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CHARACTERIZATION OF DEGRADED SOILS IN THE HUMID ETHIOPIAN HIGHLANDS

Tigist Y. Tebebu[1], Haimanote K. Bayabil[2], Cathelijne R. Stoof[3], Shree K. Giri[1], Azalu A. Gessess[4], Seifu A. Tilahun[4], Tammo S. Steenhuis[1,4]*

[1]*Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY, USA*
[2]*College of Agriculture and Human Sciences Prairie View A&M University, Prairie View, TX 77446, USA*
[3]*Soil Geography and Landscape Group, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands*
[4]*Faculty of Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia*

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ABSTRACT

Hardpan is a major cause of land degradation that affects agricultural productivity in developing countries. However, relatively, little is known about the interaction of land degradation and hardpans. The objective of this study was, therefore, to investigate soil degradation and the formation of hardpans in crop/livestock-mixed rainfed agriculture systems and to assess how changes in soil properties are related to the conversion of land from forest to agriculture. Two watersheds (Anjeni and Debre Mewi) were selected in the humid Ethiopian highlands. For both watersheds, 0–45 cm soil penetration resistance (SPR, n = 180) and soil physical properties (particle size, soil organic matter, pH, base ions, cation exchange capacity, silica content, bulk density and moisture content) were determined at 15 cm depth increments for three land uses: cultivated, pasture and forest. SPR of agricultural fields was significantly greater than that of forest lands. Dense layers with a critical SPR threshold of ≥2000 kPa were observed in the cultivated and pasture lands starting at a depth of 15–30 cm but did not occur in the undisturbed forest land. Compared with the original forest soils, agricultural fields were lower in organic matter, cation exchange capacity, and exchangeable base cations; more acidic; had a higher bulk density and more fine particles (clay and silt); and contained less soluble silica. Overall, our findings suggest that soil physical and chemical properties in agricultural lands are deteriorated, causing disintegration of soil aggregates, resulting in greater sediment concentration in infiltration water that clogged up macro-pores, thereby disconnecting deep flow paths found in original forest soils. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: hardpan soil; penetration resistance; deforestation; soil degradation; East Africa; Horn of Africa

INTRODUCTION

Land degradation occurs worldwide and is a serious threat to food security in developing countries where people live on the edge of poverty (FAO, 2011; Temesgen *et al.,* 2012a). Land degradation can take on many forms, ranging from desertification to salinized lands in semi-arid lands to low producing compacted soils with low permeability and poor root development in more humid climates (Hawando, 1997; Johnson *et al.,* 1997; Hanson *et al.,* 2004b; Ahmad *et al.,* 2007; Elhaja *et al.,* 2014).

Here, the primary concern is degraded soils in humid climates that form slowly permeable soil layers commonly known as hardpans. According to Soil Science Society of America, hardpans are defined as soil layers with physical characteristics that restrict downward soil water movement and reduce moisture storage capacity. They usually occur between 7·5 and 90 cm deep (Litchfield & Mabbutt, 1962; Hoogmoed & Derpsch, 1985; Radcliffe *et al.,* 1989; Mulholland & Fullen, 1991; Kılıç *et al.,* 2004). Hardpans also limit root's capacity to penetrate the soil profile and to uptake nutrients from the lower strata that are critically needed for improved crop production (Busscher & Bauer, 2003; Raper *et al.,* 2005). For example, a study in Pakistan showed that hardpans caused a reduction of cotton yield by up to 15% (Raza *et al.,* 2007), by reducing nutrient and water uptake and availability. In many coastal plain soils of the southeastern USA, hardpans cause a reduction of corn grain yield by up to 2·4 Mg ha^{-1} (Busscher *et al.,* 2001). In addition, during wet periods, since infiltration is limited, hardpans make the upper soil layers wetter. This in turn results in yield reduction due to root infections (Allmaras *et al.,* 1998) and an increase in runoff and erosion because the soil can store only limited amounts of water before runoff starts. As a consequence, the occurrence of hardpans in the soil profile increases erosion (Tebebu *et al.,* 2015) and sediment concentration in rivers such as in the Blue Nile (Steenhuis & Tilahun, 2014; Steenhuis *et al.,* 2014).

The factors that affect hardpan formation vary widely across locations, soil types and agro climatic conditions. Litchfield and Mabbutt (1962), Gerard (1965) and among others reported that natural soil formation can over time result in horizons of high density by translocation of clay and loam particles from the layers above. Such processes can be enhanced by several anthropogenic factors such as wheel pressure from farm machinery (Radcliffe *et al.,* 1988;

*Correspondence to: T. S. Steenhuis, Department of Biological and Environmental Engineering, Cornell University, 206 Riley Robb Hall, Ithaca, NY, 14853, USA
E-mail: tss1@cornell.edu

Busscher & Bauer, 2003; Raper *et al.,* 2005), livestock trampling during free grazing (Mulholland & Fullen, 1991), and plowing of farmlands at the same depth for many years (Leye, 2007; Temesgen *et al.,* 2009), particularly when the soil is wet (Ahmad *et al.,* 2007). Soil compaction is facilitated by high moisture content (Hamza & Anderson, 2005).

Studies on the formation and amelioration of hardpans have been largely limited to studies on the compaction of heavy machinery during tillage operation. However, heavy machinery cannot explain the extensive hardpan formation in the Blue Nile basin of the humid Ethiopian highlands where, for the smallholder rainfed farming, most of all tillage operations are performed either by hand or by the traditional oxen pulled *Maresha* plow. The few studies on hardpan formation in Ethiopia were limited to the semi-arid areas (Mwendera & Saleem, 1997; Leye, 2007; Biazin *et al.,* 2011; Temesgen *et al.,* 2012b) with one exception of the Temesgen *et al.* (2012b) study in the humid Choke Mountain area.

This one study in the Choke Mountain shows only the occurrence of hardpans but does not provide sufficient information to understand the drivers for hardpan formation. From earlier studies, it is known that land degradation is associated with the conversion of land from forest ecosystem to agricultural use. For instance, Tebebu *et al.* (2010) showed that the incision and development of gullies at the lower parts of the landscapes are related to the clearance of forests at the hillsides. This is because the removal of vegetation disrupts the local hydrology and increases surface and subsurface runoff from the hillside to the valley bottoms. Similarly, Tebebu *et al.* (2015) reflected that intensive cultivation after the clearance of forests shorten the duration to peak flow in rivers after a storm event because of the major modification in the length of the flow path of the subsurface flow as a result of impermeable layers. Thus, it is reasonable to examine the formation of hardpans associated with land use changes. Consequently, the objectives of this study are to investigate the differences in soil physical and chemical properties under original forest and converted lands and to better understand hardpan formation associated with land use changes.

MATERIALS AND METHODS

Description of Study Areas

This study was carried out in two watersheds in the humid highlands of Ethiopia, namely, the Anjeni and Debre Mewi watersheds (Figure 1). Like elsewhere in the humid Ethiopian highlands, small holder farmers in these watersheds rely on rainwater to grow crops. Tillage operations are conducted using a traditional oxen pulled, single-tooth cultivator, *Maresha*, at shallow depth of 10–15 cm. Farming systems in both watersheds are a mixture of crop and livestock production. The main land uses are cultivated land (more than 90%), communal grazing land and some natural forest land left mainly around the Orthodox Christian church yard. The forest land at the church compounds has never been tilled or grazed and is therefore assumed to represent the original soil profile.

The *Anjeni watershed* (10°40′N, 37°31′E) is located 320 km northwest of Addis Ababa south of the Choke Mountains. The watershed is one of the experimental stations established under the Soil Conservation Research Program with the collaboration of the Ethiopian Ministry of Agriculture and the Swiss Agency for Development and Cooperation in the 1980s (Hurni *et al.,* 2005). The watershed, covers 113 ha, is oriented north to south and flanked on three sides (northeast, north and northwest) by plateau ridges with elevation ranges from 2407 to 2507 m (Table I). On average, the watershed receives 1700 mm rain annually with 16°C mean daily temperature (Setegn *et al.,* 2010; Bayabil *et al.,* 2015). Soils have developed from basalt and volcanic ash, with dominant soil types being Alisols, Cambisols and Nitosols (Hurni *et al.,* 2005; Tilahun, 2012; Tilahun *et al.,* 2013). Graded soil bunds have been employed since the mid 1980s to reduce erosion. Most of the grazing (pasture) land in the Anjeni watershed is located on the degraded hill slopes at the northwest side of the watershed while the croplands are in the downslope, midslope and non-degraded upper slope areas of the three sides. The forest land is located in the upper slope at the northwest side.

The second watershed, *Debre Mewi (*37°24′E, 11°20′N), is located 200 km north of Anjeni, approximately 30 km south of Lake Tana, Bahir Dar. The total land area of the watershed is 523 ha; for this study, sampling was performed in a 95-ha sub-watershed where elevations ranged from 2187 to 2345 m. Mean annual rainfall in the watershed is 1250 mm, and the mean daily temperature is 20°C (Table I). Soils have developed from highly weathered and fractured basalt, with Nitosols and Vertisols being the dominant soil types (Abiy, 2009; Tebebu *et al.,* 2010). Since early 2012, intensive soil and water conservation practices have been implemented that consist of soil bunds and *Fanya-Juu* with deep furrows (Dagnew *et al.,* 2015). *Fanya-Juu* (‘throw uphill’ in Swahili language) bunds are constructed by digging a trench and throwing the removed soil uphill to form a bund. Pasture lands are found in the low lying periodically saturated areas, while cropland is found on the middle and upper slopes where it is intermixed with brush on the shallower soils.

Field Measurements and Soil Sampling During the Cropping Season of 2014

In each watershed, three land uses were selected: cultivated (crop), pasture and adjacent natural forest lands for performing the soil penetration tests and to collect soil samples. In the humid and sub humid highlands of Ethiopia, most forest lands have been converted to cultivated and pasture lands, and very few patches of forest are left. These patches are found in churchyards. Sampling in these protected churchyards can offer an exclusive look into what the original soils in the area must have looked like and thus can give insight into the effects of forest clearing

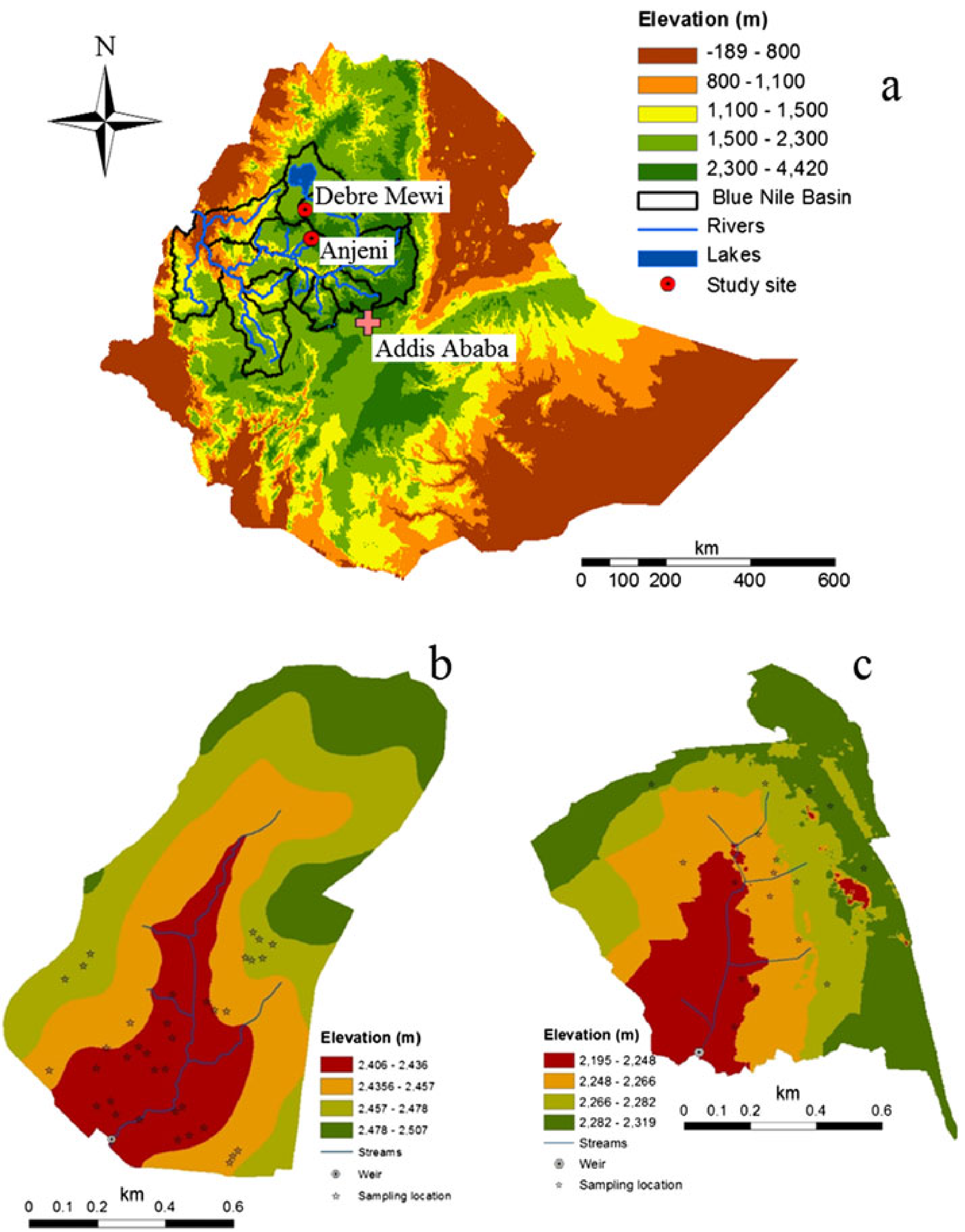

Figure 1. Location of study watersheds in the Blue Nile Basin: (a) map of Ethiopia, (b) Anjeni and (c) Debre Mewi. [Colour figure can be viewed at wileyonlinelibrary.com]

and land use change on soil degradation in the form of hardpans and the related effects on limited crop water availability, disruption of local hydrology and gully formation.

Since soil penetration resistance (SPR) varies with moisture content (Hamza & Anderson, 2005), sampling was performed in the wet and dry seasons. The wet season set of measurements was performed at the beginning of the growing season in July 2014, following a rain event that brought the soil to field capacity. At this set of measurements, all sampling locations were located with GPS units (horizontal accuracy ~2·5 m) to revisit exact locations during the dry season set of measurements. For each season, using a handheld cone penetrometer (DICKEY-john TM Soil Compaction Tester, Ben Meadows Company, Janesville, WI, USA) at 117 and 63 locations, SPR measurements were taken in Anjeni and Debre Mewi watersheds,

Table I. Summary of characteristics of study sites

Watershed	Area (ha)	Mean annual precipitation (mm)	Dominant soil type	Dominant conservation practice
Anjeni	113	1700	Alisols, Cambisols and Nitosols	Graded soil bunds
Debre Mewi	95	1250	Nitosols and Vertisols	Soil bunds and Fanya-Juu with deep furrows

respectively. The sampling density was determined systematically based on the watersheds homogeneity and the size of each land use in the watershed.

In the Anjeni watershed, cultivated land is distributed on the three sides, and thus, for each side, three representative locations were systematically selected at the upper, middle and low slopes. Pasture land is located only in the northwest side, and three sampling locations were selected at the three slopes. Because of the size of the forest land, only three locations were selected. For each sampling location, SPR measurements were taken from 0 to 15 cm, 15 to 30 cm and 30 to 45 cm consecutive depths. The sampling design yielded a subtotal of 51, 27 and 9 sampling points at cultivated, pasture and forest lands, respectively. Because of its smaller size and a relative homogeneity in watershed characteristics, lesser number of sampling locations were selected in Debre Mewi. For each of the cultivated and pasture lands, three representative sampling locations were chosen at the upper, middle and lower slopes. In forest land, three locations were selected. Similar to Anjeni, measurements and samples for each location were taken from three consecutive depths at 15 cm increments and the design yielded a subtotal of 27, 27 and 9 sampling points for cultivated, pasture and forest lands, respectively. At the same time during the wet season set of SPR measurements, 500 g disturbed soil samples were collected at all three SPR profiles for analysis of texture, soil organic carbon (SOC) content, pH, exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), cation exchange capacity (CEC) and silicon. In addition, one soil core (5 cm high, 5 cm diameter) was taken at 5, 20 and 35 cm depth at all SPR profiles for analysis of dry bulk density. Volumetric soil moisture readings at all sampling locations were collected with time domain reflectometry probes (FieldScout TDR 100 Soil moisture meter, Spectrum Technologies, Inc., Aurora, IL, USA) using 20 cm long rod at 0–20, 20–40 and 40–60 cm depth.

The dry season set of SPR measurements with volumetric soil water contents were taken after crop harvest in December 2014 by revisiting the same locations as the wet season set of measurements. Soil sampling was not repeated in the drier season.

Laboratory Analyses

Soil laboratory analyses were performed at Adet Agricultural Research Center and Bahir Dar University (Ethiopia) and Cornell University (USA). Disturbed soil samples were air dried and passed through a 2-mm sieve before analyses. The particle size distribution was determined following Bouyoucos hydrometer procedure (Sahilemedhin & Taye, 2000). SOC was determined following the Walkley and Black procedure wet digestion method (Sahilemedhin & Taye, 2000). Soil organic matter, SOM, was estimated by multiplying SOC by a factor of 1·724. The pH was measured with the pH-water method using a 1:2·5 soil/water suspension following the procedure described by Sahilemedhin and Taye (2000). Exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) contents and CEC were determined using inductively coupled plasma spectrometry. Similarly, silica content was determined after measuring Silicon using inductively coupled plasma emission spectrometry (ICP_ES) by Thermo, model iCAP 6100. Bulk density was determined after oven drying undisturbed soil cores at 105°C for 24 h.

Statistical Analyses

Descriptive statistics (minimum, maximum, mean, standard deviation and coefficient of variation) of SPR were determined separately for each land use at each depth for the two watersheds. Statistical data analysis was performed using R (R Development Core Team 2014) and 'lme4' package (Bates *et al.,* 2014). A linear mixed effect model was fitted to test the effect of land use change and soil depth on soil degradation. In the fitted model, land use type and soil depth were used as fixed effects and sampling locations was used as random factors. Post hoc mean comparison tests for the significant effects of fixed factors were performed using 'lsmeans' package. All significant tests were performed at a significance level of ($p < 0{\cdot}05$) unless specified. In addition, the relationship between SPR and studied soil parameters were determined using nonlinear and linear regression models, and variables with better correlations were identified.

RESULTS

Assessment of SPR across the three land uses are presented first followed by the differences in soil properties among all the three land uses and the relationships between SPR and measured soil physical properties. The discussion mainly focuses on measurements taken in July, because they were taken during the growing season and the difference in moisture contents between the land uses were small. Results from the drier period, measured after crop harvest (in December), are presented in the supplementary material and only discussed briefly in the text.

Soil penetration resistance, bulk density and soil water content

Descriptive statistics of SPR measurements and selected soil physical characteristics for the three land uses at three soil depths are presented in Figures 2, 3 and 4 and Tables S1, S2 and S3.

For the three land uses, SPR varied between 34 kPa for forest soils and 4137 kPa for cultivated lands. Debre Mewi had relatively greater mean SPR values than that of the respective land uses of Anjeni watershed. In Anjeni, observed mean SPR values were 141 kPa (forest land), 1776 kPa (cultivated land) and 1948 kPa (pasture land), while in Debre Mewi observed means were 326 kPa (forest land), 1861 kPa (cultivated land) and 2074 kPa (pasture land) (Figure 2a,b).

As expected, SPR was significantly greater in cultivated and pasture lands than that of the nearby forest churchyard lands in both watersheds (Figure 2a,b). SPR increased with depth in both watersheds for all three land uses (Figure 3a, b). Surface soils of pasture lands had greater SPR than the cultivated lands; however, differences were significant only for Anjeni. Below 15 cm SPR readings from both pasture and cultivated soils were significantly greater than that of forest soils; however, there was no significant difference between pasture and cultivated lands.

An SPR value of 2000 kPa indicates the presence of hardpan, where roots cannot penetrate, and soil water movement is restricted (Taylor & Gardner, 1963; Hamza & Anderson, 2005). Overall, over 58% of the total observations and 70% of the subsoil (below 15 cm) observations in cultivated and pasture lands in the Debre Mewi watershed had SPR values of 2000 kPa or greater, whereas in the Anjeni watershed, only 37% of the total observations and 47% of the subsoil observations in the agricultural (cultivated and pasture) lands were above the critical threshold value. In contrast to the agricultural lands, the forest soils that were never tilled had all SPR measurements distinctly below the critical threshold value of 2000 kPa. The increase of SPR with depth for the forest lands is a natural phenomenon (Litchfield & Mabbutt, 1962) where clay particles migrate downward through macropores to a deeper depth than for the agricultural soils because only part of the soil profile takes part in the transport allowing the particles to travel to greater depth before settling out.

Mean bulk density of cultivated and pasture lands were significantly greater than that of forest lands (Figure 3c,d). Mean volumetric soil water content during the measurement period (wet season) ranged from 44% to 48% in the Anjeni and 45% to 56% in the Debre Mewi watersheds (Figure 3e,f). Although there were no significant differences for the forest soils, the mean soil water content values were greatest at the 40–60 cm depth, which could likely be due to bypass flow through the first 45 cm of soil.

Mean SPR measured in December, after crop harvest, showed an increase for all land uses (Figure 2c,d) in both watersheds. This increase was associated with the decrease in soil water content. On average, SPR increased by 82% in forest land, 47% in cultivated land and 36% in pasture land, while soil water content decreased by 25% in forest, 40% in cultivated and 70% in pasture lands.

Soil Properties

To understand the underlying reasons for the increase in SPR (Figure 3 and S1 and Table S3) after conversion of forest to agricultural land, we examined a number of soil physical and chemical properties including texture, SOM, divalent exchangeable base cations, CEC, pH and silica content. Mean percentage of fine particles (clay plus silt) was significantly greater in agricultural fields of both watersheds at all sampling depths than that of forest lands adjacent to the agricultural fields (Figure 4a,b). Sand and fine fractions were not significantly different between cultivated and pasture lands. In Anjeni watershed, the mean percentage of fine particles was especially remarkable at the surface soil in the forest (40%) and almost 80% in the agricultural lands after conversion and implementation of soil and water conservation practices.

The mean SOM content for the forest soil (varying between 6% and 11% depending on the depth) was two to three times greater than for cultivated land in both watersheds (Figure 4c,d). Pasture lands had greater SOM than that of the cultivated lands at all sampling depths of both watersheds, and the difference was significant in Anjeni (Figure 4c). The pH for the cultivated and pasture lands showed

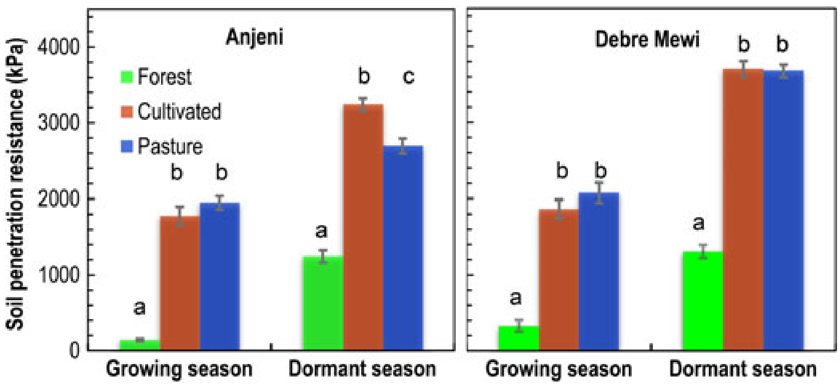

Figure 2. Mean soil penetration resistances for the three land uses in Anjeni and Debre Mewi watersheds measured in July during crop growing period and in December after crop harvest. Error bars represent a standard error around the mean values. For each watershed, letters followed by different letter are significantly different ($p < 0{\cdot}05$). [Colour figure can be viewed at wileyonlinelibrary.com]

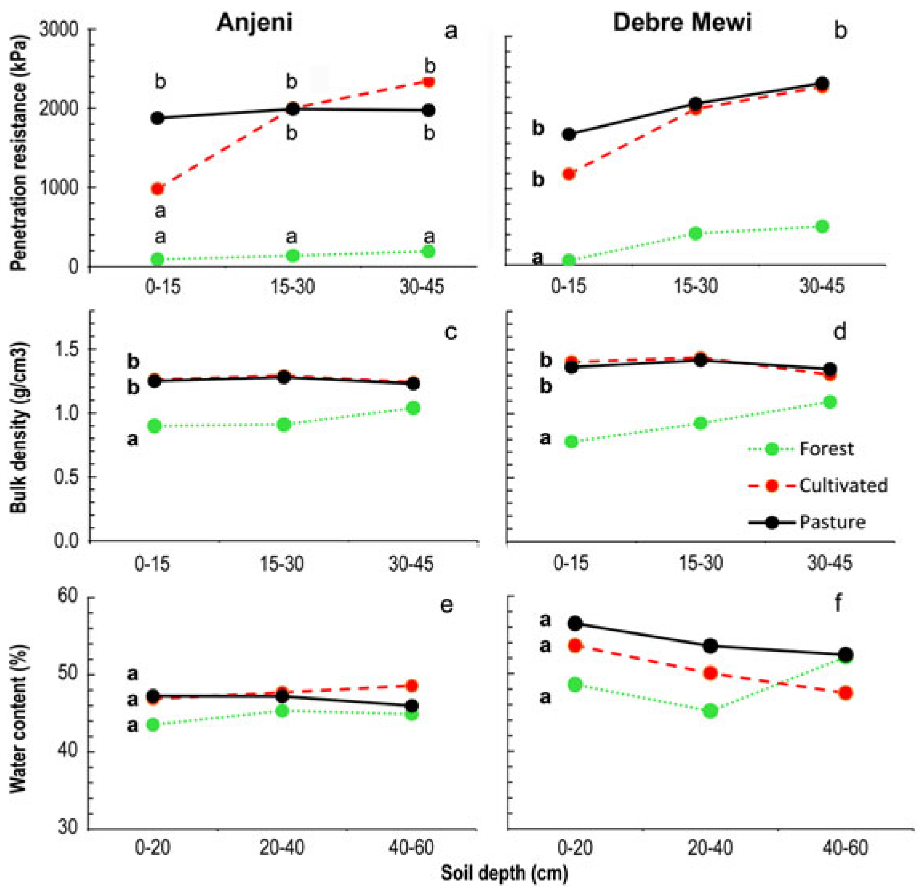

Figure 3. Soil properties for forest, cultivated and pasture lands measured in July during crop growing period: soil penetration resistances, bulk density and volumetric soil water content for Anjeni (a, c and e, respectively) and Debre Mewi (b, d and f) watersheds. Soil penetration resistance and bulk density were measured at 15 cm increments while soil water content was measured at 20 cm increments. For each watershed, values with different letters at a given depth on a given land use are statistically significant at $p < 0{\cdot}05$. For each watershed, bold letters with different letters are significantly different at $p < 0.05$ for each depth. Regular letters in (a) refer to significant differences at a particular depth. [Colour figure can be viewed at wileyonlinelibrary.com]

significantly lower pH (between 5 and 6) than that of forest soils (near neutral) at all sampling depths in both watersheds (Figure 4e,f). Similarly, CEC was significantly lower in agricultural fields as compared with that of forest lands at all sampling depths of both watersheds (Figure 4g,h). The CEC of pasture and cultivated lands was less than 30 $cmol_c\ kg^{-1}$ in Anjeni and was relatively greater (around 35 $cmol_c\ kg^{-1}$) in pasture lands in Debre Mewi of.

Divalent exchangeable base cations (Ca^{2+} and Mg^{2+}) showed a significant difference between agricultural fields and forest lands. However, the amount of monovalent cations (Na^+ and K^+) in both watersheds was negligible. Exchangeable Ca^{2+} was significantly greater in forest lands than that of agricultural fields at all sampling depths in both watersheds (Table S3); however, there was no consistent trend in terms of Mg^{2+} content among land uses in the two watersheds. In Anjeni watershed, mean Mg^{2+} was significantly greater in cultivated lands than pasture lands at both sampling depths. It was relatively similar in pasture and forest lands. In Debre Mewi watershed, pasture land had significantly lower Mg^{2+} than that of cultivated and forest lands, but the latter two land uses had a relatively similar Mg^{2+}.

Soluble silica content analysis was performed for the surface soil samples. Results (Figure 5a,b) show that, in both watersheds, forest land had significantly greater silica content: 120 $cmol_c\ kg^{-1}$ in Anjeni and 200 $cmol_c\ kg^{-1}$ in Debre Mewi than that of cultivated; 43 $cmol_c\ kg^{-1}$ in Anjeni and 131 $cmol_c\ kg^{-1}$ in Debre Mewi and pasture land; 65 $cmol_c\ kg^{-1}$ in Anjeni and 115 $cmol_c\ kg^{-1}$ in Debre Mewi. Silica content in pasture land was significantly greater compared with cultivated land in Anjeni (Figure 5a) while it was relatively greater in cultivated land as compared with pasture land (Figure 5b).

DISCUSSION

Assessment of Soil Penetration Resistance

Mean SPR values in the agricultural fields (Figure 3a,b) are within the normal range reported in other studies in Ethiopia. For instance, Temesgen *et al.* (2012a) found a range of 500–3500 kPa in the cultivated lands of Enerta watershed, located at Choke Mountain in the humid highlands, and Biazin *et al.* (2011) found a range of 200–1780 kPa in the grazing and cultivated fields of Central Rift Valley in the

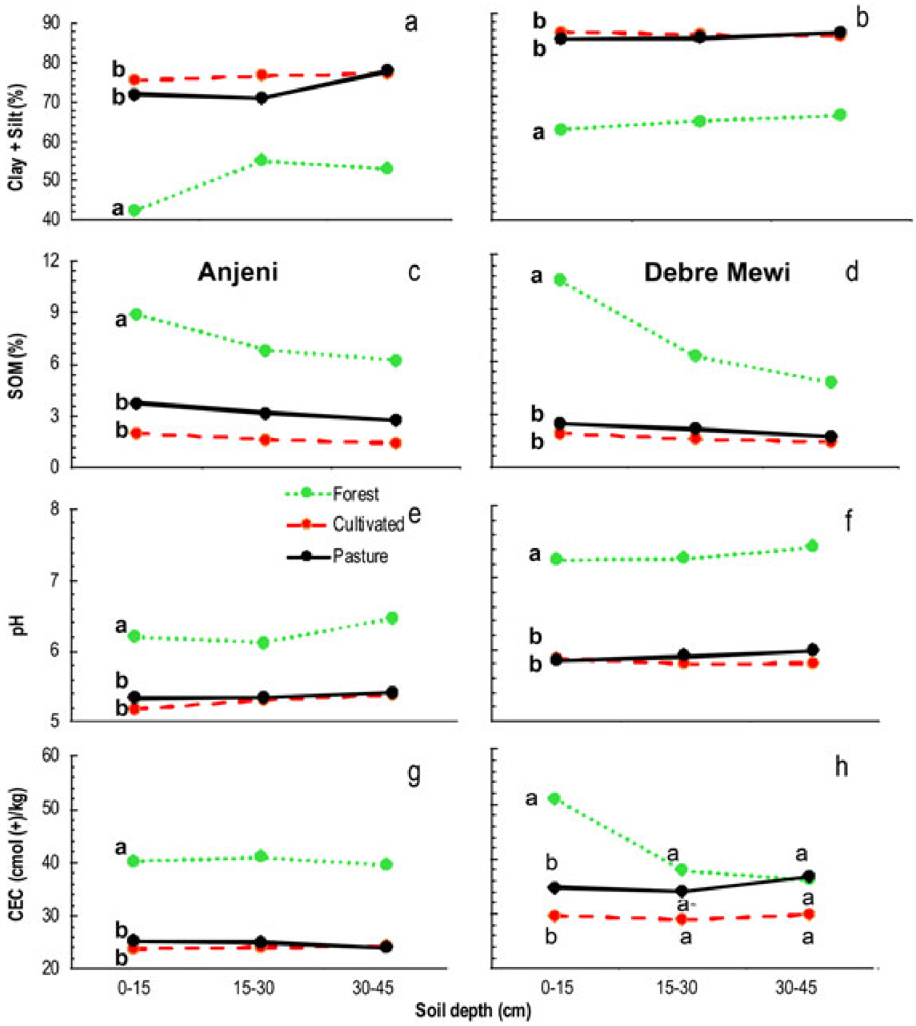

Figure 4. Mean values of selected soil parameters are as follows: fine particles (clay plus silt content), pH, soil organic matter content (SOM), cation exchange capacity (CEC) for Anjeni (a, c, e, and g, respectively) and Debre Mewi (b, d, f and h, respectively) watersheds. For each watershed, bold letters with different letters are significantly different at $p < 0{\cdot}05$ for each depth for the forest, pasture and cultivated land. Regular letters in (h) refer to a particular depth. [Colour figure can be viewed at wileyonlinelibrary.com]

semi-arid region. Comparison of our measurements to the previous studies indicates that SPR in the humid region is relatively greater than that of the semi-arid region. The significant rise in penetration resistance (2000 kPa or above), starting at a depth of 15–30 cm suggests the occurrence of restrictive soil layers (i.e. hardpans) in the subsoil of agricultural fields. This finding is in agreement with the elevated penetration resistance of soil below 10 cm reaching its maximum at a depth of 18–25 cm in the studies of Leye (2007), Temesgen *et al.* (2012a), Temesgen *et al.* (2012b) and Biazin

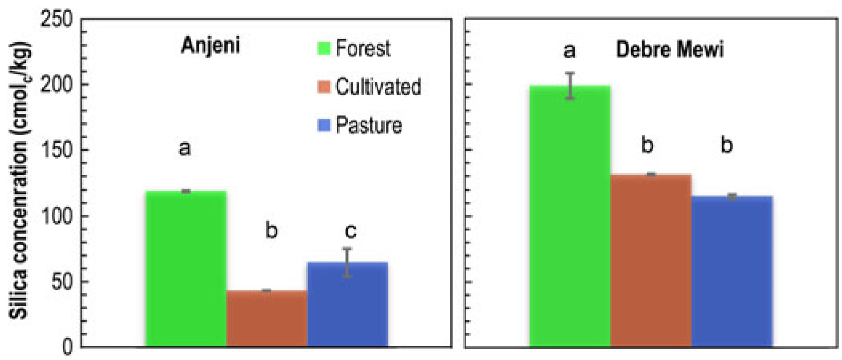

Figure 5. Mean silica content at forest, cultivated and pasture lands of the Anjeni and Debre Mewi watersheds. Values with different letters at a given land use are significantly different at $p < 0{\cdot}05$. [Colour figure can be viewed at wileyonlinelibrary.com]

et al. (2011). The smaller SPR in forest land indicates the absence of a hardpan in the original soils. The increase of SPR with depth in forest land indicates the existence of natural processes where clay minerals are slowly migrating downward to deeper depths.

The greater SPR in pasture land than that of crop land at the top surface in both watersheds (Figure 3a,b) is either associated with cattle trafficking during wet condition in the pasture or with loosing up the soil in the top 10–15 cm by the *Maresha* plow on cultivated land. Mwendera and Saleem (1997) found greater soil compaction in the farm plots of Debre Zeit with an increased number of cattle passes.

An increment of SPR in the drier season in December measurement as compared with that of the wet season in July (Figure 2c,d) indicates the dependency of SPR on soil water content. Results from Vaz *et al.* (2011) and de Moraes *et al.* (2013) corroborate our findings by demonstrating that a decrease in soil water content increases SPR.

Relationships of SPR and Soil Properties

The relationships between SPR and some of the measured soil parameters were well explained by a power type equation as shown in Figure 6 and by a linear relationship in Tables S4 and S5. The relationship between SPR and fine particles was positive and significant ($R^2 = 0{\cdot}37$ in Anjeni, Figure 6a; and $R^2 = 0{\cdot}68$ in Debre Mewi, Figure 6b). This relationship is in agreement with the findings of Zisa *et al.* (1980) who reported that soils with a large amount of fine particles have smaller pore diameter and higher resistance to penetration than soils with large amount of coarse particles.

The SPR was significantly (negatively) correlated with SOM ($R^2 = 0{\cdot}66$ in Anjeni, Figure 6c; and $R^2 = 0{\cdot}76$ in Debre Mewi, Figure 6d). Likewise, the relationship between fine particles and SOM was significant and negative ($R^2 = 0{\cdot}68$ in Anjeni, Figure 6e; and $R^2 = 0{\cdot}68$ in Debre Mewi, Figure 6f). The negative relationship of SPR with SOM indicates that a reduction of organic matter in the soil

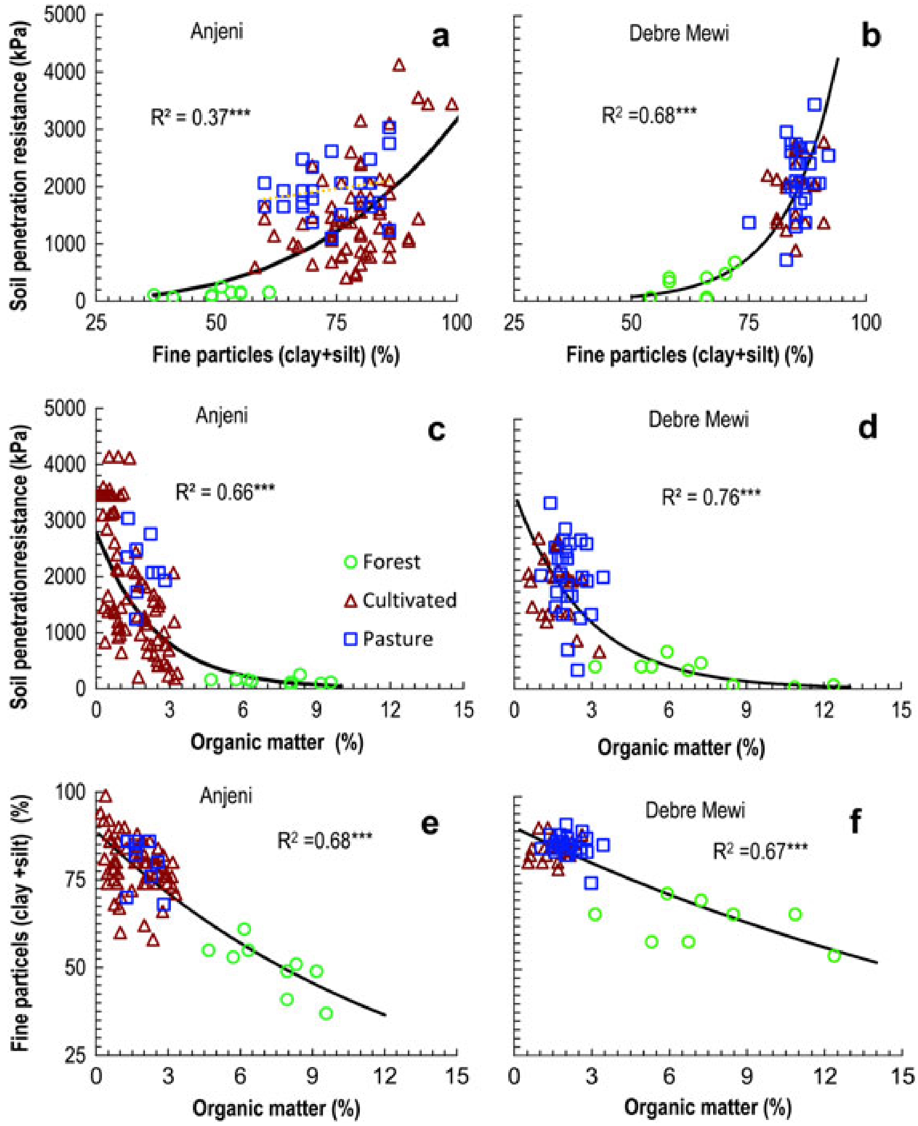

Figure 6. The relationship between soil penetration resistance with soil organic matter and fine particles (clay plus silt content) and fine particles with soil organic matter in Anjeni (a, c and e, respectively) and Debre Mewi (b, d and f, respectively) watersheds. *Significant at $p < 0{\cdot}05$ level; ** significant at $p < 0{\cdot}01$ level; and *** significant at $p < 0{\cdot}001$ level. [Colour figure can be viewed at wileyonlinelibrary.com]

decreases the binding potential of soil aggregates that promotes the development of good soil structure. Similarly, Wortmann and Jasa (2003) and Hoorman *et al.* (2011) stated that soils with lower organic matter content are more susceptible to soil compaction than those with higher organic matter content. Combining results from all land uses showed that the values at the lower tails (i.e. low SPR and low fine particles, low SPR and high SOM, and low fine particles and high SOM) are soils from forest lands.

As expected, bulk density was positively correlated with SPR. The correlation coefficients were significant (R^2 = 0·40 in Anjeni and R^2 = 0·63 in Debre Mewi, Tables S4 and S5). The relationship between pH and basic cations was positive. In particular, the correlation between pH and Ca^{2+} was significant (R^2 = 0·54 in Anjeni and R^2 = 0·76 in Debre Mewi). The relationship of pH with basic cations (Ca^{2+}) mainly shows that acidic pH in agricultural fields allows the basic cations, particularly Ca^{2+}, to leach because of the replacement of cations on exchange sites by acidic cations, H^+ and Al species (Haynes & Swift, 1986). In addition, reduction of CEC in agricultural fields aggravates the reduction of pH.

Effect of Land Use on Soil Properties and Hardpans Formation

In this study, comparison of soil physical and chemical properties between never-tilled forest lands and agricultural fields (Figures 3, 4 and 5 and Table S3) suggest that soils in the agricultural fields were originally characterized by high organic matter content, high CEC, high exchangeable base cations, a neutral pH, high soluble silica and low bulk density. But due to a prolonged use of land for agriculture, such soil properties are deteriorated over time. They have become lower in SOM content, exchangeable basic cations (particularly Ca^{2+}), CEC, higher in finer particles (clay and silt content), bulk density and insoluble silica and acidic in pH.

The elevated levels of SOM, soluble silica, pH and divalent ions in forest soils (Figures 3 and 4a,b) bind soil particles together as aggregates and provide a good soil structure. Decrease in organic matter content and other binding agents in the cultivated and pasture fields breaks up aggregates (Tisdall & Oades, 1982; Zhou *et al.,* 2013), and this is the reason that cultivated and pasture soils have a finer texture than forest soils (Figure 3a,b). Fine particles are likely to be easily dislodged by splashing raindrops than coarse aggregates (McIntyre, 1958), have a lower settling velocity once entrained in the water and stay much longer in suspension than large aggregates (Hjulstrom, 1939). This degradation process is reflected in increasing sediment concentration in the rivers of the Ethiopian highlands during the last 40 years (Steenhuis *et al.,* 2009; Steenhuis & Tilahun, 2014).

In addition, reduced soluble silica in the agricultural fields indicates its availability in the insoluble form. This situation favors binding of clay particles. The process is aggravated by the climatic condition of the region (humid climate). Wet climatic conditions increase clay deposition and silica cementation at the lower profiles (Litchfield & Mabbutt, 1962).

Based on our results previously, the enhanced anthropogenic formation of hardpans can be explained as follows: most of the rainwater infiltrates in unsaturated soils because saturated hydraulic conductivities are extremely high in forest soils and soils derived from volcanic material (Mendoza & Steenhuis, 2002; Hanson *et al.,* 2004; Bayabil *et al.,* 2010). Initially, under forest conditions where the organic matter concentrations are high and base cations are not leached, sediment concentrations in the water are extremely low and consist mainly of colloidal matter that infiltrates below 45 cm where the penetration resistance (Figure 3a,b), bulk density (Figure 3c,d) and the percentage of fine particles (Figure 4a,b) are greater than at the surface. Once the forests are cut down and the soil is plowed, the organic matter and other binding agents decrease, and the aggregates become unstable, raindrops pick up the fine sediment that moves down in the profile and settles into the pores. When the downward moving water stops, these sediment plugs pore in the top part (60 cm) of the profile as shown in Figure 7.

In agreement with our findings, other studies have shown that most agricultural activities in the rainfed agricultural system of Ethiopian highlands reduce soil quality. For instance, Emiru and Gebrekidan (2013) and Habtamu *et al.* (2014) noted that complete removal of crop residues after crop harvest for the purpose of animal fodder and fuel wood consumption increases loss of SOM. Likewise, Temesgen *et al.* (2009) showed repeated tillage for the purpose of soil turnover causes excessive soil pulverization, resulting in poor soil structure. In addition, Mwendera and Saleem (1997) and Tebebu *et al.* (2010) reported that clearing of

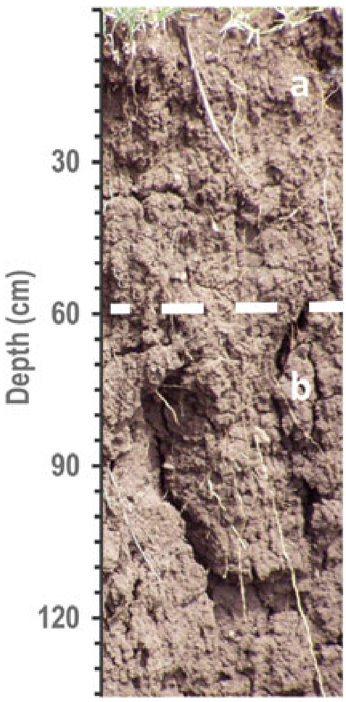

Figure 7. A degraded soil profile: the original flow paths are only present in the lower part of the profile (below 60 cm): (a) top soils with large pores filled with surface soil and (b) original macroporous network is still visible. [Colour figure can be viewed at wileyonlinelibrary.com]

vegetation and overgrazing is accelerating soil erosion and runoff. Soil erosion and runoff facilitate strong leaching of exchangeable cations particularly Ca^{2+} and Mg^{2+} (Hodnett & Tomasella, 2002; Emiru & Gebrekidan, 2013), which also results in an increase in soil acidity. Besides, continuous weathering processes (Hodnett & Tomasella, 2002; Amare *et al.,* 2013) and continuous use of ammonium source fertilizers (Emiru & Gebrekidan, 2013) increase soil acidity.

CONCLUSIONS

Agricultural fields in Anjeni and Debre Mewi watersheds have hardpans that impede root growth and restrict soil water movement. Our results show that hardpan formation is linked with the conversion of a forest ecosystem to agricultural use. In the past, when population pressure was low, shifting cultivation with long fallow periods was practiced. Organic matter levels remained high and hardpans did not form. However, recently, due to increasing population (96·5 million with 2·9% annual growth), land has become intensively cultivated, resulting in a loss of organic matter, leaching of base cations, disintegration of aggregates and increased sediment concentrations in overland flow. The sediment laden water that infiltrates is accelerating hardpan formation by plugging up the large pores. The overall findings of this study imply that hardpans in degraded soils are common in the humid Ethiopian highlands. Management interventions to decrease runoff and soil loss from the uplands should include increasing long-term infiltration rates through the hardpans.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site:

Table S1. Statistical summary of soil penetration resistance (SPR, kPa) and volumetric soil water content (SWC, %) in Anjeni and Debre Mewi watersheds measured under the three land uses during crop growing period. Measurements are at three depths: at 15 cm increments for SPR and 20 increments for SWC.
Table S2. Statistical summary of soil penetration resistance (SPR, kPa) and volumetric soil water content (%) in Anjeni and Debre Mewi watersheds measured under the three land uses after crop harvest. Measurements are at three depths: at 15 cm increments for SPR and 20 increments for SWC.
Table S3. Mean exchangeable base cations (Ca2+, Mg2+, K+ and Na+) as a function of land use. For each watershed at each soil parameter, land uses followed by the same letters are not significantly different at ($p < 0{\cdot}05$).
Table S4. Correlation between SPR and soil properties in the Anjeni watershed (Pearson correlation).
Table S5. Correlation between SPR and soil properties in the Debre Mewi watershed (Pearson correlation).

