Soil Fertility in Relation to Slope Position and Agricultural Land Use: A Case Study of Umbulo Catchment in Southern Ethiopia

Awdenegest Moges · Nicholas M. Holden

Abstract A study was conducted in southern Ethiopia to evaluate the nutrient status on smallholder farms with respect to land use class (garden, grassland, and outfield) and slope position (upper, middle, and lower). Soil physical and chemical properties were quantified using soil samples collected at two depths (0–15 and 15–30 cm). Available phosphorous was significantly different among the three land use classes. However, organic carbon and total nitrogen were lower in the outfield compared to the garden and grass land but not significantly different. The lower than expected nutrient status of the garden and grassland, which receive almost all available organic supplements, was attributed to the overall low availability of these inputs. Similarly, pH and cation exchange capacity were not significantly different among the different land use classes. However, the sum of the exchangeable cations was significantly higher in the garden compared to the outfields. Comparison at landscape level revealed that the sand fraction was significantly greater, whereas the silt fractions were significantly smaller, on the lower slopes relative to the middle slopes. Moreover, the organic carbon, total nitrogen, cation exchange capacity, Ca, and Mg values were significantly less on lower slopes than upper and middle slopes. Perhaps this is because of leaching and the effect of deposition of coarser sediments from the prevailing gully system. Overall, the fertility of the soil was adequate for supporting smallholder farming, but consideration must be given to reducing pressure on the land resources, addressing erosion problems, and providing a line of credit for purchasing inputs.

Keywords Land use class · Food insecurity · Slope position · Soil fertility · Sustainability · Ethiopia

The concept of soil degradation encompasses soil erosion, fertility decline, and associated changes in the physical properties of soils. Soil degradation can be both the cause of and a consequence of land cover and land use change. In order to get a clear picture of the degradation status of an area, all components of soil degradation need to be addressed. Previous work in the Umbulo Catchment, southern Ethiopia, focused on farmer perception of soil degradation (Moges and Holden 2007) and on major gully erosion features in the catchment (Moges and Holden 2008). In Ethiopia soil fertility studies have been conducted at the national and region level relating to land use (Haileselassie and others 2005) and at the farm level (Haileselassie and others 2006; Elias and others 1998). The present work addresses the soil fertility status of agricultural lands in a catchment and associated differences in soil properties. It further contributes to the knowledge of soil degradation and its relationship with food security by evaluating soil fertility of agricultural land at the farm and catchment scale and placing the results within the framework of known farmer perception, erosion processes, and land use class at the farm scale.

At the regional scale in Ethiopia fertility studies have indicated negative trends, with depletion rates of 122 kg ha^{-1} year^{-1} for nitrogen, 13 kg ha^{-1} year^{-1} for phosphorous, and 82 kg ha^{-1} year^{-1} for potassium being reported

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(Haileselassie and others 2005). However, the same study estimated that in southern Ethiopia, unlike other regions with similar levels of agricultural management, a slower decline in fertility status was occurring than elsewhere in the country. Studies of soil quality after land uses change in the highlands of Ethiopia (Bewket and Stroosnijder 2003; Lemenih and others 2004; Negassa and Gebrekidan 2004) reported that forest and shrub lands had higher fertility compared to grass and cultivated areas, and variations in fertility status call for different policy options and fine-tuning of soil improvement recommendations (Bewket and Stroosnijder 2003). Elsewhere similar results have also been reported from China (Wang and others 2001). However, the above-mentioned research has tended to ignore the variation found within a farm due to differences in land use.

Farmers in Umbulo catchment perceive a decline in soil fertility on their farms (Moges and Holden 2007). No data are available to identify whether this perceived degradation of the soil is different under the different land use classes. Knowledge about this situation would permit fine-tuning of the possible interventions that may be recommended in the area to improve food security. Furthermore, as Umbulo catchment is characterized by downslope gully development and deposition areas on the lower slopes (Moges and Holden 2008), the erosion/deposition processes have been identified by farmers as indicators of soil fertility status (Moges and Holden 2007). However, the extent of this process as a factor affecting soil degradation has not been quantified. The effect of slope position on nutrient status has been studied in northern Ethiopia (Wolde and others 2007) and southern Ethiopia (Alemayehu 2007), where it was found that upslope areas had lower nutrient concentrations than lower areas as a result of erosion of top soil and subsequent deposition on lower slope positions. Similar findings have also been reported in China (Fu and others 2004; Wang and others 2001). Gregorich and others (1998) reported progressive organic carbon losses in upslope shoulder slope positions, while lower slope positions and level depressions undergo organic carbon accumulation, which is attributed to erosion and depositional processes. On the other hand, Hao and others (2002) found an insignificant difference in soil organic carbon between upper and lower slope positions. Tillage erosion also plays an important role, causing soil quality variation in a landscape, as it contributes to the removal and redistribution of topsoil. On the Chinese Loess Plateau soil movement by tillage has been found to control the spatial patterns of soil quality on terraced and cultivated hillslopes (Li and Lindstrom 2001). Walle and Sims (1999) reported a decreasing fertility gradient downslope in naturally formed terraces as a result of deposition of eroded sediment. In general the effect of deposition on lower slopes is dependent on whether the material is nutrient enriched or depleted.

Studies to investigate the nutrient status of farm units are rare in Ethiopia. Moreover, because land management on a farm is variable depending on local customs, the area available, and the resources at the disposal of the farmers, it is not possible to take reported data from other regions to assess the situation in Umbulo catchment. Improving soil fertility management among smallholder farmers is widely recognized as a critical aspect in addressing food insecurity and poverty. For this work, we hypothesized that soil fertility and physical properties would vary by land use class (garden, grassland, and outfields) and relative slope position in the catchment (upper, middle, and lower). The objective of the study was to quantify soil fertility at different slope positions and under the three management practices used on farms in the Umbulo catchment, and to establish whether there were meaningful differences that could contribute toward improved management of the agricultural land in the catchment.

Materials and Methods

Description of the Umbulo Catchment

Umbulo catchment (38°17′E, 7°01′N) is situated in the rift valley in the Sidama region, southern Ethiopia (Fig. 1). The average annual rainfall for the area is 1067 mm. The rain falls in a bimodal pattern of two rainy seasons: the short rains (*Belg* season) between March and May (peak in May) and the long rains (*Kremt* season) between June and October (peak in September). The dry season occurs between November and February. The area is known for experiencing great variability in the timing and volume of rainfall, and this has caused drought and crop failure (Debub University 2003). The catchment is categorized as one of the food-insecure areas in the region and is receiving food assistance in exchange for community work such as soil and water conservation activities. The moisture deficiency due to erratic rainfall regime and recurrent drought are environmental contributions to the overall food insecurity. Family size (average eight per household) and fragmented land holding with an average size of 0.75 ha (Table 1) also contribute to food security issues.

The topographic setting of Umbulo catchment is shown in Fig. 1. The upper, steep-sloped badland area of the catchment lacks vegetation and is currently under enclosure for grass production and tree protection to try to promote ground cover and reduce erosion. The remaining area of the catchment is under cultivation by smallholder subsistence farmers. This area is dissected by large gullies that run down the slope, the lower part of which is a
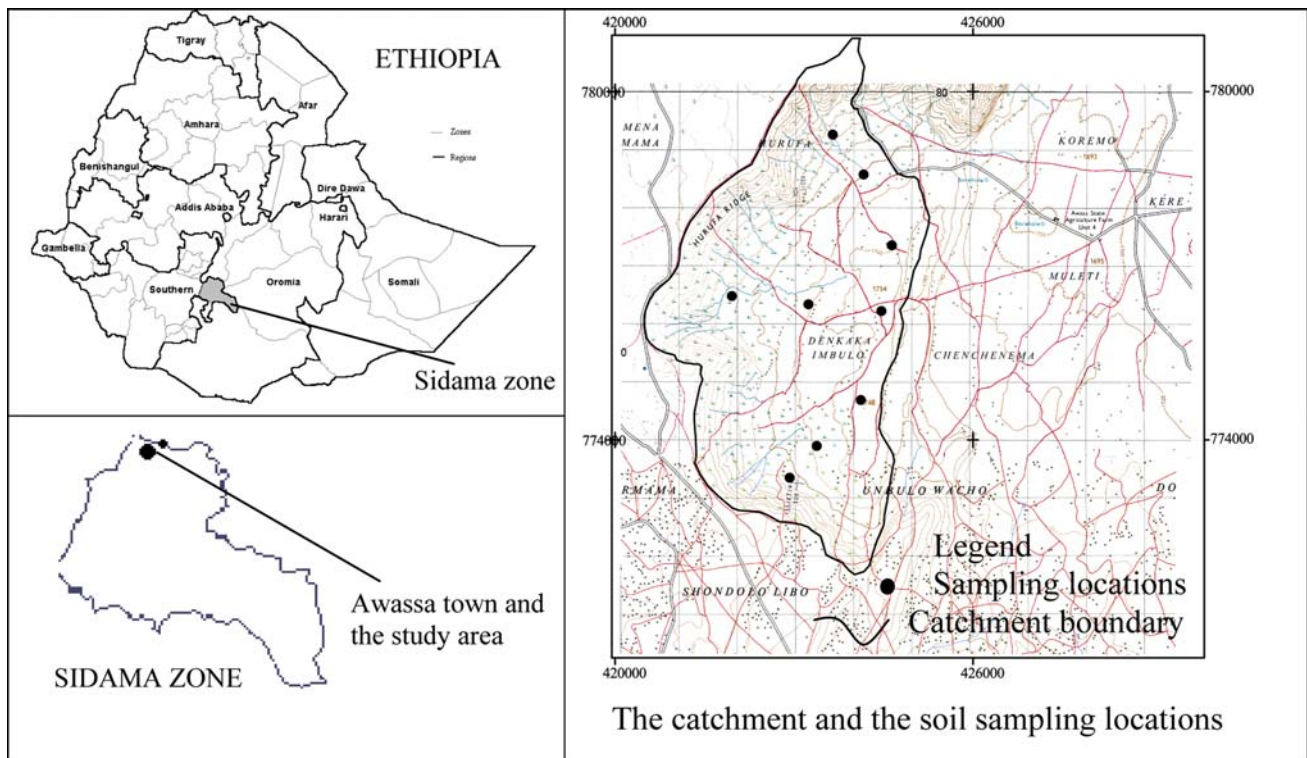
Fig. 1 The study area and the locations of the sampled farms in the catchment

Table 1 Households and land characteristics in the Umbulo catchment (partly adapted from Moges and Holden 2007)

Characteristic	
Mean house hold family size	8.3
No. of livestock	2.56 TLU[a]
No. of farms studied	9
Range land per household	0.25–2.0 ha
Garden	0.07–0.25 ha
Grass area	0.02–0.10 ha
Farm field	0.25–2.0 ha
Range	
Upper slope	8–11%
Middle slope	3–5%
Lower slope	1–2%

[a] TLU (tropical livestock unit) is a convenient method for quantifying a wide range of different livestock types: 1 TLU = 250 kg of cattle live weight

depositional area. These gullies developed rapidly over the last 30 years, with the average rate of soil loss ranging from 11 to 30 tons ha^{-1} year^{-1} (Moges and Holden 2008).

Land Use in the Catchment

Agriculture in the area is characterized by subsistence mixed crop-livestock farming, with very limited minimum cash crop and livestock production. The main sources of nutrient inputs for maintaining soil fertility are organic materials such as manure, household wastes, and some crop residues. Urea and diamonium phosphate (DAP) are also applied when farmers can afford to buy them. The use of nutrient inputs varies by land use class on the farm. A farm in each household in Umbulo catchment (and more widely in the Sidama region) can be described as having three distinct land use classes.

The *garden* is close to the homestead and is mainly planted with *Enset* (*Enset ventricosum*), *Khat* (*Catha edulis*), vegetables, and perhaps sugarcane. It receives available household waste, plant residues, and manure to maintain fertility. The garden is a system with minimum dependence on external inputs such as fertilizer (Tesfaye 2005). The shortage of organic matter and the importance of *Enset* as a food source are the main reasons for the restricted use of manure mainly to the garden, though labor scarcity and possible loss by erosion from outfields are also important (Tilahun and Mulugeta 2005). In Kenyan smallholding farms, similar management of organic resources has been reported (Murage and others 2000). In food-insecure areas, the garden plays a major role (particularly during drought) and farmers' preference for allocating inputs to the garden is justified. In Umbulo catchment *Enset* is used as a subsidiary crop, introduced 30 to 40 years ago from the highland areas, where it has been used for centuries (Kippie 2002). In southern Ethiopia the

garden-based *Enset* farming system supplies 25–85% of food demand when grown as either a subsidiary crop or a major food crop, respectively (Tsegaye 2002).

The area in front of the homestead is kept as *grassland*, which is used for controlled tethered grazing most of the time, as there is little common grazing land in the catchment. Apart from the dung and urine from the grazing animals, farmers apply as much additional manure as is available to the grassland area to promote grass growth to support the animal feed requirement. In other parts of the region such fields do not receive inputs, but in Umbulo catchment farmers prefer to apply manure to grasslands because of the scarcity or absence of common grazing in the catchment. Other sources of feed for their animals are *Enset* leaves, crop residue, and strips along gully border lines.

The *outfields* are located farther from the homestead and used mainly to grow maize and beans by intercropping, and these receive no manure or household wastes because of the distance from the homestead (requiring more labor), the scarcity of these inputs, and the high risk of loss of the organic matter due to erosion. In Umbulo catchment, the use of inorganic fertilizer is very low because farmers are unable to pay or get credit (Moges and Holden 2007). In the Wolaita area (southern Ethiopia) it has been estimated that inorganic fertilizer contributes as little as 20% to soil fertility and that cropped fields experience very low soil fertility status as a result (Tilahun and Mulugeta 2005).

The Experimental Setup

The cultivated area in the catchment covers an elevation range of 120 m, and it was divided into three sections—upper, middle, and lower slopes—according to relative elevation and topography. The transect line, sampling positions, and slope ranges are given in Table 1 and Fig. 1. The upper and middle sections have large gully erosion features and the lower section is a depositional area. Within each slope section, three sample areas were selected, giving a total of nine slope segments. With the help of topographic maps and aerial photographs, farms that had been functioning for at least 30 years were selected in each of the nine slope segments. For each farm three land use classes were identified (garden, grassland, and outfield), thus a total of 27 sampling sites were selected for soil sampling under different land uses and slope positions. The soil of the study area is a dark-yellowish brown, loam, well drained and developed from volcanic ash parent material. It is classified as Mollic Andosol according to the FAO soil classification (FAO 1998).

Soil Sampling and Analysis

For each sample site (27 in total), nine soil samples were randomly collected from surface 0 to15 and 15 to 30 cm

down the soil profile. The samples from each depth were mixed thoroughly in a plastic bucket to form a composite sample. Approximate 1 kg of composite sample was then put into two plastic bags, secured, and labeled for transport to the laboratory. The soil samples were air-dried, grounded with a mortar and pestle, and passed through a 2-mm sieve before laboratory analysis. The soil analysis was conducted at the National Soil Research Centre of the Institute of Agricultural Research following standard laboratory procedures and soil analysis methods (NRC 2000). Organic carbon (OC) was determined by the Walkley-Black oxidation method (Allison 1965). Total nitrogen (TN) was determined using the Kjeldahl digestion method (Bremmer 1965), and available phosphorous (AP) was determined using Olsen's extraction method (Olsen and Dean 1965). The exchangeable Ca and Mg were measured by atomic absorption spectrophotometry, and the exchangeable K and Na by flame photometer (Rich 1965). The cation exchange capacity (CEC) was determined by extraction with sodium acetate and ammonium acetate (Chapman 1965). Soil pH was determined at a 1:2.5 soil-to-water ratio and particle size analysis was determined by the hydrometer method (Day 1965).

Additional samples were also taken from each sample site at 0 to 15 and 15 to 30 cm for porosity and bulk density measurement. Bulk density was determined by the core method (Blake and Hartge 1965), and total porosity by the water displacement method. Undisturbed samples were collected using a core sampler. The samples were then saturated for 1 to 2 days in a water-filled trough. They were weighed before and after oven drying at 105°C for 24 h.

Statistical Analysis

Slope position (upper, middle, and lower) and land use class (garden, grassland, and outfield) were used as independent variables (factors), and the soil parameters as the dependent variables. The significance of the mean difference in soil properties by land class and slope position was tested using a two-way ANOVA (at $p < 0.05$), and then a multiple-comparison test was performed to identify which of the factors were statistically different (at $p < 0.05$) using the Tukey HSD (honestly significant difference) test. These were carried out using the GLM procedure in SPSS release 11 (SPSS Inc. 2001).

Results and Discussion

The soil fertility and physical property data averaged by slope position and land use class are presented in Tables 2 and 3. The mean values of the soil properties differed by land use class and slope positions in many cases (values underlined in Table 3). There was no significant interaction effect between slope position and land use class. This

Table 2 Mean ($n = 3$) soil properties (0- to 15- and 15- to 30-cm depths) at three slope positions under the three land use classes on farms in Umbulo catchment, southern Ethiopia

Soil parameter	Depth (cm)	Grass			Garden			Field		
		Upper	Middle	Lower	Upper	Middle	Lower	Upper	Middle	Lower
Sand (%)	0–15	46	40	57	42	30	52	46	44	49
	15–30	48	44	54	42	34	50	43	44	40
Silt (%)	0–15	35	41	27	39	47	31	35	35	30
	15–30	33	37	31	37	41	31	35	33	45
Clay (%)	0–15	19	19	16	20	23	17	20	21	21
	15–30	20	18	15	20	25	19	22	23	15
BD (g cm^{-3})	0–15	1.07	1.02	1.09	0.92	0.87	0.90	0.99	0.92	1.02
	15–30	1.00	1.00	1.07	0.95	0.95	0.95	1.07	1.04	0.99
Porosity (%)	0–15	54	54	49	59	61	57	55	59	51
	15–30	55	54	50	55	54	54	51	51	52
OC (%)	0–15	3.36	3.08	1.60	2.87	3.29	1.66	2.62	2.07	1.16
	15–30	2.06	1.77	1.16	1.90	2.17	1.00	1.58	1.37	0.98
TN (%)	0–15	0.27	0.25	0.11	0.22	0.25	0.16	0.18	0.16	0.08
	15–30	0.14	0.15	0.10	0.15	0.13	0.12	0.14	0.08	0.07
AP (ppm)	0–15	8.18	21.63	11.39	21.72	32.35	35.44	6.90	9.53	7.96
	15–30	3.85	11.09	7.87	10.70	22.28	11.69	3.39	6.62	5.79
PH	0–15	7.2	7.4	7.7	7.3	7.7	7.8	7.1	7.2	7.4
	15–30	7.4	8.0	8.0	7.2	7.5	7.8	7.1	7.2	7.7
CEC (meq/100 g)	0–15	25.73	27.53	16.13	28.47	31.00	19.60	25.53	23.87	20.20
	15–30	22.87	21.27	31.07	24.87	27.13	18.40	23.53	22.93	20.47
Na$^+$ (meq/100 g)	0–15	0.38	0.28	0.38	0.32	0.45	0.61	0.28	0.31	0.39
	15–30	0.65	0.66	0.56	0.53	0.55	0.63	0.52	0.52	0.60
K$^+$ (meq/100 g)	0–15	5.15	7.48	5.55	4.78	6.98	6.96	3.17	3.67	3.40
	15–30	3.76	5.80	5.18	4.20	5.74	4.24	2.34	2.88	3.44
Ca^{2+} (meq/100 g)	0–15	11.09	11.20	7.37	13.52	15.17	8.88	12.10	12.27	9.36
	15–30	9.68	10.38	7.78	11.11	12.44	8.33	11.05	12.48	11.48
Mg^{2+} (meq/100 g)	0–15	1.84	1.95	1.04	1.89	2.25	1.32	1.34	1.75	1.18
	15–30	1.59	1.62	1.34	1.53	1.86	1.15	1.53	2.03	1.37
Total exchangeable Cations (meq/100 g)	0–15	18.47	20.90	14.34	20.52	24.84	17.77	16.88	18.01	14.33
	15–30	15.67	18.46	14.86	17.38	20.59	14.35	15.45	17.90	16.89

suggests that there is no slope position that has resulted in differences within the land use classes, and vice versa. The post hoc Tukey HSD test results (Table 4) indicated which land use class and/or slope position was significantly different from the others in each case.

Soil Physical Properties as Influenced by Land Use Class

The soil bulk density under the different land use classes was generally low, ranging from 0.90 for the garden to 1.06 for the grassland, and was associated with porosity ranging from 52% to 57%. Significant differences in bulk density and porosity were obtained due to land use class ($p < 0.05$), and multiple-comparison test revealed that the differences were mainly between the grassland and the garden. The grassland had a higher bulk density and a lower porosity, which was attributed to compaction by animals and humans, while tillage in the garden maintained a low bulk density and a higher porosity. The outfield had values between those of the garden and those of the grassland. Cultivation of the outfield lowered bulk density and raised porosity compared to grassland, but the effect did not extend to 30 cm as was the case for the garden. The texture of the soils was loam and there was no significant difference in the clay, sand, or silt content by land use class, which suggested that any difference in the nutrient status of the different land use classes of the farms could probably be attributed to management rather than soil variation. Texture is a soil property that will not be changed by management in a short period of time.

Table 3 Mean ($n = 9$) soil properties (0- to 15- and 15- to 30-cm depths) for the three slope positions and the three land use classes on farms in Umbulo catchment, southern Ethiopia

Soil parameter	Depth (cm)	Land management			Slope position		
		Garden	Grassland	Outfield	Upper	Middle	Lower
Sand (%)	0–15	41	48	46	<u>44</u>	<u>38</u>	<u>53</u>
	15–30	42	49	42	44	41	48
Silt (%)	0–15	39	34	33	<u>36</u>	<u>41</u>	<u>30</u>
	15–30	36	34	38	35	37	35
Clay (%)	0–15	20	18	21	19	21	18
	15–30	21	18	20	<u>21</u>	<u>22</u>	<u>16</u>
BD (g cm^{-3})	0–15	<u>0.90</u>	<u>1.06</u>	<u>0.98</u>	0.99	0.94	1.00
	15–30	<u>0.95</u>	<u>1.03</u>	<u>1.03</u>	1.01	1.00	1.00
Porosity (%)	0–15	<u>59</u>	<u>52</u>	<u>55</u>	<u>56</u>	<u>58</u>	<u>52</u>
	15–30	54	53	51	54	53	52
OC (%)	0–15	2.61	2.68	1.95	<u>2.95</u>	<u>2.82</u>	<u>1.47</u>
	15–30	1.69	1.66	1.31	<u>1.85</u>	<u>1.77</u>	<u>1.05</u>
TN (%)	0–15	0.21	0.21	0.14	<u>0.23</u>	<u>0.22</u>	<u>0.12</u>
	15–30	0.13	0.13	0.10	0.14	0.12	0.10
AP (ppm)	0–15	<u>29.84</u>	<u>13.74</u>	<u>8.13</u>	12.27	21.17	18.26
	15–30	<u>14.89</u>	<u>7.60</u>	<u>5.27</u>	<u>5.98</u>	<u>13.33</u>	<u>8.45</u>
pH	0–15	7.6	7.4	7.2	<u>7.2</u>	<u>7.4</u>	<u>7.7</u>
	15–30	7.5	7.8	7.3	<u>7.2</u>	<u>7.6</u>	<u>7.8</u>
CEC (meq/100 g)	0–15	26.36	23.13	23.20	<u>26.58</u>	<u>27.47</u>	<u>18.64</u>
	15–30	23.47	25.07	22.31	23.76	23.78	23.31
Na$^+$ (meq/100 g)	0–15	0.46	0.35	0.32	0.33	0.35	0.46
	15–30	0.57	0.62	0.55	0.57	0.58	0.59
K$^+$ (meq/100 g)	0–15	<u>6.24</u>	<u>6.06</u>	<u>3.41</u>	<u>4.37</u>	<u>6.05</u>	<u>5.30</u>
	15–30	4.72	4.91	2.89	3.43	4.81	4.28
Ca^{2+} (meq/100 g)	0–15	<u>12.53</u>	<u>9.89</u>	<u>11.24</u>	<u>12.24</u>	<u>12.88</u>	<u>8.54</u>
	15–30	10.63	9.28	11.67	10.61	11.77	9.20
Mg^{2+} (meq/100 g)	0–15	1.82	1.61	1.42	<u>1.69</u>	<u>1.98</u>	<u>1.18</u>
	15–30	1.52	1.52	1.64	<u>1.55</u>	<u>1.84</u>	<u>1.29</u>
Total exchangeable cations (meq/100 g)	0–15	<u>21.05</u>	<u>17.90</u>	<u>16.40</u>	<u>18.62</u>	<u>21.25</u>	<u>15.48</u>
	15–30	17.44	16.33	16.74	16.17	18.98	15.36

Note: Underlined values indicate a significant difference ($p < 0.05$)

Organic Carbon, Available Phosphorus, and Total Nitrogen by Land Use Class

Although the average soil OC of the grassland was slightly higher than that of the garden and the outfield, the difference was not significant, and in all cases the values were low (Table 5). TN followed the same trend as OC (which combine as a proxy for organic matter content and status of the soil) and, likewise, showed no significant difference by land use class and could also be regarded as low (Table 5). The garden and grassland soils were expected to contain a greater OC and TN content than that of the outfields because (i) farmers apply organic wastes on the grassland and garden, (ii) animals provide dung and urine deposition (particularly in the grassland), (iii) erosion is more common in the outfield areas, (iv) residues are cleared for fuel and animal feed from the outfields, and (v) intensive cultivation in the garden and the grassland affect mineralization of organic matter (Sanchez 1976). Limenih and others (2004), in their study of Andosols soil in the central Ethiopian rift valley also suggested mineralization of organic matter as a factor in decreasing the organic matter content of an intensively cultivated mechanized farm compared to traditional farming. The lower than expected OC and TN levels in the garden and grassland could possibly be explained by the poor resources available to the farmers in Umbulo catchment. Each household owns a few animals and these are the major source of additional

Table 4 Multiple-comparison post hoc Tukey HSD test ($p < 0.05$) for soil properties (0- to15-cm depth) with a significant difference ($p < 0.05$) by (a) land use class and (b) slope position

Soil property	Significant contrast		p
(a) By land use class			
BD (g cm^{-3})	Grass	Garden	0.010
Porosity (%)	Grass	Garden	0.006
AP (ppm)	Grass	Garden	0.002
	Garden	Field	0.000
K$^+$ (meq/100 g)	Grass	Field	0.000
	Garden	Field	0.000
Ca^{2+} (meq/100 g)	Grass	Garden	0.022
Total exchangeable cations (meq/100 g)	Grass	Garden	0.046
	Garden	Field	0.003
(b) By slope position			
Sand (%)	Middle	Lower	0.005
Silt (%)	Middle	Lower	0.007
Porosity (%)	Middle	Lower	0.023
OC (%)	Upper	Lower	0.003
	Middle	Lower	0.006
TN (%)	Upper	Lower	0.037
	Middle	Lower	0.046
pH	Upper	Lower	0.034
CEC (meq/100 g)	Upper	Lower	0.001
	Middle	Lower	0.000
K$^+$ (meq/100 g)	Upper	Middle	0.015
Ca^{2+} (meq/100 g)	Upper	Lower	0.002
	Middle	Lower	0.000
Mg^{2+} (meq/100 g)	Upper	Lower	0.061
	Middle	Lower	0.003
Total exchangeable cations (meq/100 g)	Upper	Lower	0.046
	Middle	Lower	0.000

Table 5 Broad rating for soil parameters: critical values and ranges that could be used for general purposes, compiled and adapted from Landon (1984)

Nutrient	Critical value
OC	
High	>10%
Medium	4–10%
Low	<4%
TN	
High	>0.5%
Medium	0.2–0.5%
Low	<0.2%
AP	
Adequate, low-demand crop	>8 ppm
Adequate, high-demand crop	>21 ppm
CEC	
Minimum value	8–10 meq/100 g soil
Indicates infertility	<4 meq/100 g soil
K	
High, sufficient	>0.4–0.5 meq/100 g soil
Low, will respond to fertilizer	<0.2 meq/100 g soil
Ca	
High value	>10 meq/100 g soil
Fertilizer will improve growth	<0.2 meq/100 g soil
Mg	
High, sufficient	>0.5 meq/100 g soil
Medium	0.2–0.5 meq/100 g soil
Fertilizer required	<0.2 meq/100 g soil
Na	
Used as boundary between sodic and nonsodic soils	ESP[a] = 15%

[a] Exchangeable sodium percentage: the ratio of exchangeable sodium to the cation exchange capacity expressed as a percentage. ESP level is very dependent on the type of crop: for very sensitive crops boundary values are as low as 2–10%; for tolerant crops, >60%

fertility for the soil. Moreover, farmers cannot afford to purchase inorganic fertilizers.

The AP was significantly higher in the garden soils compared to the grassland and the outfield (Table 4). The major cause of the differences could be the application of cattle dung and household wastes for soil improvement to the garden and grassland area compared to the outfield. The outfield gets no P from inorganic fertilizers or from manure. Despite this, the AP is sufficient (Landon 1984) for all the land use class types provided that low-P-demand crops are grown in the field (Table 5), which is in agreement with previous reports (Hailesellasie and others 2006; Elias and Scoones 1999).

pH, Cation Exchange Capacity, and Exchangeable Cations by Land Use Classes

The pH of the soils in the garden was highest (7.6), followed by that of the grassland (7.4) and outfield (7.2), but there was

no significant difference due to land use class. The higher pH values of the garden and grassland soils were probably the result of manure application. Nutrient availability is optimal when the pH is close to neutral, and acidic soils tend to limit nutrient availability (Brady and Weil 1996), so the situation in Umbulo catchment is favorable for crop production.

CEC is used as an overall assessment of the potential fertility of a soil and to assess the possible response to fertilizer application. The CEC of the soils was rated medium to high (Landon 1984), being in the narrow range of 23 to 26 meq/100 g of soil, and can be regarded as well above adequate levels (Table 5). The highest CEC was found in the garden, but there was no significant difference among the three land use classes. The lack of a significant

difference in clay content, combined with the CEC data, suggests that there is no inherent soil fertility difference among the soils of the land use classes and that management is the main factor causing differences in the soil fertility for different areas of the farms.

There was a significant difference in the sum of exchangeable cations (Ca + Na + Mg + K) due to land use class, and there were significant differences in K and Ca among the different land use classes. The garden soil had the highest exchangeable cations, whereas the field exhibited the lowest. As in most agricultural soils, Ca was the dominant cation (Wild 1993) in the exchangeable complex, followed by K and Mg. The garden soil had significantly higher Ca than the grassland but there was no significant difference compared to the outfield. The Ca content of the outfield was higher than the grassland but no significant difference was determined (Table 4). Generally, the concentrations of exchangeable cations were in excess of minimum fertility requirements (Table 5). The exchangeable Mg, K, and Na values were higher in the garden soil, followed by those of the grassland and then the outfield. The Tukey HSD test revealed that the outfield had significantly lower K than the grassland and garden. However, the exchangeable K value in the outfield was high compared to the level of 0.4 meq/100 g of soil required for fertilizer supplement (Table 5). Generally K is considered to be sufficiently available in Ethiopian soils, as most Ethiopian soils are derived from parent materials rich in feldspar (Mesfin 1998). The significant difference in K may be accounted for by the difference in the type of crop/vegetation growing in the different land use classes, and the outfield could not be considered to be deficient in K. The Na content was the smallest component of the exchangeable cations. The exchangeable sodium percentage (ESP) was well below the critical boundary defining sodic soils (Table 5).

Overall the garden and grassland areas of the farms in Umbulo catchment had better nutrient status than the outfield areas. Favoring the garden with soil amendments is important because these areas contribute an important proportion of food requirement. Likewise the grassland receives dung and urine from grazing animals, thus maintaining slightly better fertility. While the soil is inherently suitable for subsistence agriculture, as evidenced by the loam texture, CEC, and supply of critical nutrients, the low OC and TN values, despite organic additions to the garden and grassland, indicate that the farm soils in Umbulo catchment are subject to an excessive pressure for food supply. This pressure is possibly leading to a spiral of soil degradation that is contributing to the food insecurity in the area.

Physical Properties as Influenced by Slope Position

The clay fraction was always lower compared to sand and silt in all three slope positions. The sand fraction was significantly greater, whereas the silt fraction was significantly smaller on the lower slopes relative to the middle slopes (Table 4). The higher sand content on the lower slopes was attributed to the deposition of sediments from the gully system operating in the catchment (Moges and Holden 2008). The gullies transport coarse soil materials from the highly degraded ridge (badland), which is the source of the gully system. Finer particles are only transported when collapse of the gully walls occurs and thus the highest proportion of transported material is coarse, which is eventually deposited on the lower slope regions. The expected trend over a landscape is for increased fine particles on lower slopes (Morgan 1996), but the gully processes seem to have had a different effect in Umbulo catchment. Furthermore, the significant difference in silt but not clay content indicated that there was no selective removal of the clay particles from the soil surface and transport to the lower slope, but the highly erodible silt materials have been transported to the lower slope position. As a result, the soil texture was classified as loam for the upper and middle slopes, while the lower slope was classified as sandy loam. At the 15- to 30-cm depth, the clay fraction was slightly less on the upper slopes and slightly more on the lower slopes, while exhibiting a significant difference between the lower and the middle slopes (Table 4).

There was no significant difference in bulk density of the soils at the different slope positions and porosity also followed a similar pattern. The overall bulk density of the 15- to 30-cm soil was slightly higher than that of the 0- to 15-cm soil, perhaps due to the combined effect of lower organic matter and no tillage in the 15- to 30-cm soil compared to the 0- to 15-cm soil. Overall, the physical properties of the soils at all slope positions were good and favored water and air movement for creating a good environment for vegetation growth in the whole of the agriculturally managed part of the catchment.

Organic Carbon, Available Phosphorus, and Total Nitrogen by Slope Position

At 0- to 15-cm soil depth, OC and TN were significantly different by slope position, but AP was not. At 15 to 30 cm OC and AP were significantly different but TN was not. Generally OC and TN had higher values on the upper and middle slopes compared to the lower slope, but these were still low compared to the critical values (Table 5). The soil of the lower slope was significantly lower in OC and TN than the middle and upper slopes as revealed by the Tukey HSD test (Table 4). This was probably because of (i) the deposition of coarser subsoil sediment on the lower slope due to the gully system operating in the catchment (Moges and Holden 2008); (ii) more leaching on the lower slopes

as a result of water from runoff over the upper and middle slopes (mainly via the gully system) and the shallower slope encouraging a greater proportion of vertical infiltration; and (iii) possibly a lower soil temperature causing less decomposition of plant residues and manure (Sanchez 1976) on the lower slopes.

There was no significant difference in AP between slope positions at 0 to 15 cm (Table 3), but a significant difference at 15- to 30-cm depth (following the same trend as seen at the surface). The soil and management practices did not cause this situation, and hence it might have resulted from the interaction of surface runoff, leaching, and deposition processes, but the exact mechanism cannot be identified at present. Overall, the AP status at all the slope positions was sufficient (Table 5).

pH, Cation Exchange Capacity, and Exchangeable Cations by Slope Position

There was a significant difference in pH by slope position at both 0 to 15 cm and 15 to 30 cm. The pH increased with distance downslope.

CEC values on the lower slope were significantly different from those on the upper and middle slopes (Table 4), with values in the order upper slope > middle slope > lower slope. CEC depends mainly on the organic matter content and clay content of the soil (Rowel 1994; Wild 1993). Both OC and clay content followed the same trend as did the CEC of the soils (Table 3), and the increase in sand content downslope also explains the pattern observed. This suggests that ongoing deposition of sediment on the lower slopes (Moges and Holden 2008) has the potential to reduce the suitability of the soil for cultivation and will put households in this part of the catchment under increased food supply pressure.

The exchangeable cation content was lower on the lower slope compared to the upper and middle slopes (Table 4). The lower slope had significantly less Ca and Mg compared to the other slope positions. This is consistent with the CEC data. Na did not show any significant difference by slope position. The lower slope receives more water through runoff, and at times experiences standing water (particularly in the outfield and grassland areas), which might have contributed to the differences observed down the soil profile (Table 3). This has implications for management of the soils on the lower slope, where planting deep-rooted crops might be advantageous. It has been reported that farmers plant sugarcane on the lower slopes because it is resistant to erosion (Moges and Holden 2006), and further modifications of crop choice might be beneficial in the future.

The lower nutrient status of the lower slope compared to the upper slopes is not consistent with data from other studies that took account of slope positions when evaluating nutrient availability (Alemayehu 2007; Wolde and others 2007; Fu and others 2004; Wang and others 2001). The main reasons for this might be as follows. (i) Soil material transported through the gully system is erosion from the badland and gully wall collapse, which is dominated by subsoil material. The deposition of these coarser soil particles on the lower slope as a result of the gully erosion overrides surface processes that could have enriched the lower area through finer sediment deposition on the top soil. (ii) Averaged across different land use classes (unlike the single land use comparison in the other studies), the effect seems to be different.

Critical Values for Soil Nutrients, Food Insecurity, and Sustainable Production

The critical values of soil nutrients for optimal growth are essential for judging or evaluating the status of the soil under agriculture in Umbulo catchment. These values indicate the required inputs for increased production as well as allowing estimates of resource requirements to reduce food insecurity. Ideally the critical values reported in Table 5 would be determined through experiments in the locality, however, this was not possible. Factors such as the type of crop, husbandry, harvesting, and analytical methods can all influence the results of such trials. In the absence of detailed local data, generalized values have been relied on for comparison purposes (Table 5). Comparing the nutrient status of the three land use classes and the slope position with the critical values in Table 5, it can be seen that all the major nutrients are above the limiting values, suggesting that the productivity of the land could be improved further by adding organic and inorganic inputs, but resource limitations and erosion are the major challenge to sustainability and food insecurity.

At present a large proportion of the farmer households in Umbulo catchment receives food aid because production is too low to feed the population. The inability to produce sufficient food is a critical problem but it is not related to inherent soil fertility problems. There are three major challenges for sustainable land management in Umbulo catchment. The most visible issue is that of soil erosion, mainly due to the gully system in the catchment, but in addition, the issue of low levels of inputs means that the soil fertility status will not be maintained or improve over time. The third issue is the weight of population pressure on the natural resources of the catchment. Planners need to consider these issues when developing an integrated action plan for the catchment. Agricultural production cannot be improved and sustained with the current situation and level of input. The challenge for improving production and becoming food secure and sustainable is to address (i) the population pressure on the land by a combination of

approaches, including decreasing the population by relocating farmers to more productive areas in the region (FDRE 2002) and encouraging off-farm income activities that will allow food to be purchased; (ii) aid support to the catchment population, which needs to supply the means to purchase inorganic fertilizers to improve production, but should perhaps be linked to an incentive requiring conservation activities in exchange for facilitating credit and debt protection measures, which could be built on the current Ethiopian "safety net" program; (iii) intervention within the catchment, which will require different approaches at different landscape positions, so on the lower slopes agricultural management needs to focus on making use of the runoff (building water conservation ponds and channels) and identifying crops tolerant to deposition of sediment (like sugarcane), while on the midslopes extending *Enset* farming to outfields and constructing water conservation ponds might be beneficial; and (iv) the best use of animal dung and crop residue, as the grassland may not achieve maximum benefit compared to use on the outfield areas. Before making active recommendations, however, it will be necessary to examine these issues from both social and economic perspectives in order to achieve sustainable agricultural management approaches that would actually be adopted by the population.

The study presented in this paper has contributed new knowledge of soil degradation and its relationship to food security by evaluating soil fertility of agricultural land at both the farm and the catchment scale, and by placing the results within the framework of known farmer perception, erosion processes, and land use class at the farm scale. In the studied region of Ethiopia, and many other regions of the world, it is known that farmers have knowledge of soil degradation and that soil fertility improvement is required to raise productivity, but the development of a meaningful administrative policy to improve matters requires appropriate information. The work presented in this paper has contributed to our improved understanding of the type of local (or site-specific) information that is needed. This approach can be utilized for analysis of systems anywhere in the world and is necessary because findings from one scale (e.g., region, catchment, and farm) can sometimes be counterintuitive when applied at a different scale. For example, a farm-averaged assessment of nutrient status does not capture the effect of different management practices within the farm, and the effect of landscape position can also override management effects. This study has shown that depositional areas do not necessarily have an improved fertility status due to erosion processes but, depending on the material being transported, can also be degraded of nutrients. The findings indicate that it is very important to gain a holistic understanding of soil in the environment by considering land use and management

influence on soil fertility at the appropriate scale. In this case, the field scale is appropriate, as it reflects how the livelihood of the farmer is supported and how the land is actually managed, but an analysis at the catchment scale is also required to gain full insight into the fertility limitations within the catchment.

Conclusion

The main conclusions of this study are as follows.

1. Farmers have given priority to specific land use classes for nutrient inputs (for a number of reasons; see, e.g., Tilahun and Mulugeta 2005), which may have been at the expense of the sustainability of the whole farm (see also Hailesselassie and others 2006), and in the case of Umbulo catchment, intervention is needed to address this situation.
2. The lack of differences in most soil properties as a result of management is probably due to the low level of inputs being used, and while this is the case, food security will be difficult to achieve.
3. The deposition of sediment on the lower slope has had a pronounced effect on the soils, more so than the difference in management between areas of the farm. The implication of this is that gully erosion (apart from causing physical damage), is affecting the area by changing the soil properties, and erosion must be addressed to reduce soil degradation.
4. The nutrient level of the different land use classes and slope positions, compared to the critical values, were adequate and there is no obvious limiting nutrient. There is no inherent soil nutrient problem in the area but management of organic matter, which is also related to the economic pressure on the farmers, plays a major role in limiting production and driving food insecurity.

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