33
	GirarJarso	38.89 ± 74.43	9.105 ± 16.22	2.954 ± 0.963	16.30 ± 35.08	31.82 ± 38.62	4.758 ± 16.28	19.79 ± 16.91	4.607 ± 5.608	93.64 ± 70.62
	Munessa	20.44 ± 18.04	5.729 ± 14.43	2.829 ± 0.783	8.275 ± 17.72	36.50 ± 27.60	6.172 ± 13.89	20.33 ± 18.90	2.722 ± 1.929	71.67 ± 40.12
Bahir Dar	Bure	54.22 ± 47.58	3.603 ± 7.261	2.720 ± 0.467	4.294 ± 11.76	19.68 ± 18.84	2.835 ± 7.268	20.09 ± 7.718	4.958 ± 3.649	34.91 ± 20.56
	Dera	43.78 ± 41.80	1.311 ± 3.438	2.288 ± 0.985	1.995 ± 0.946	20.43 ± 15.31	1.033 ± 2.899	17.15 ± 8.018	3.847 ± 3.575	28.24 ± 22.47
	Jabitenan	57.89 ± 51.13	2.623 ± 6.052	3.323 ± 0.730	4.640 ± 8.483	17.97 ± 15.67	3.907 ± 9.379	21.78 ± 7.705	6.457 ± 5.141	33.22 ± 20.23
	South Achefer	57.34 ± 53.41	2.265 ± 5.436	3.138 ± 0.412	2.694 ± 1.691	16.26 ± 14.20	6.681 ± 9.584	25.15 ± 6.993	6.162 ± 4.972	31.28 ± 20.82
Haramaya	Gurawa	25.05 ± 34.54	6.521 ± 21.14	2.138 ± 0.783	2.236 ± 5.715	23.62 ± 28.76	9.956 ± 20.35	8.608 ± 5.236	2.868 ± 3.570	6.219 ± 16.60
	Habro	13.99 ± 25.46	2.228 ± 5.817	2.271 ± 0.842	3.069 ± 4.185	19.47 ± 22.74	4.438 ± 6.923	8.520 ± 5.702	1.685 ± 2.304	5.347 ± 22.05
	Haramaya	59.05 ± 63.10	16.85 ± 47.31	2.230 ± 0.796	1.876 ± 0.669	41.65 ± 46.08	11.13 ± 20.65	10.77 ± 7.346	6.013 ± 6.389	1.261 ± 8.610
	Haro Charchar	21.35 ± 23.21	10.25 ± 26.76	2.279 ± 0.698	1.925 ± 0.590	22.32 ± 22.79	6.251 ± 8.721	6.972 ± 3.201	2.782 ± 3.122	0 ± 0
	Kombolcha	43.95 ± 48.23	10.63 ± 25.17	2.346 ± 0.789	2.066 ± 1.475	25.29 ± 28.07	8.025 ± 18.07	10.77 ± 6.483	4.876 ± 4.817	13.77 ± 27.91
Hawassa	Bule	8.276 ± 40.07	9.756 ± 44.18	1.873 ± 1.161	1.701 ± 0.952	26.85 ± 68.51	1.452 ± 12.05	7.544 ± 8.236	1.797 ± 5.768	21.63 ± 58.23
	Cheha	33.16 ± 85.80	9.169 ± 50.59	1.541 ± 0.508	1.510 ± 0.494	26.96 ± 58.95	9.744 ± 45.59	7.637 ± 9.228	4.156 ± 10.44	15.61 ± 37.78
	Enemorena Ener	29.38 ± 73.97	15.57 ± 57.62	1.673 ± 1.100	1.509 ± 0.915	17.52 ± 42.00	3.922 ± 23.41	6.780 ± 8.323	3.336 ± 7.937	17.81 ± 40.50
	Malga	21.27 ± 74.73	11.24 ± 33.89	1.958 ± 1.185	1.776 ± 0.969	21.34 ± 50.68	3.821 ± 29.54	9.105 ± 9.428	3.525 ± 8.659	20.18 ± 52.11
	Misraq Azernet Berbere	27.28 ± 57.75	21.31 ± 62.91	1.600 ± 1.136	1.650 ± 1.390	22.34 ± 47.20	5.632 ± 36.08	8.446 ± 9.827	4.113 ± 8.485	15.76 ± 31.13
Jimma	Beddellee	17.28 ± 29.77	2.745 ± 12.51	4.776 ± 0.859	3.858 ± 0.687	16.59 ± 24.18	1.377 ± 3.242	48.35 ± 15.53	3.793 ± 4.057	3.230 ± 16.07
	Dhidheessa	26.16 ± 35.30	0.848 ± 3.038	4.643 ± 0.916	3.838 ± 1.173	24.98 ± 32.39	0.826 ± 4.671	42.67 ± 16.71	4.474 ± 4.225	4.298 ± 16.12
	Geeraa	23.44 ± 35.19	1.743 ± 6.836	4.609 ± 0.994	3.729 ± 0.798	19.32 ± 24.17	0.357 ± 1.431	53.47 ± 20.10	4.270 ± 4.073	7.822 ± 24.31
	Limmu Saqqaa	19.90 ± 29.80	0.639 ± 1.867	4.800 ± 0.637	3.883 ± 0.513	26.21 ± 33.41	0.955 ± 2.884	50.29 ± 15.10	3.923 ± 3.503	0.618 ± 3.488
	Omo Nada	24.54 ± 35.31	2.475 ± 7.050	4.874 ± 1.113	4.312 ± 3.610	23.09 ± 33.31	2.628 ± 5.749	47.88 ± 17.72	4.396 ± 4.320	0.436 ± 1.402
Mekelle	Alaje	44.20 ± 60.12	16.29 ± 45.75	2.345 ± 0.658	5.877 ± 12.79	31.13 ± 31.90	8.046 ± 15.63	14.31 ± 11.00	5.243 ± 6.484	19.25 ± 29.46
	Endamehoni	48.74 ± 70.29	8.454 ± 16.82	2.338 ± 0.760	3.352 ± 6.344	31.59 ± 34.09	7.963 ± 11.94	13.77 ± 8.833	5.134 ± 6.032	13.21 ± 21.11
	Ofla	41.91 ± 60.66	5.561 ± 11.30	2.438 ± 0.777	3.426 ± 5.894	42.43 ± 40.93	9.666 ± 17.07	12.45 ± 9.414	3.931 ± 4.561	17.34 ± 29.15
	Raya-Alamata	11.91 ± 35.72	3.785 ± 15.93	2.002 ± 0.787	2.482 ± 6.315	19.53 ± 29.83	3.715 ± 6.100	10.19 ± 7.858	1.502 ± 2.778	10.54 ± 18.49
	Raya-Azebo	18.62 ± 61.79	7.167 ± 38.85	2.261 ± 0.671	3.438 ± 7.764	15.76 ± 31.73	3.889 ± 9.806	14.35 ± 11.06	2.904 ± 7.316	7.226 ± 10.84

Table 6 Nutrient balances of CASCAPE and previously reported values for Ethiopia (kg ha^{-1})

References	Farming system	N	P	K
This study	Mixed, smallholder	−24	9	−7
Stoorvogel and Smaling (1993)	National level	−47	−7	−32
Elias (1998); Aticho et al. (2011)	Enset—coffee (Wolaita)	+3	+5	n.d.
Haileslassie et al. (2006)	Cereal (Central Ethiopia)	−50	−4	−64
Haileslassie et al. (2006)	Enset (Guraghe highlands)	+68	+7	−23
Haileslassie et al. (2006)	Cereal (western Ethiopia)	−46	+3	−75
Asefa et al. (2003)	Low potential Tigray (Atsbi)	−65	−6	−34
Elias (2002)	National average	−92	+5	−49

n.d. no data

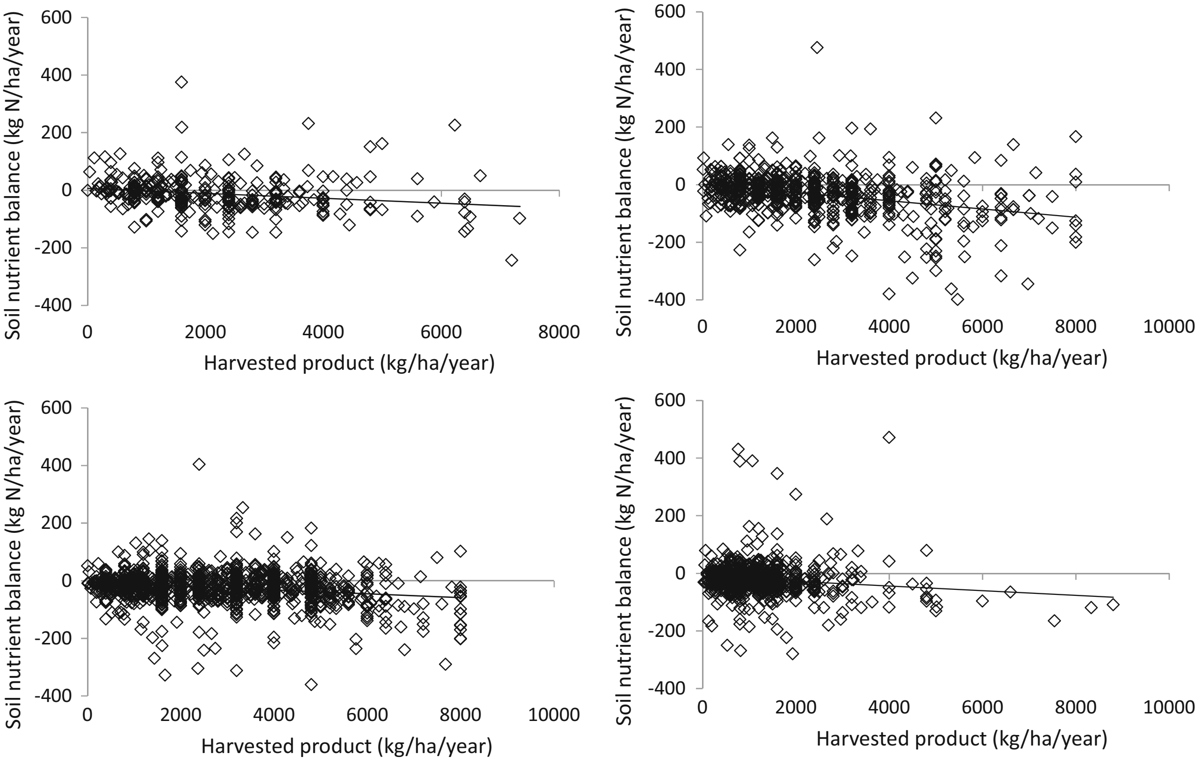


Fig. 8 Relation between yields and soil N balances for barley (*upper left*), wheat (*upper right*), maize (*below left*) and teff (*below right*). *Each symbol* represents a unique field-season combination. *Solid line* shows linear regression

personalities of farmers cause high variabilities in farm management, including nutrient management. High variability between soil nutrient balances within a specific region was confirmed by Elias (2002) and Aticho et al. (2011) who found considerably variabilities in soil nutrient balances across socio-economic groups and agro-ecological zones in Southern and Western Ethiopia, respectively. For another part, the variability is caused by biases in yield estimations by local enumerators and farmers. In this study, flows of nutrient inputs and outputs were estimated by the farmers and local enumerators. Although this approach may have contributed to biases in our dataset, it also gives a genuine reflection of farmers' appreciation of nutrient flows. Moreover, the high number of data records (6944 records in total, each record representing a unique plot-season combination) compensates for the relatively high variability.

We tried to relate soil nutrient balances to farm and farmer characteristics like size of the farm, age and education level of the household head etc., but could not find convincing relations. Contrarily, Haileslassie et al. (2007) found that environmental conditions, farming systems (e.g. crop selection), access to resources (e.g. land, livestock and fertilizer) and smallholders' source of off farm income determined the magnitude of nutrient fluxes.

Context specific interventions

This study shows that, at present, soil fertility decline in the highlands of Ethiopia is continuing and, on average, is worsening. Continuing soil degradation is a serious threat to future food security. Bindraban et al. (2012) emphasised that a comprehensive approach is needed to assess both extent and impact of soil degradation interlinking various scales. To effectively combat soil nutrient depletion, various spatial scales should interact to link depletion (rural) areas with accumulation (urban) areas. Notably, depletion and accumulation of nutrients (the polarization of the nutrient system) expresses at several spatial scales: organic wastes pile up at the homestead fields, but also at the city borders and at the global level where developed countries experience the environmental hazards of superfluous nutrients through eutrophication while developing countries are struggling to maintain and, preferably, increase food production. In fact, these are two sides of the same coin caused by unbalanced nutrient management at various spatial scales. According to Dietz et al. (2012), urbanization goes hand in hand with globalization and population growth. Although current urbanization level in Africa is only 36 %, this number is rapidly increasing because of population growth and rural–urban migration. Many Africans combine a rural and an urban existence, others move from rural areas to small towns and then to Africa's booming cities. These trends may have serious consequences for nutrient polarization and may lead to increased soil nutrient depletion in the production sites when nutrient removal is not sufficiently addressed. Recycling of organic waste streams is a potential way out, but requires willingness, legislation and investment, all being limited in many developing countries. At the same time, Nigussie et al. (2015) found that less than about 10 % of manure and crop residues available to smallholder farmers in Ethiopia was applied to soils, indicating that re-use efficiency can be largely improved at the farm level.

Erosion was a key determinant of the negative nutrient balances emphasizing the need for improved soil and water conservation measures at farm and at watershed level. Current efforts on increased inputs like blended mineral fertilizers are a step in the good direction, but to really halt and reverse soil fertility decline, organic fertilizer application and soil and water conservation (SWC) measures should be an integral part of the intervention strategy.

Halting the current trend of soil nutrient depletion will remain a major challenge and needs context specific solutions. Farmers (and donors) look for immediate, or at least short term effects. Yirga and Hassan (2010) found that smallholder farmers tend to discount the future at higher rates leading to overexploitation of soil nutrients, whereas soil conservation or restoration efforts become effective only at the medium or long term. Tenure security is a crucial element to overcome the costs of time dimensions related to soil management.

Conclusions

Nutrient balances in the highlands of Ethiopia, typically the high potential areas for agricultural production are currently exposed to severe nutrient depletion. Yet, agricultural production in this area is increasing which benefits farmers livelihoods and contributes to food security of the country as a whole, but at the expense of the natural resource base. To maintain the current increase in food production, the trade-offs towards soil nutrient depletion need to be counterbalanced by improved soil management. Erosion is a key determinant of the negative nutrient balances emphasizing the need for improved soil and water conservation measures at farm level and at catchment level. It was, therefore, recommended that an effective strategy to increase the productive capacity of land in the studied *woredas* include targeted soil and water conservation measures and improved integration of organic matter management with mineral fertilizer application.

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