doi: 10.17221/117/2015-SWR

Linking Selected Soil Properties to Land Use and Hillslope – A Watershed Case Study in the Ethiopian Highlands

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Abstract

Addis H., Klik A., Oweis T., Strohmeier S. (2016): Linking selected soil properties to land use and hillslope – A watershed case study in the Ethiopian Highlands. Soil & Water Res., 11: 163–171.

Deforestation of native forests for crop production in the Gumara-Maksegnit watershed, located in the Lake Tana basin, Ethiopia, dramatically increases the vulnerability of the soil for rainfall driven erosion. Hence, the central task of the study is to investigate general links of land-use and topography related to selected soil properties. The 53.7 km^2 watershed was divided into a 500 × 500 m square grid to sample bulk density (ρd), pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), and texture of topsoil. Such properties were investigated with respect to the two main land-uses, forest and agriculture, and three different slope steepness classes, 0–10%, 10–30%, > 30%. Descriptive statistics and correlation analyses were undertaken to explore potential dependencies of the obtained soil parameters according to land-use and slope steepness. The study indicates higher SOC, TN, silt and sand content in forest soils compared to agricultural soils, while solely ρd is lower in the forest soil. Overall increases of SOC, TN, silt, and sand content from the gentle to the steep slopes have been observed for both land-uses. In contrast, clay content and ρd seem to increase from steep to gentle slopes on agricultural areas, which might be due to accumulation of particularly fine soil particles eroded from the steep areas. Basic correlations valid for all land-uses and slope steepness classes have not been detected. Nevertheless, the study suggests slope steepness as a tool to assess the potential drivers of soil depletion in the Ethiopian Highlands.

Keywords: agricultural watershed; slope steepness; soil attributes; soil erosion

Soil variability is inherent in nature due to different soil forming factors (Wei *et al.* 2008) in which climate, time, topography, living organisms, and parent materiel have been indicated as the main drivers of soil genesis (Jenny 1941). The effects of vegetation on soil formation are related to the impacts on microclimate, soil erosion, microbial activity, organic matter accumulation, clay minerals, infiltration, and nutrient cycling (Foth 1984). Meanwhile, hillslope orientation and slope steepness affect the soil profile development, especially in areas where rainfall and runoff enforce the detachment and the translocation of soil (Foth 1984). The described soil forming factors interact across different spatial and temporal scales (Iqbal *et al.* 2005). Insight into the variability of the soils affected by different soil forming factors is essential for evaluating the impacts of future land use and climate changes on the soil status (Kosmas *et al.* 2000), and consequentially, for understanding the entire ecosystem response (Townsend *et al.* 1995).

Recently, the reduction of the soil quality and thus crop productivity has become severe in some regions of the Ethiopian Highlands (Habtamu *et al.* 2014). Some of the factors causing considerable nutrient depletion in agricultural lands are related to the cultivation of the steep and fragile soils, limited recycling of dung and crop residues, deforestation and overgrazing (Habtamu *et al.* 2014), poor soil management and soil erosion by water (Kosmas *et*

doi: 10.17221/117/2015-SWR

al. 2000; Amare *et al.* 2013). Particularly, soil erosion by water, leaching of nutrients due to intensive rainfall events, organic matter depletion as a result of continuous removal of crop residues, and use of cow dung for different purposes were detected as the driving factors for poor soil productivity in the Ethiopian Highlands.

As a matter of fact, the study site covers only smaller parts of the Ethiopian Highlands, at which large areas of the landscape still have not been explored in detail; however, the opportunity of linking soil specific case study results with other aspects of watershed research may support integrated watershed assessment. The specific task of this research is to assess the impact of land use and slope steepness on selected soil properties. Nevertheless, general outcomes and linkages may be used as a starting point for advanced soil quality assessment even at field level to aim for sustainable land management for the fragile Ethiopian Highlands ecosystem.

MATERIAL AND METHODS

Description of the study area. The study was conducted in the Gumara-Maksegnit watershed (53.7 km^2) located in the northwestern Amhara region, Ethiopia, between 12°24' and 12°31'N, and between 37°33' and 37°37'E (Figure 1). The soil types are predominately Cambisol and Leptosol in the upper and central part of the watershed, and Vertisol in the lower catchment near the outlet. The mean annual rainfall is 1170 mm of which more than 90% occurs during the three month period, June to August. Average daily maximum and minimum temperatures are 28.5°C and 13.6°C, respectively. The elevation of the study watershed varies from 1920 m at the outlet to 2850 m in the northern mountains. The majority of the study watershed is mountainous and consists of dissected terrain with steep slopes (Addis *et al.* 2015).

The 53.7 km^2 watershed was divided into a 500 × 500 m square grid. Approximately at the centre of each grid soil samples of about 2 kg were collected from the surface soil horizon (0–25 cm) for chemical and physical analyses. Composite soil samples from agricultural and forest land use systems under three slope steepness classes: 0–10% (18.77 km^2) (gentle slope), 10–30% (17.66 km^2) (moderate slope), and greater than 30% (17.26 km^2) (steep slope) were collected using bucket auger and core cylinder equipment resulting in 230 sampling points (Figure 2a). A few

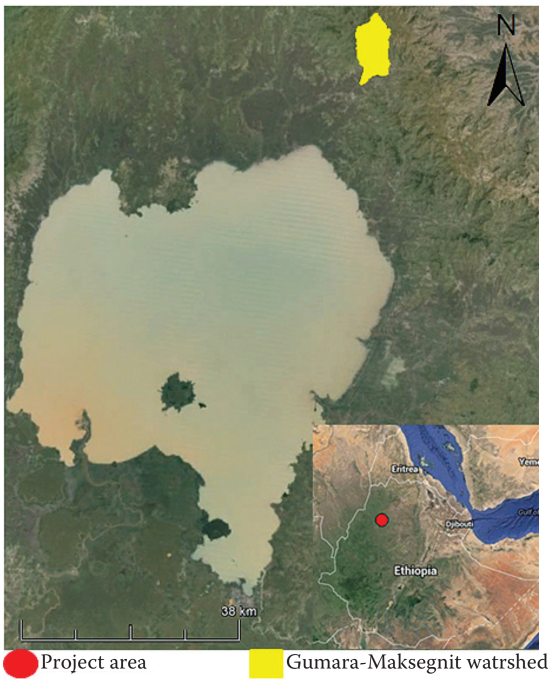

Figure 1. Overview of the project watershed area in the northwest Amhara region, Ethiopia

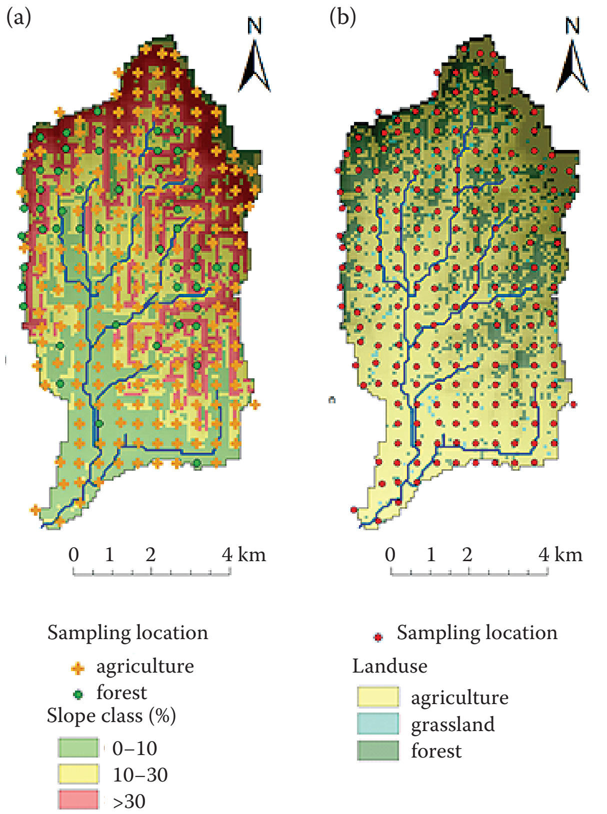

Figure 2. Distribution of soil sampling points (a) under different slope steepness classes and (b) under different land use systems

doi: 10.17221/117/2015-SWR

soil samples were collected outside the periphery of the study watershed, however, such soil samples were not considered during the analyses. Meanwhile, the land use types of the study watershed are mainly agricultural land (63.5%) followed by forest (24.3%) and grassland (12.2%) (Figure 2b). Although there exists a consensus regarding the soil characteristics of grassland are largely different from arable land, neither the soil sampling intensity nor the relative distribution of soil samples on the grassland of the study watershed is optimal for the statistical analyses, therefore, this research only analyzed soil samples collected on agricultural and forest land use systems, which were located at three different slope steepness classes.

Statistical analyses. The selected soil attributes were subject to descriptive statistics which includes mean, standard deviation (SD), and coefficient of variation (CV) using R software (R Development Core Team 2013). Two-way analysis of variance (ANOVA) was executed to evaluate the effects of land use and slope steepness on the observed soil properties. The least significant difference ($LSD_{0.05}$) was used for determination of statistical significance ($P < 0.05$).

RESULTS AND DISCUSSION

Soil textural classes. Five different soil textural classes were determined within the Gumara-Maksegnit watershed: sandy clay loam, sandy loam, clay loam, loam, and clay. The descriptive statistics were derived based on the mean values gained from the soil textural analyses, classified for the different land use and slope steepness classes (Table 1). The resulting soil textures seem significantly dependent on land use and slope steepness (Table 2), which was also indicated by Wei *et al.* (2008). In this study, the average silt, sand, and clay contents in different land uses and slope steepness classes vary between 28.4 and 37.1%, 29.3 and 41.7%, and 21.2 and 42.3%, respectively (Table 2). Generally, higher silt and sand contents were found in forested areas compared to agricultural lands. This contradicts the studies conducted by Wei *et al.* (2008), and Ezeaku and Eze (2014) where land use does not affect particularly the silt fraction. Compared to the other slope steepness classes, clay contents tend to be higher on the gentle slopes of both land uses. The increasing clay content with decreasing slope steepness might be a result of the long-term soil erosion and accumulation processes, as reported by several studies (Ogban & Babalola 2009; Obalum *et al.* 2011). As a standardized measure of variance, the coefficient of variation (CV) was used to describe the shape of the frequency distribution of the observations. Based on the CV values, silt, sand, and clay contents may be generally considered as moderately variable (CV ranges from 14 to 37%). Silt content at gentle slopes of the forest is least variable (CV less than 14%), while clay content at gentle slopes of agricultural areas has largest variation (CV equals to 38%).

Bulk density. The descriptive statistical summary of bulk densities for both land uses and slope classes is presented in Table 1. Mean soil bulk density varies from 1.4 ± 0.24 g/cm^3 to 1.3 ± 0.09 g/cm^3 at gentle slope, from 1.2 ± 0.02 g/cm^3 to 1.2 ± 0.04 g/cm^3 at moderate slope, and from 1.2 ± 0.02 g/cm^3 to 1.1 ± 0.04 g/cm^3 at steep slope classes. Mean bulk density on forested areas is significantly lower compared to agricultural areas (Figure 3a). This could be associated with low rooting density and higher organic matter accumulation (Barker & Pilbeam 2007), well-developed fine to medium granular structure and high organic matter contents in forested soils (Cardelli *et al.* 2012). On agricultural areas, bulk density seems to be significantly affected by the slope steepness. In contrast, there is no a statistically significant difference between the mean values measured in the forest with respect to the different slope steepness classes. However, bulk density measured at gentle slope seems to be higher than at the other slope classes (Table 2). Significant changes of soil bulk density on agricultural areas might be – among other impacts – related to the agricultural practices applied. Similarly, Emadi *et al.* (2008) documented compaction of topsoil layer due to intensive cultivation increased bulk density.

Soil pH. The descriptive statistical summary of measured soil pH indicates a mean value of 6.7 ± 0.03 (Table 1). Variation in soil pH, with respect to the interaction of land uses and slope classes is mostly non-significant, which was also shown by Worku (2014). However, focusing only on agricultural lands, soil pH might change slightly for different slope classes (Table 2). The highest pH value was obtained on agricultural land, similar to the results reported by Bewket and Stroosnijder (2003).

Several studies also indicate that forest soils are often more acidic than agricultural soils (Barker & Pilbeam 2007; Binkley & Fisher 2012). Soils in high altitudes often related to steeper slopes tend to lower pH value, which likely indicates the washing

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Table 1. Overview of the descriptive statistics of the selected soil properties classified based on land use and slope steepness

Soil properties	Agriculture									Forest								
	0–10%			10–30%			> 30%			0–10%			10–30%			> 30%		
	mean	SD	CV	mean	SD	CV	mean	SD	CV	mean	SD	CV	mean	SD	CV	mean	SD	CV
ρd (g/cm^3)	1.4	0.19	0.1	1.2	0.16	0.1	1.2	0.15	0.1	1.3	0.24	0.2	1.2	0.15	0.1	1.1	0.2	0.1
pH	7.0	0.44	0.1	6.7	0.40	0.1	6.6	0.35	0.1	6.7	0.33	0.1	6.7	0.21	0.0	6.6	0.2	0.0
Silt (%)	28.4	8.17	0.3	35.3	5.64	0.2	36.1	6.26	0.2	30.3	9.98	0.3	38.0	7.60	0.2	37.1	4.9	0.1
Sand (%)	29.3	8.75	0.3	39.6	7.36	0.2	39.9	8.56	0.2	31.6	6.22	0.2	39.9	10.50	0.3	41.7	7.8	0.2
Clay (%)	42.3	14.00	0.3	25.1	8.89	0.4	24.0	8.64	0.4	38.1	14.70	0.4	22.0	4.47	0.2	21.2	4.4	0.2
SOC (%)	1.0	0.57	0.6	1.7	1.01	0.6	2.0	1.09	0.6	1.1	0.54	0.5	1.8	0.87	0.5	2.1	1.1	0.5
TN (%)	0.2	0.16	1.0	0.2	0.13	0.5	0.3	0.12	0.5	0.3	0.12	0.5	0.3	0.06	0.2	0.3	0.1	0.4
AP (ppm)	12.8	12.80	1.0	16.7	15.80	1.0	12.6	15.40	1.2	16.6	25.50	1.1	8.4	4.95	0.6	10.4	12.0	1.1

ρd – bulk density; SOC – soil organic carbon; TN – total nitrogen; AP – available phosphorus; SD – standard deviation; CV – coefficient of variation

Table 2. Interaction effects of observed soil properties at different land uses and slope steepness classes

Soil properties	Agriculture					Forest					Overall sample	
	0–10%	10–30%	> 30%	LSD	mean	0–10%	10–30%	> 30%	LSD	mean	LSD	CV
ρd	1.4	1.2	1.2	0.06***	1.3	1.3	1.1	1.1	ns	1.2	0.05***	0.2
pH	7.0	6.7	6.5	0.15*	6.7	6.7	6.7	6.6	ns	6.7	ns	0.1
Silt	28.4	35.3	36.1	2.52***	33.3	30.3	38.0	37.1	6.12*	35.2	2.38**	0.2
Sand	29.3	39.6	39.9	3.04***	36.3	31.6	39.9	41.7	7.47*	37.7	3.01*	0.3
Clay	42.3	25.1	24.0	4.06***	30.4	38.1	22	21.2	5.79***	27.1	4.09**	0.4
SOC	1.0	1.7	1.9	0.34***	1.4	1.1	1.8	2.1	0.81*	1.7	0.31*	0.6
TN	0.2	0.2	0.3	0.05***	0.2	0.2	0.3	0.3	0.08*	0.2	0.04*	0.6
AP	12.8	16.7	12.6	ns	14.0	16.6	8.4	10.4	ns	11.8	ns	1.0

ρd – bulk density; SOC – soil organic carbon; TN – total nitrogen; AP – available phosphorus;*, **, ***significant at $P \leq 0.05$, 0.01, and 0.001, respectively; ns – not significant; LSD – least significant difference

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out of solutes and very high leaching of bases and clay particles from these areas as a result of intensive rainfall in the watershed. Some of the factors which are responsible for the reduction of pH at steep slope classes of forested soils might be associated with dense vegetation cover and slow decomposition leading to plenty of organic matter accumulation, eventually reducing soil pH. Similarly, DLAPA *et al.* (2011) stated that soil pH has a close relationship with soil organic carbon (SOC) as pH is commonly decreased with increasing SOC. Meanwhile, slightly higher soil pH on agricultural areas could probably be due to the long-term cultivation practices as indicated by DLAPA *et al.* (2011). Generally, the observed soil pH is the least variable (CV less than 7%) compared to the other soil properties. Similarly, ABU and MALGWI (2011) indicate low coefficients of variation for pH compared to other soil properties.

Effects of land use and slope on soil chemical properties. The nutrient supplying power of the soil is determined by the chemical properties of the soil which are also the most important factors that affect soil fertility (HABTAMU *et al.* 2014). In this research, the most essential chemical properties of the soil such as soil organic carbon (SOC), total nitrogen (TN), and available phosphorus (AP) were analyzed and displayed in Tables 1 and 2.

For both land use types higher SOC was observed at the steeper slopes, particularly steep slopes of the forested areas, this might be due to the different litter decomposition rate (TSUI *et al.* 2004), types of vegetative cover (GRIGAL & OHMANN 1992), and the intensity of human interaction (REYNOLDS *et al.* 2007). In this study, SOC is generally low on agricultural areas with high clay content. Low SOC on cultivated areas may be attributed to unfavourable soil conditions due to the utilizations of crop residues as fuel and animal fodder, but also due to continuous farming and soil erosion impacts mentioned in the literature (CRASWELL & LEFROY 2001; EMADODIN *et al.* 2009).

Comparison of the topsoil TN grouped for agriculture and forest suggests that overall TN on forested areas is significantly higher compared to the agricultural lands (Table 2). This may be explained by the higher soil organic matter (SOM) in the forest soils. Such results were in agreement with DÍAZ-RAVIÑA *et al.* (2005) who stated the changes in SOM could lead to changes in TN as more than 95% of soil N comes from SOM. Similarly, BELACHEW and ABERA (2010) indicated that the contribution of SOM to TN is significantly high. On the other hand, performed ANOVA suggests that AP does not significantly change between both land uses and slope steepness

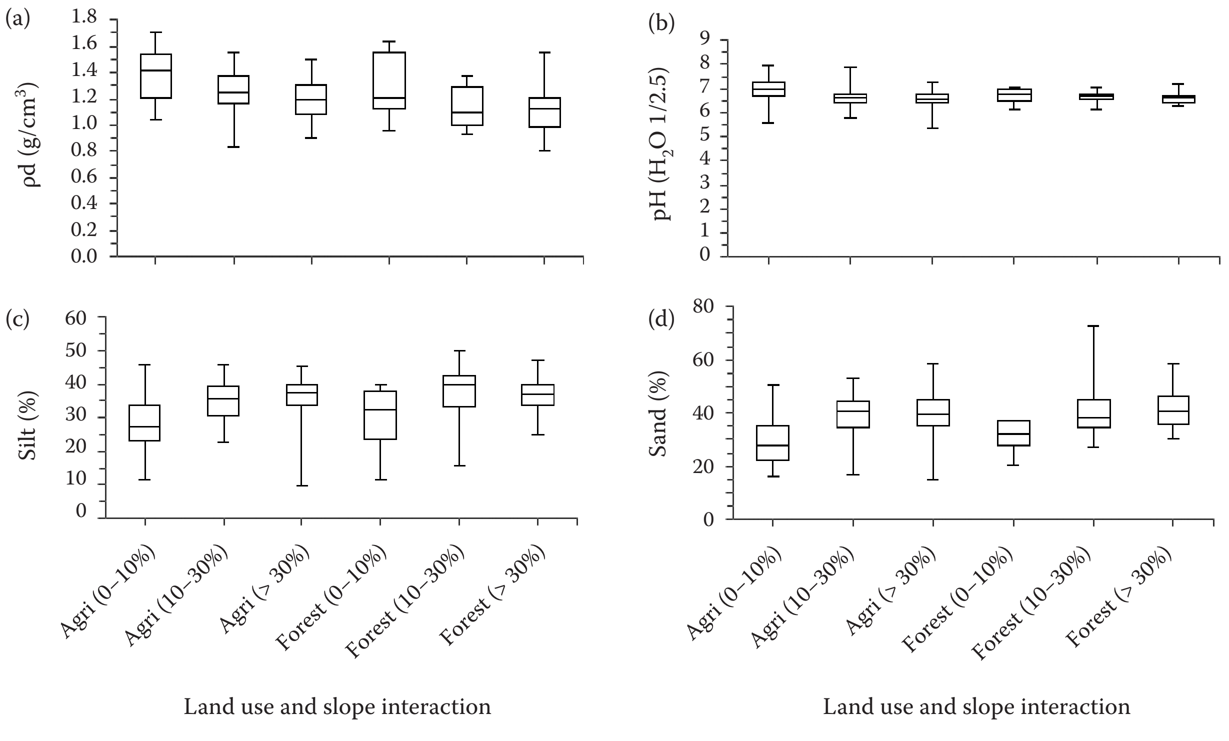

Figure 3. Distribution (box plots with 25th, mean, and 75th percentile) across the different land uses and slope steepness classes: bulk density (ρd, g/cm^3) (a), pH (b), silt (%) (c) and sand (%) (d)

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classes. The AP content in the watershed ranges from 1.2 to 77.2 (ppm), with an arithmetic mean of 12.40 (ppm). The coefficient of variation, standard deviation, and basic statistical parameters of AP for both land uses and slope steepness show that AP has relatively large variance (CV equals 101%). This may be related to the heterogeneity of the land use patterns, overlaid with random application of inorganic fertilizer and also severe but variable erosion occurrence within the watershed. Similarly, Addis *et al.* (2015) documented the highest CV for AP.

Correlations among the soil attributes. Correlation of the eight soil attributes related to the different land uses and slope steepness classes were evaluated based on the correlation coefficient and the corresponding significance level (Tables 3 and 4). The correlation analysis indicates that bulk density (ρd) seems significantly positively correlated with pH and significantly negatively correlated with SOC and silt, while clay is significantly positively correlated with pH. These findings follow the general principle that bulk density mostly increases with decreasing soil SOC (Cardelli *et al.* 2012) and pH commonly increases with decreasing SOC (Dlapa *et al.* 2011). AP was found to be significantly negatively correlated with bulk density and clay content, while significantly positively correlated with TN. Observed TN is significantly negatively correlated with pH and clay content, while significantly positively correlated with SOC. Focusing on single pairwise correlations, many of the observed soil properties seem to be significantly linked with the others. However, there is no clear indication that any of the measured soil properties is correlated with the other variables across the combined classes – slope steepness classes and land uses allowing generalized statements. Nevertheless, potential trends for the correlation of different soil properties

Table 3. Matrix of the correlation coefficients among the measured soil properties in all the slope positions at agricultural land use

Slope position	Variables	ρd	pH	Silt	Sand	Clay	SOC	TN
> 30% n = 65	pH	0.51**						
	Silt	–0.39**	–0.45**					
	Sand	–0.25	–0.16	0.37**				
	Clay	0.39**	0.36**	–0.82**	–0.84**			
	SOC	–0.26*	–0.43**	0.17	–0.1	–0.03		
	TN	–0.02	–0.27*	–0.05	0.02	0.02	0.36**	
	AP	–0.15	–0.01	0.3*	0.18	–0.28*	0.14	0.28*
10–30% n = 67	pH	0.44**						
	Silt	–0.26*	–0.3*					
	Sand	0.003	–0.16	–0.08				
	Clay	0.16	0.32**	–0.57**	–0.77**			
	SOC	–0.26*	–0.3*	0.24*	0.15	–0.28*		
	TN	–0.25*	–0.43**	0.52**	0.16	–0.46**	0.38**	
	AP	0.02	0.06	0.32**	–0.09	–0.13	0.19	0.12
0–10% n = 49	pH	0.01						
	Silt	–0.1	0.07					
	Sand	0.06	0.45**	–0.35*				
	Clay	0.01	–0.49**	–0.37**	–0.74**			
	SOC	–0.09	–0.11	–0.06	0.17	–0.12		
	TN	–0.38**	–0.22	0.23	0.06	–0.23	0.34*	
	AP	–0.24	–0.09	0.11	0.11	–0.19	0.04	0.43**

ρd – bulk density; SOC – soil organic carbon; TN – total nitrogen; AP – available phosphorus; *, **, ***correlation is significant at $P \leq 0.05$, 0.01, and 0.001 (two-tailed), respectively; n – number of samples

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Table 4. Matrix of the correlation coefficients among the measured soil properties in all the slope positions at forest land use

Slope position	Variables	ρd	pH	Silt	Sand	Clay	SOC	TN
> 30% n = 7	pH	0.85*						
	Silt	–0.9**	–0.71					
	Sand	–0.72	–0.67	0.62				
	Clay	0.92**	0.77*	–0.94**	–0.85*			
	SOC	–0.55	–0.81*	0.38	0.51	–0.48		
	TN	–0.79*	–0.98**	0.58	0.63	–0.66	0.8*	
	AP	0.21	0.05	–0.29	0.16	0.13	0.29	–0.07
10–30% n = 17	pH	–0.25						
	Silt	–0.35	–0.16					
	Sand	0.23	0.28	–0.93**				
	Clay	0.04	–0.39	0.48	–0.77**			
	SOC	–0.15	0.19	–0.2	0.23	–0.2		
	TN	–0.27	–0.26	0.15	–0.14	0.09	0.42	
	AP	–0.49*	–0.12	0.1	–0.19	0.27	–0.04	0.11
0–10% n = 25	pH	0.01						
	Silt	–0.2	–0.02					
	Sand	0.17	0.13	–0.85**				
	Clay	–0.07	–0.2	0.39	–0.81**			
	SOC	–0.51**	–0.07	0.42*	–0.26	–0.009		
	TN	–0.29	–0.2	–0.12	0.2	–0.22	–0.001	
	AP	–0.35	–0.03	0.05	0.003	–0.06	0.11	0.48*

ρd – bulk density; SOC – soil organic carbon; TN – total nitrogen; AP – available phosphorus; *, **, ***correlation is significant at $P \leq 0.05$, 0.01, and 0.001 (two-tailed), respectively; n – number of samples

for individual combinations of land uses and slope steepness classes are evident, which may enable the link of specific soil properties for certain areas considering a proper level of uncertainty.

Slope steepness has been indicated as the main abiotic factor that controls the soil genesis on a local scale (Buol *et al.* 1997). The steeper the slopes, the higher the runoff as well as the greater the relocation of soil materials downslope through rainfall driven erosion. In the study watershed, slope has a significant effect on the majority of obtained soil properties and there were a number of soil properties which have also been found to be strongly correlated with slope steepness. The highest positive correlations with slope were found, in descending order, for sand, SOC, silt, and TN. The highest negative correlations with slope were found, in ascending order, for AP, pH, bulk density, and clay content. The box plot diagrams (Figures 3 and 4) give insight into the distribution of the different soil properties. Particularly, larger variances of SOC, TN, and AP might indicate different impacts of human interferences, such as local fertilization and individual agricultural management, overlaid with variable hillslope processes – for example surface runoff induced soil erosion and translocation of soil materials. This may inhibit a clear statement on parameter dependence, even though general trends and interactions seem detectable based on the box plots (Figures 3 and 4).

CONCLUSION

This study aimed for the investigation of potential interactions and linkages between selected soil properties across different land uses as well as topographic conditions (three slope steepness classes: 0–10%, 10–30%, > 30%), sampled within mountainous watershed in the Ethiopian Highlands. The study showed that forested areas of the Gumara-Maksegnit

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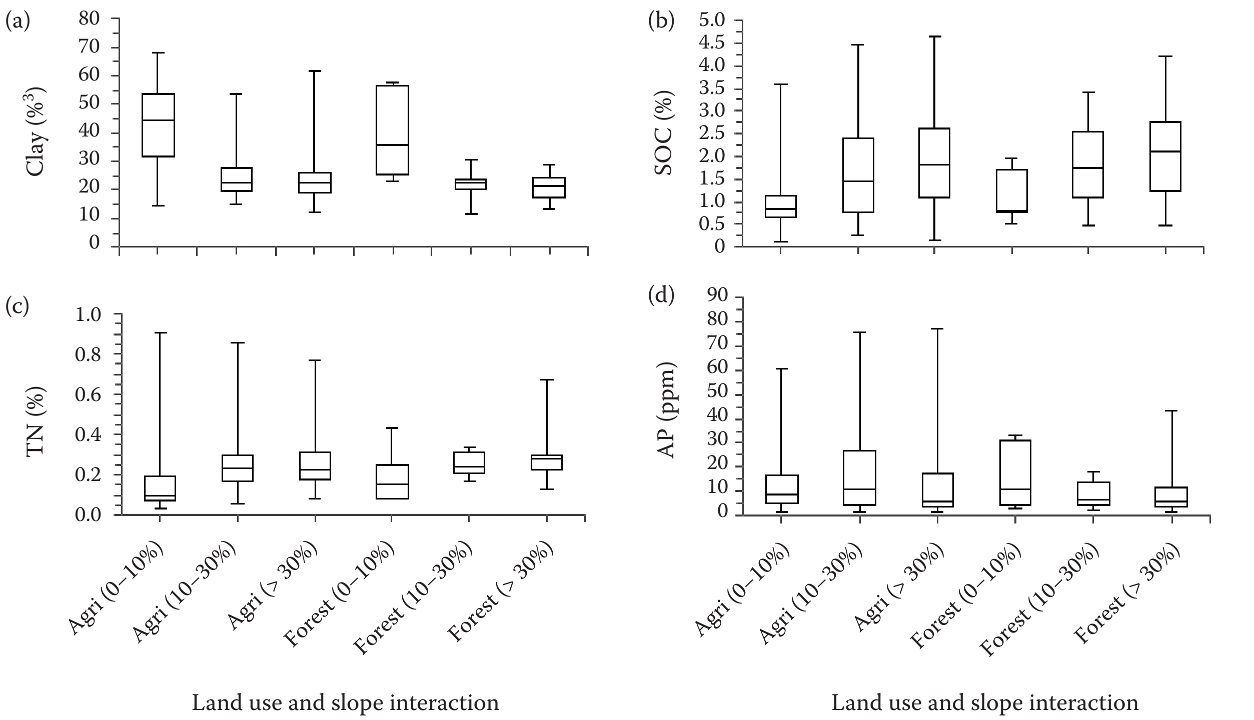

Figure 4. Distribution (box plots with 25th, mean, and 75th percentile) across the different land uses and slope steepness classes: clay (%) (a), soil organic corbon (SOC, %) (b), total nitrogen (TN, %) (c), and available phosphorus (AP, ppm) (d)

watershed tend to have higher soil nutrients (SOC and TN) as well as higher silt and sand contents compared to agricultural lands, while bulk density is lower in the forest. On the other hand, available phosphorus did not indicate any form of dependence. Concerning SOC, TN, silt, and sand content an overall increase from gentle to steep slope classes have been observed for both land uses. The study also points out high levels of clay content and bulk density occurred on the gentle slopes of agricultural lands. Higher clay content on flat agricultural areas might be due to the deposition of clay particles eroded from the adjacent upper hillslope areas. Generally, the obtained results suggest certain potential for using slope steepness classification as a tool for soil property definition in the Ethiopian Highlands. Based on the applied correlation statistics, some of the soil properties are significantly linked (correlated) to the others, which may support the allocation of the most endangered regions concerning land degradation. However, basic linkages valid for all land uses and slope steepness classes have not been detected. Nevertheless, significant parameter correlations considering specific land use and slope steepness may help delimit required soil sampling for future research. In fact, soil property pattern assessed in the present study may be used as a basis for specific task related to research at field level – to assess the potential drivers of soil depletion and to come up with proper interventions to counteract ongoing land degradation in the Ethiopian Highlands.

Acknowledgements. This study was financed by Austrian Development Agency (ADA). We would like to recognize the contribution by the staff of Gondar Agricultural Research Center, Soil and Water Management Research Directorate and Gondar Soil Laboratory Office.

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Received for publication June 19, 2015
Accepted after corrections January 22, 2016
Published online May 24, 2016

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