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Assessing drivers of soil properties and classification in the West Usambara mountains, Tanzania

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ABSTRACT

Improved soil information in tropical montane regions is critical for conservation, sustainable agricultural management, and land use planning, but is often challenged by topographic and land-use heterogeneity. The West Usambara mountains are a part of the Eastern Arc chain of mountains of Tanzania and Kenya, a globally important tropical montane ecoregion made up of isolated fault-block mountain complexes characterized by high biological endemism, population density, and agronomic productivity. We synthesized novel and legacy soil data from published and unpublished studies to better understand the drivers of soil property distributions and soil diversity in the West Usambaras, and to serve as a foundation for improved soil mapping efforts across the Eastern Arc. Analysis of the resulting dataset of 468 sites (ranging in elevation from 1040 to 2230 m.a.s.l.) revealed that soil properties varied more significantly by land use and topography than by soil type, suggesting that future mapping efforts in the region should focus primarily on soil property prediction and secondarily on soil classification. Sites under cultivated land uses had the lowest topsoil soil organic carbon (SOC) concentrations and highest pH values, and SOC generally increased with increasing elevation. Valley soils had significantly lower surface SOC concentrations but higher exchangeable bases and pH values than all other landscape positions. Soil pH decreased by an average of 3.5 units across the entire elevation gradient and decreased by 1 unit with elevation even after SOC, land use and landscape position were included in multiple regression models. The relationship of cation exchange capacity (CEC) to SOC and clay content varied by landscape position. Therefore, particularly in montane regions where soils can vary significantly over short distances, multiple functions may be necessary to produce improved estimates of parameters such as CEC. Soil classification was driven most strongly by topography, with Acrisols (WRB Reference Group) and Ultisols (U.S. Soil Taxonomy (ST)) as the dominant soil types, located primarily on mid slope, upper slope and crest landscape positions, making up 47% and 75% of observed profiles, respectively. However, five ST Orders and seven WRB Reference Groups were present in the dataset, with the highest soil diversity occurring at lower slope landscape positions. Conclusions drawn from this large dataset support previous work in the West Usambaras and provide a conceptual foundation from which to build improved soil maps across the Eastern Arc and in other tropical montane systems throughout the world.

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1. Introduction

East Africa's biologically, agronomically, and culturally important Eastern Arc Mountains (a series of isolated fault-block mountains) pass through Kenya and Tanzania (Hall et al., 2009) and include, among others, the Pare, Usambara, Uluguru and Udzungwa mountain complexes (Burgess et al., 2007; Conte, 2010). Forest ecosystems in the Eastern Arc are hotspots of regional terrestrial carbon storage and are critically linked to the soil resources that support them (Hamilton, 1998; Hall et al., 2009). The Usambara mountains in particular have long been of significant interest to biologists and agronomists because of their temperate climate, unique vegetation, water resources, agronomic potential (Milne, 1944), and high degree of biological diversity and endemism (Burgess et al., 2007).

The deeply dissected plateau region of the West Usambara mountain block rises in a steep escarpment from the Maasai Plains, and is an important physiographic region where land-use change, post-colonial population pressure and intensive agricultural land use is most pronounced (Conte, 1999, Fig. 1). Indigenous agriculture has been practiced on the West Usambaran plateau for millenia and originally consisted mostly of valley cultivation, with strong societal values placed on the forest resource (Conte, 1999). Increasing population pressure and post-independence resource management has resulted in extensive land use change and significant soil erosion and soil degradation (Kaoneka and Solberg, 1994; Jambiya, 1998; Conte, 1999).

Since that time, considerable scientific effort has been invested in understanding and modeling rates of soil erosion (Lundgren, 1980; Vigiak et al., 2005, 2006,b; Vrieling et al., 2006; Minderhound, 2011; Gorter, 2012), soil conservation practice adoption and planning (Mbaga-Semgalawe and Folmer, 2000; Tenge et al., 2004; Tenge, 2005; Nyanga et al., 2016), the evaluation of the efficiency and effectiveness of those practices (Tenge et al., 2005; Msita et al., 2009; Wickama et al., 2014, 2015), surveys of soil fertility and plant nutrient deficiencies (Smithson et al., 1993; Wickama and Mowo, 2001; Ndakidemi and Semoka, 2006), and the effects of land-use change on soil resources in general in the West Usambaras (Meliyo et al., 2016; Winowiecki et al., 2016).

Most existing national and regional scale maps and databases (including data from the Soil and Terrain database (SOTER), Eschweilier, 1998) are based on the work of De Pauw (De Pauw, 1984), who produced small scale maps of Tanzania (1:2 million), in which the West Usambaran plateau region is represented as a single map unit of Umbric Acrisols (De Pauw, 1984). In contrast to adjacent physiographic regions (the East Usambaran plateau and the piedmont and plain below the West Usambaran escarpment) which have been mapped in detailed projects due to their importance in the production of sisal and other plantation crops (i.e. Hartemink, 1989, 1997), limited soil mapping work has been conducted in the plateau region of the West Usambaras, where elevation gradients are much larger and smallholder systems are dominant. Two detailed soil characterization and mapping efforts in the West Usambaras of limited scale (Meliyo et al., 2001; Massawe, 2011), have demonstrated a high level of variability in soil properties and classification which may dramatically influence management recommendations. More recent efforts to map soil properties at larger scales based on legacy databases (Leenaars et al., 2014) and a combination of remote sensing and systematic soil sampling have dramatically improved information availability and prediction quality (Winowiecki et al., 2016,b). Despite these efforts, a critical demand for improved soil information in the West Usambaras remains, and there is a need for increased understanding of the distribution of soil properties and soil types on the plateau.

The objectives of this work were therefore to (1) synthesize and analyze published, unpublished, novel and legacy data for soils of the West Usambaran plateau, in order to (2) better understand the drivers of soil property distributions and soil diversity in the West Usambaras. New information generated from these objectives can be utilized to

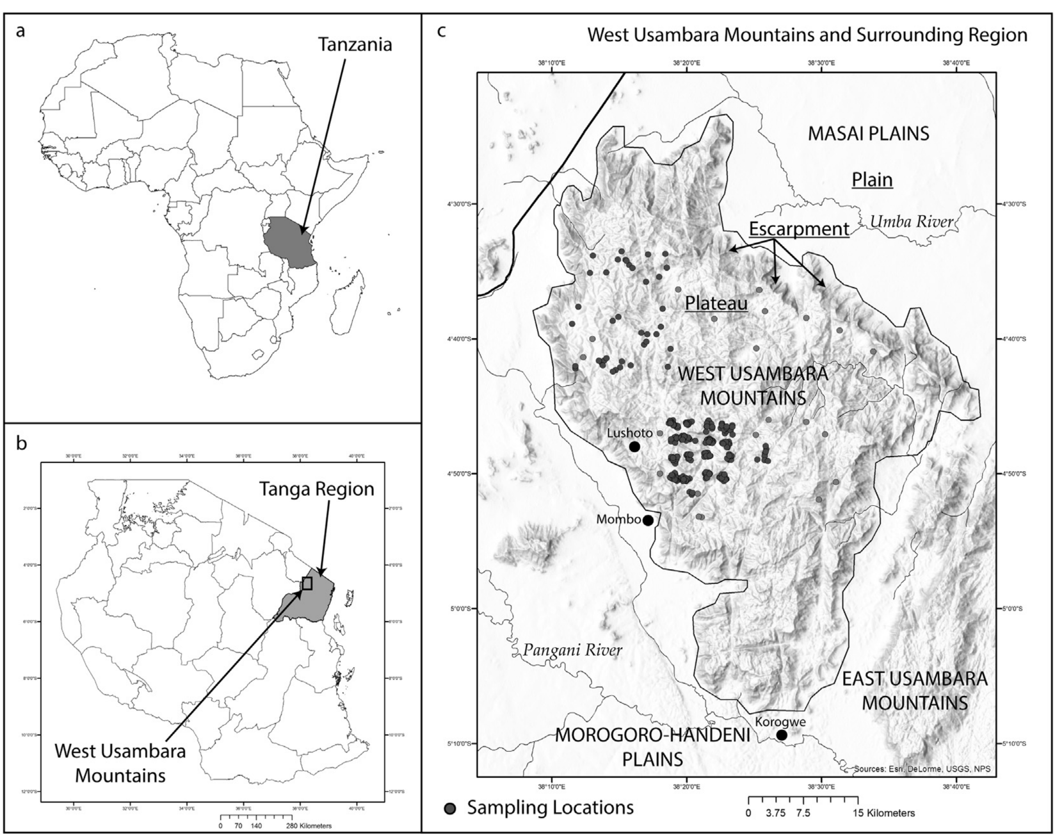

Fig. 1. Location, physiographic context, and distribution of sampling locations across the plateau region of the West Usambara mountains.

improve ongoing and future efforts in soil mapping and soil management in the West Usambaras.

2. Data sources and methods

2.1. Plateau geology, vegetation, and soil parent materials

The West Usambaran plateau is a deeply dissected block mountain complex with a maximum elevation of 2230 m.a.s.l. (Mount Magamba) comprised largely of Pre-Cambrian basement rocks of the Usangaran belt (Appel et al., 1998). These metamorphic rocks have been subjected to a complex history of faulting, uplifting, and erosion (Maboko and Nakamura, 2002) and are dominated by intermediate gneiss comprised largely of quartzo-felspathic granulites which also contain hornblende, pyroxene, andesine, and diopside (Hartemink, 1997; Maboko and Nakamura, 2002). Bedrock-controlled uplands on the West Usambaran plateau are highly dissected by both narrow and broad, bowl-shaped valleys (Meliyo et al., 2001). Extensive cultivation of valley and hillslope soils occurs for household and commercial production – common crops include maize, beans, potatoes, cassava, high value vegetables, coffee and temperate fruits (Lyamchai et al., 2011). Additional land use practices include agroforestry systems utilizing *Albizzia* spp. and *Grevillea* spp., pasture, shifting cultivation, and charcoal production (Kaoneka and Solberg, 1994). Native vegetation on the plateau includes submontane, montane, upper montane, and dry montane forest ecosystems (Kaoneka and Solberg, 1994; Hall et al., 2009). Soil parent material groupings on the West Usamabaran plateau include (1) gneissic residuum at crest positions, (2) residuum, colluvium and local alluvium (colluvio-alluvium) on upper slopes, (3) colluvium and local alluvium (colluvio-alluvium) on lower slopes, and (4) colluvium and alluvium in valleys (Meliyo et al., 2001; Massawe, 2011).

2.2. Data sources

We compiled published and unpublished data from studies on the West Usambaran plateau which contained soil morphological or soil property characterization data that reached deeper than 25 cm. Some of these sources also contained points with data shallower than 25 cm – in this case, as long as the individual dataset as a whole contained points with data deeper than 25 cm, we included all available data from the study, regardless of depth. The data compiled in this manuscript therefore originates from several published and unpublished sources (Meliyo et al., 2001; Mbogoni, 2011; Massawe, 2011; Leenaars et al., 2014; Winowiecki et al., 2016; Jelinski, Unpublished Data; Meliyo, Unpublished Data) (Fig. 1).

We will refer to the compiled sampling locations collectively as “sites”. Our data synthesis resulted in a compiled dataset of 468 unique sites containing information on soil properties to an average of 65 ± 34 cm in depth (ranging from 20 to 200 cm in depth; Supplementary material, Fig. SM1a). Both cation exchange capacity (CEC) and base saturation (BS) data are required to definitively classify many tropical soils at the highest levels of both the U.S. Soil Taxonomy (ST) (Soil Survey Staff, 2014a) and UN-FAO World Reference Base (IUSS Working Group WRB, 2015) systems. Of these 468 data points, 69 sites (15% of sampling points) had morphological data and laboratory CEC and BS values, and thus were able to be definitively classified with available data ($n = 69$, “pits” in Supplementary material, Fig. SM1). The remaining 399 sites were all sampled by depth increment and had no associated morphological information or soil classification. Of the 468 sites, 389 (83%) contained data deeper than 50 cm in depth, and 107 (23%) contained data deeper than 100 cm in depth (Fig. S1a). Additional information regarding the distribution of sites between land use and landscape position categories is provided in the Supplementary material (Section SM1).

2.3. Land use, landscape position and soil classification

Four generalized land use categories were chosen to represent the broad range of sites in our dataset: (1) Cultivated, (2) Low Intensity (Shrubland, Pasture and Fallow), (3) Mature Forest (forests generally > 50 years old), and (4) Charcoal Production Areas. We defined Charcoal Production Areas as intensively utilized areas where biomass has been accumulated, burned, covered with soil materials, and converted into charcoal for household or commercial purposes. We chose to separate Charcoal Production Areas from other land use categories because these areas tended to have highly unique soil morphologies (characterized by thick accumulations of organic soil materials) and soil organic carbon (SOC) profiles, regardless of where they occurred in the landscape. In order to properly synthesize site information across authors and studies, each site was assigned to one of five generalized landscape positions (Valley, Lower Slope, Mid Slope, Upper Slope and Crest). These five landscape positions focused predominantly on the broader geomorphologic setting instead of localized complex hillslopes.

Sampling points were classified according to the four land use categories utilizing expert knowledge, consultation with original authors, and field notes; and into one of the five landscape position categories using digital elevation models, expert knowledge, consultation with original authors, and field notes. 450 sites (96%) had associated land-use information, 464 sites had associated elevation and slope aspect data, and all 468 (100%) of the sampling points contained landscape position information. Slope aspect was divided into two categories, based on effects of slope aspect on microclimate in the Usambaras (south and east facing slopes (45–225°) are typically moister and cooler, while noth and west facing slopes (225–45°) are typically drier and warmer (Burgess et al., 2007).

2.4. Laboratory analyses

Although our consolidated dataset represents a number of studies carried out over a number of years, the range of methodologies and laboratories utilized is relatively small and highly comparable. Three laboratories were utilized for wet chemical analysis (Soil Testing Laboratory – Sokoine University of Agriculture, Morogoro, Tanzania; Agricultural Research Insitute (ARI) Mlingano, Tanga, Tanzania; and Crop Nutrition Laboratory Services, Nairobi, Kenya). Soil chemical analysis procedures in each of these laboratories followed established protocols: wet chemical analysis of soil organic carbon (SOC) was determined by the Walkley-Black method (Walkley, 1947; Soil Survey Staff, 2014b), involving a permanganate oxidation process, $FeSO_4$ titration, and accepted recovery factor estimates (Soil Survey Staff, 2014b). Total nitrogen was determined by the Kjeldahl N wet chemical method (Soil Survey Staff, 2014b). Soil texture (clay and sand %) was determined by hydrometer. Available phosphorus data for comparative purposes in our dataset was restricted to Bray-1 (only 2% of samples in the dataset had pH values > 7) and was determined by the Bray-1 colorimetric method (Bray and Kurtz, 1945). Total P was determined on samples ($n = 99$) from a single study in our dataset (Jelinski et al., Unpublished) and utilized a nitric acid-microwave digestion procedure (Tadon et al., 1968). pH was determined in 1:2.5 slurries of soil and distilled water (McLean, 1982; Soil Survey Staff, 2014b). Cation exchange capacity (CEC), individual exchangeable base concentrations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}), and total exchangeable bases were determined by ammonium acetate extraction and flame AAS analysis (Sokoine and Mlingano) or ICP-OES (Crop Nutrition Services) (Soil Survey Staff, 2014b).

Two studies (Winowiecki et al., 2016 and Jelinski, Unpublished) utilized mid-Infrared (MIR) spectroscopy, calibrated to wet chemical analyses conducted by a commercial laboratory (Crop Nutrition Laboratory Services, Nairobi, Kenya) and SOC by dry combustion at Iso–Analytical Laboratory (Cheshire, UK), to estimate several soil properties of interest in the dataset (SOC, Total Nitrogen (TN), pH, total exchangeable bases, and clay). These proximal soil sensing techniques were shown to correlate extremely well (SOC: $R^2 > 0.98$; total nitrogen: $R^2 > 0.99$; pH: $R^2 > 0.96$, total exchangeable bases: $R^2 > 0.92$ and clay: $R^2 > 0.94$) with wet chemical methods. Further information on MIR results, methods and correlations is provided in Winowiecki et al. (2016). No significant systematic variability in soil property values between authors or laboratories was detected in this compiled dataset.

We acknowledge that the synthesis of data across studies may unintentially introduce temporal trends in the data, particularly for dynamic soil properties such as SOC. However, we believe, at least in the case of our dataset, that any such trends are minimal for the following reasons: (1) 91% of the data (425 of 468 sites) was collected between the years 2010–2014, with only 8% of the data (35 of 468 sites) collected between the years 1999–2001 and 1% of the data (4 of 468 sites) collected in 1988; (2) a comparison of site average 0–20 cm SOC (a metric which should be temporally sensitive under environmental change) revealed no significant differences between authors or studies compiled in this dataset. By this reasoning, we do not imply that there would be no temporal effect on soil properties, but instead that any potential temporal signal in the case of our particular dataset is likely minimized relative to the importance of other factors. We believe that the benefits of the inclusion of the older data in this analysis (particularly with regard to understanding relationships between soil properties and expanding the spatial extent of the dataset) outweighs any potential risk of the inclusion of major temporal trends and also note that legacy data has been compiled and utilized extensively (with appropriate caveats) in other studies across sub-Saharan Africa (Leenaars et al., 2014).

2.5. Statistical analyses

All statistical analyses were performed in R (version 3.3.1, R Core Team, 2016). We utilized Kendall's tau-b (b) non-parametric rank correlation coefficient (with Holm's correction for multiple comparisons) to examine the relationship between measured soil properties across all samples because (1) we did not assume linear relationships between variables and (2) several variables had a significant number of tied values. Post-hoc analyses for significant differences in response variables between groups after ANOVA analyses were conducted using Tukey's Honest Significant Difference (HSD) in group means. Unless otherwise mentioned in manuscript text or figure captions, all reported uncertainties represent a single standard deviation around the mean.

Because our dataset represents a mixture of sites sampled by genetic horizon and others by depth increment, we chose to utilize Land Degradation Surveillance Framework (LDSF) (Vågen et al., 2013) standardized depth increment (0–20 cm, 20–50 cm, and 50–100 cm (combining the 50–80 cm and 80–100 cm LDSF standardized depth increments into one 50–100 cm increment) weighted averages to compare soil properties by depth between sites. We calculated the weighted averages of all available soil properties by depth increment for each sampling site using the “slab” function in the AQP package in R (Beaudette et al., 2013; R Core Team, 2016). These standardized depth-increment weighted averages were utilized to examine the relationships between soil properties and site-level characteristics such as elevation, land use, and landscape position.

The effects of land use, landscape position and elevation on SOC and pH were evaluated using both ANOVA (for categorical variables land use and landscape position) and multiple regression models (including both categorical variables and the continuous co-variates elevation and SOC or pH, respectively). To build our multiple regression models, we began with a specific set of site factors: elevation, land use, landscape position, aspect, and evidence for the coupling of SOC and pH. We checked for the inclusion of highly correlated (co-linear) predictors by calculating pairwise correlations and variance inflation factors (VIF).

Our purpose for conducting these regressions was to understand the relationships between variables, but not prediction for its own sake. Therefore, we used a forward selection process in which all models began by single regressions of elevation, land use, landscape position, or aspect on either SOC or pH. The factor with the highest R^2 was retained in the model. Multiple regression models including that factor with the other remaining factors were then constructed and, again, the model with the highest R^2 was retained. This was repeated until either all factors were in the model, or the remaining factors could be eliminated due to non-significance. Once the final model without interactions was constructed, interaction terms were tested and (for the purposes of interpretability), only the most significant interaction term was retained in the model. Finally, backwards stepwise selection was performed on the full model. In all cases, all terms in the full model were retained.

3. Results

3.1. Soil property distributions and relationships between soil properties

The distribution statistics for all measured soil properties in our compiled database are shown in Table 1. Clay content, pH, BS and bulk density were the most symmetrically and normally distributed variables, while the distributions of most other soil properties were skewed to the left (many observations at lower values) and heavy tailed (few observations at much higher values).

SOC and pH were significantly correlated to more soil properties (10 and 9 other measured properties, respectively) than any other measured variables (Table 2). Total Nitrogen (TN) was also significantly correlated to the same 10 variables as SOC, however due to strong collinearity with SOC ($\tau_b = 0.87$), we consider the high correlation of TN with the other variables to be a consequence of its relationship with SOC (Supplementary material Section SM2.3.1). SOC was significantly negatively correlated with depth, clay content, and pH; and significantly positively correlated to TN, C/N Ratio, Bray P, Total P, Soil Color (as parameterized by the Hurst Index (Hurst, 1977) – Supplementary material Section SM2.3.4), and CEC.

Across all samples, pH was most strongly correlated with BS ($\tau_b = 0.63$) (Table 3). Observed BS values ($n = 183$) ranged from 1% to 100%, and were most strongly correlated with pH. We evaluated a constrained logistic (lower asymptote constrained to 0 and upper asymptote constrained to 100) and linear model to derive an empirical relationship between pH and BS. The constrained logistic model performed better than a linear model, with a prediction efficiency of 43% (Supplementary Table S1, Fig. 2). The relationship between pH and Total Exchangable Bases was best represented by a polynomial model (Fig. 2), with a prediction efficiency of 30%.

Other soil properties were significantly correlated with only six (clay content, C/N ratio, exchangeable Ca and K), five (BS, exchangeable Mg, clay-normalized CEC, CEC, Bray P, sand), four (total exchangable bases), three (total P, soil color (Hurst Index)), or two (exchangable Na) other variables. The only correlations in the dataset which were significantly ($p < 0.01$) > 0.6 (positive or negative) were between pH and BS ($\tau_b = 0.63$), clay and sand ($\tau_b = -0.67$), exchangeable Ca and BS ($\tau_b = 0.66$), total exchangeable bases and BS ($\tau_b = 0.71$), SOC and TN ($\tau_b = 0.87$) and exchangeable Ca and total exchangeable bases ($\tau_b = 0.89$) (Tables 2 and 3).

3.2. Cation exchange capacity

Across all samples, cation exchange capacity (CEC) was most strongly correlated to SOC ($\tau_b = 0.36$), and secondarily to clay content ($\tau_b = 0.16$). CEC values ranged from 2 to 90 $cmol_c\ kg^{-1}$, with a mean and standard deviation of 17.9 ± 10.0 $cmol_c\ kg^{-1}$, while clay-normalized CEC values ranged from 3.6–432.4 $cmol_c\ kg^{-1}$ with a mean of 34 ± 38 $cmol_c\ kg^{-1}$. Multiple regression of CEC using all individual samples containing CEC data ($n = 183$) resulted in a linear model with

Table 1
Descriptive statistics of the distribution of soil properties and site variables (elevation and observation depth) for all dataset samples in the plateau region of the West Usambara mountains.

Property	N	Range (min–max)	Mean	Median	25th Percentile	75th Percentile	CV (%)	Skew	Kurtosis
Individual samples									
Clay (%)	1276	5–93	61	63	52	72	24	− 0.7	3.3
Sand (%)	1276	2–80	23	21	14	29	58	1.2	4.7
pH (1:1 H_2O)	1276	3.9–8.1	5.7	5.8	4.9	6.3	14	− 0.2	2.0
SOC (g 100 g^{-1})	1276	0.1–27.0	3.4	2.5	1.7	3.9	85	2.3	10.7
TN (g 100 g^{-1})	1208	0.01–1.19	0.28	0.23	0.16	0.35	69	1.5	5.3
CEC (cmolc kg^{-1})	183	2.2–90.5	17.9	15.8	12.2	22.3	56	2.5	16.9
Clay-normalized CEC (cmolc kg-$clay^{-1}$)	182	3.7–432.4	34.0	26.9	19.1	35.8	112	7.1	69.4
Ex Ca (cmolc kg^{-1})	265	< 0.1–3.5	6.2	4.3	1.6	9.1	98	1.5	5.8
Ex Mg (cmolc kg^{-1})	265	< 0.1–6.8	0.9	0.4	0.09	1.22	138	2.3	9.5
Ex K (cmolc kg^{-1})	265	< 0.1–7.82	0.74	0.30	0.08	1.02	157	3.2	15.9
Ex Na (cmolc kg^{-1})	265	< 0.1–0.91	0.18	0.12	0.06	0.26	93	1.8	7.0
TEB (cmolc kg^{-1})	1174	< 0.1–49.3	10.8	9.3	5.8	14.2	67	1.4	6.5
B.S. (%)	183	< 1–100	42.3	45.1	11.3	65.4	70	0.2	2.0
Bray P (ppm)	269	< 0.1–99.5	8.6	3.0	1.5	7.7	182	3.4	16.2
Total P (ppm)	99	48–3493	631	578	430	723	75	3.8	22.2
C/N ratio	1208	4–70	12.2	11.5	10.5	13.0	29	6.1	78.6
Hurst index	228	4–100	20.0	15.0	10.9	22.5	75	2.2	10.0
Bulk density (g/cm3)	97	0.39–1.63	0.97	0.92	0.79	1.14	28	0.3	2.8
Sites									
Elevation (m)	464	1040–2240	1504	1522	1287	1675	15	0.3	2.5
Depth of observation (cm)	468	20–200	65	50	20	36	53	1.3	4.3

Table 2
Correlations (Kendall's tau-b) between SOC and pH with other measured soil properties for individual samples across combined dataset.

Property	Depth (cm)	Clay (%)	Sand (%)	TN (%)	C/N Ratio	Bray P	Total P	CEC	BS	TEB	SOC	pH_H2O
N	1276	1276	1276	1208	1208	268	94	182	182	264	1276	1276
SOC (g 100 g^{-1})	− 0.36***	− 0.13***	ns	0.87***	0.26***	0.39***	0.51***	0.36***	− 0.17***	ns	1	− 0.38***
pH (H_2O)	ns	0.14***	− 0.11***	− 0.36***	− 0.33***	− 0.25***	− 0.30***	ns	0.63***	0.53***	− 0.38***	1

ns = not significant ($p > 0.05$).
*** Significant at $p < 0.001$.

both SOC and clay content as significant co-variates (CEC = 2.98751 ∗ SOC + 0.12152 ∗ Clay + 2.69575; $R^2 = 0.49$, $p < 0.0001$). Standardized coefficients for SOC and clay content in the model including all samples were 0.73 and 0.23, respectively.

When Valley sites ($n = 29$) were separated from all other landscape positions, SOC was not a significant predictor of CEC ($p = 0.39$), while clay content remained a significant predictor ($R^2 = 0.34$, $p < 0.001$), with a standardized regression coefficient of 0.61 (Fig. 3). For the subset of CEC values at non-valley ((Lower, Mid, Upper and Crest) sites ($n = 154$), both SOC and clay content were significant predictors ($R^2 = 0.62$, $p < 0.0001$) with standardized regression coefficients of 0.84 and 0.18, respectively. Clay content was not a significant predictor of CEC for hillslope soils when considered as the sole co-variate ($p = 0.11$).

3.3. Soil properties by depth and site factors – SOC

Sites under Cultivated land use had the lowest SOC concentrations across all depth increments ($p < 0.001$), and SOC concentrations were significantly affected by land use for all three standardized depth increments ($p < 0.001$, Table 4). Topsoil (0–20 cm) SOC concentrations were significantly higher than SOC concentrations in lower depth increments (20-50 cm and 50–100 cm) across all land-uses (Table 4). Valley and Lower slope landscape positions had the lowest 0–20 cm SOC concentrations, while 50–100 cm SOC concentrations were not significantly different between all landscape positions. Among hillslope soils (Lower, Mid and Upper landscape positions, excluding Valley and Crest positions), aspect did not have a significant effect across all sites after other terms were in the model so was excluded from the ANOVA analysis. The effect size (as estimated by η^2, Table 4) and significance of land use on SOC concentrations was an order of magnitude higher than the effect of landscape position at all depths. Interaction terms between land use and landscape position were significant at all depth increments and increased in magnitude with depth (Table 4). SOC concentrations were not significantly related to ST Order or WRB Reference Group ($p > 0.1$ for all cases, 1-way ANOVA) across all depths (Table 5).

Table 3
Correlations (Kendall's tau-b) between pH and base saturation (BS) with other measured soil properties for individual samples across combined dataset.

Property	Exchangable Ca (cmol$_c$ kg^{-1})	Exchangable Mg (cmol$_c$ kg^{-1})	Exchangable K (cmol$_c$ kg^{-1})	Exchangable Na (cmol$_c$ kg^{-1})	Total Exchangable Bases (cmol$_c$ kg^{-1})	pH (H2O)	B.S. (%)
N	1276	1276	1276	1208	1208	1276	1276
pH (H2O)	0.50***	0.24***	0.31***	ns	0.54***	1	0.63***
B.S. (%)	0.66***	0.41***	0.41***	0.23***	0.71***	0.63***	1

ns = not significant ($p > 0.05$).
*** Significant at $p < 0.001$.

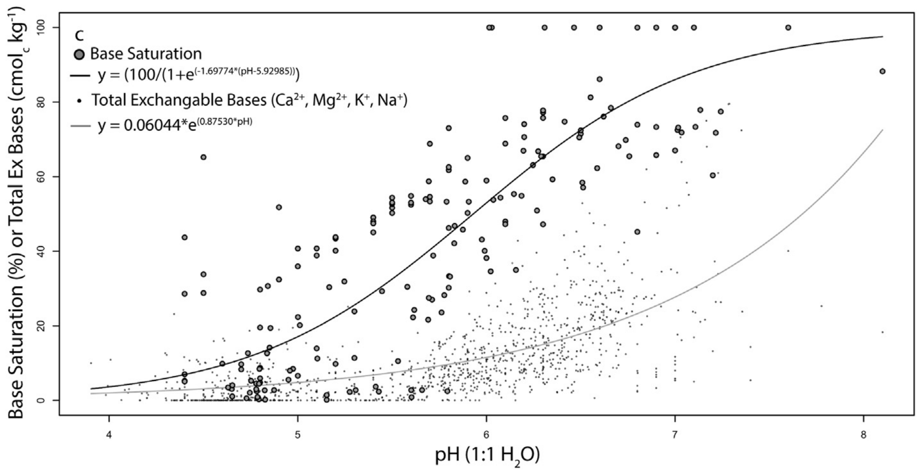

Fig. 2. pH and Base Saturation (filled grey circles) and Total Exchangable Bases (TEB) (small points). The best-fit function for the pH-Base Saturation relationship was a constrained Logistic function. The lower asymptote and upper asymptotes of this logistic function were defined as 0 and 100%, respectively. The best fit function for the pH-TEB relationship was an Exponential function.

3.4. Soil properties by depth and site factors – pH

pH was significantly different between land use categories ($p < 0.05$, Table 4) at all depths, with the exception of Mature Forest and Charcoal Production sites. Sites under Cultivated land use were significantly higher in pH than all other land use categories across all depth increments. Forest and Charcoal Production land uses were significantly lower in pH than other land use categories except for the lowest (50–100 cm) depth increment (Table 4).

In contrast to patterns in SOC concentrations, pH was driven strongly by both land use and landscape position across all depth increments. Specifically, Valley and Lower positions were significantly higher in pH than Mid, Upper and Crest positions at all depths. The effect of land use category on pH decreased in successively lower depth increments, while the effect of landscape position on pH increased (from $\eta^2 = 0.08$ in the 0–20 cm increment to $\eta^2 = 0.31$ in the 50–100 cm increment) with depth (Table 4). Among hillslope soils (Lower, Mid and Upper landscape positions, excluding Valley and Crest positions), aspect did not have a significant effect across all sites after other terms were in the model so was excluded from the ANOVA analysis.

pH differences between ST Orders were not consistent across all depth increments (Table 5). However, Ultisols had, on average, lower pH values than Inceptisols at all depth increments, and lower pH values than Mollisols in the 0–20 and 20–50 depth increments. Among WRB Reference Groups, Phaeozems had significantly higher pH values than

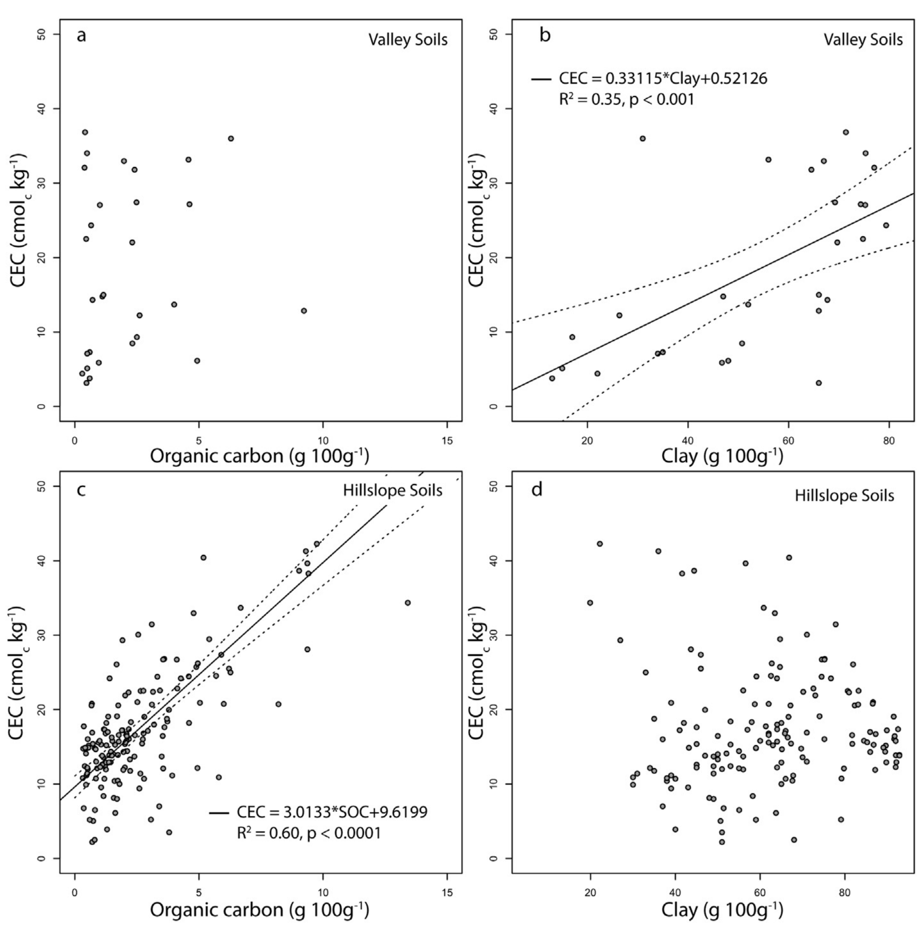

Fig. 3. Cation Exchange Capacity (CEC, $cmol_c\ kg^{-1}$) relationships: CEC and soil organic carbon (SOC) for a) Valley soils – no significant relationship. b) CEC and clay for Valley soils. c) CEC and SOC for Hillslope Soils (Lower, Mid, Upper and Crest landscape positions). d) CEC and clay for Hillslope soils – no significant relationship.

Table 4
Upper Portion: Means and standard deviations of SOC and pH for slabbed depth increments across all samples. Lower Portion: Results of two-way ANOVA analysis (using Land Use and Landscape Position as independent factors). The eta-squared values represent the proportion of variance explained by the factor once other factors are already in the model.

	N[a]	SOC (g 100 g^{-1})			pH (H_2O)		
		0–20 cm	20–50 cm	50–100 cm	0–20 cm	20–50 cm	50–100 cm
Land use							
Cultivate	(259, 215, 54)	2.9 ± 1.3 Aa[b]	2.3 ± 1.1 Ab	1.4 ± 0.9 Ac	6.0 ± 0.6 Aa	6.0 ± 0.6 Aa	6.0 ± 0.7 Aa
Low Intensity	(123, 101, 17)	5.5 ± 3.0 Ba	3.9 ± 2.6 Bb	2.9 ± 2.2 Bb	5.4 ± 0.8 Ba	5.4 ± 0.8 Ba	5.3 ± 0.6 Ba
Mature Forest	(49, 39, 12)	8.6 ± 4.7 Ca	5.7 ± 3.5 Cb	2.9 ± 2.5 Bb	5.0 ± 0.7 Ca	4.9 ± 0.6 Ca	5.1 ± 0.5 Ba
Charcoal Production	(17, 13, 1)	10.3 ± 3.7 Ca	6.4 ± 2.0 Cb	5.0	4.7 ± 0.4 Ca	4.6 ± 0.3 Ca	4.7
Landscape position							
Valley	(49, 42, 15)	2.9 ± 1.7 Aa	2.0 ± 1.2 Ab	1.2 ± 0.9 Ab	6.3 ± 0.6 Aa	6.4 ± 0.6 Aa	6.4 ± 0.8 Aa
Lower	(59, 48, 18)	3.3 ± 2.7 Aa	2.7 ± 2.4 ABa	1.7 ± 2.0 Aa	5.9 ± 0.6 Ba	5.9 ± 0.6 Ba	5.8 ± 0.9 ABa
Mid	(171, 137, 36)	4.9 ± 3.8 Ba	3.5 ± 2.6 Bb	2.1 ± 1.3 Ab	5.5 ± 0.8 Ca	5.5 ± 0.7 Ca	5.5 ± 0.7 Ba
Upper	(42, 24, 11)	4.3 ± 2.1 Ba	2.6 ± 1.1 ABb	1.8 ± 1.1 Ab	5.5 ± 0.6 Ca	5.3 ± 0.6 Ca	5.3 ± 0.6 Ba
Crest	(145, 134, 20)	5.0 ± 3.4 Ba	3.5 ± 2.3 Bb	2.1 ± 2.1 Ab	5.6 ± 0.8 Ca	5.6 ± 0.8 Ca	5.6 ± 0.7 Ba
ANOVA							
Land Use		$\eta^2 = 0.43$; $p < 0.01$	$\eta^2 = 0.31$; $p < 0.01$	$\eta^2 = 0.30$; $p < 0.01$	$\eta^2 = 0.30$; $p < 0.01$	$\eta^2 = 0.27$; $p < 0.01$	$\eta^2 = 0.23$; $p < 0.01$
Hillslope Position		$\eta^2 = 0.03$; $p = 0.03$	$\eta^2 = 0.04$; $p = 0.01$	ns	$\eta^2 = 0.08$; $p < 0.01$	$\eta^2 = 0.12$; $p < 0.01$	$\eta^2 = 0.31$; $p < 0.01$
Interaction		$\eta^2 = 0.09$; $p < 0.01$	$\eta^2 = 0.11$; $p < 0.01$	$\eta^2 = 0.41$; $p < 0.01$	ns	ns	ns

[a] Numbers in the "N" column refer to the number of sites with values contributing to the mean of that depth increment (successively, from left to right) within each Land Use or Landscape Position category – note that the numbers of contributing sites generally decrease with depth as not all sites had data to a depth of 50 or 100 cm.
[b] Numbers with different capital letters are significantly different (Tukey's HSD, $p < 0.05$) across Land Use or Landscape Position categories within the same depth increment. Numbers with different lower case letters are significantly different (Tukey's HSD, $p < 0.05$) across standardized depth increments within Land Use or Landscape Position categories.

Table 5
Means and standard deviations of SOC and pH for slabbed depth increments across all samples by U.S. Soil Taxonomy (ST) Soil Order and UN-FAO WRB Reference Group.

	N[a]	SOC (g 100 g^{-1})			pH (H2O)		
		0–20 cm	20–50 cm	50–100 cm	0–20 cm	20–50 cm	50–100 cm
U.S. ST order							
Entisol	(5, 4, 4)	2.6 ± 1.2A[b]	1.7 ± 1.0 AB	1.5 ± 1.1 A	5.3 ± 0.6 AB	5.6 ± 0.8 AB	5.6 ± 0.9 A
Inceptisol	(5, 5, 3)	2.5 ± 1.4A	1.1 ± 0.5 A	0.5 ± 0.1 A	6.3 ± 1.0 A	6.3 ± 1.1 A	6.9 ± 0.3 B
Mollisol	(5, 5, 2)	4.1 ± 1.7A	4.4 ± 1.7 B	2.4 ± 0.6 A	6.3 ± 0.9 AB	6.4 ± 1.1 A	6.5 ± 0.8 AB
Alfisol	(6, 6, 3)	3.3 ± 1.5A	2.0 ± 1.3 AB	1.0 ± 0.4 A	6.2 ± 0.3 A	6.1 ± 0.4 AB	5.8 ± 0.4 AB
Ultisol	(48, 47, 27)	4.4 ± 2.4A	2.7 ± 1.7 AB	1.9 ± 1.1 A	5.4 ± 0.6 B	5.3 ± 0.6 B	5.3 ± 0.6 A
WRB reference group							
Regosol	(2, 1, 1)	2.2 ± 0.1 A	1.7	1.4	5.2 ± 0.5 AB	5.2	5.4
Fluvisol	(5, 5, 4)	3.8 ± 1.9 A	3.1 ± 2.0 A	1.8 ± 1.3 A	5.7 ± 0.7 AB	5.8 ± 0.7 ABC	5.7 ± 0.9 AB
Gleysol	(3, 3, 2)	3.1 ± 1.6 A	2.0 ± 2.1 A	0.5 ± 0.2 A	6.3 ± 1.1 AB	6.6 ± 1.0 AC	7.1 ± 0.1 A
Cambisol	(3, 3, 1)	2.8 ± 1.9 A	1.3 ± 0.5 A	0.4	5.8 ± 1.2 AB	5.8 ± 1.2 ABC	6.7
Phaeozem	(2, 2, 1)	2.4 ± 0.7 A	3.8 ± 3.1 A	2.0	7.1 ± 0.7 A	7.3 ± 1.2 A	7.1
Luvisol	(1, 1, 0)	6.3 A	4.5	–	6.3	6.5	–
Lixisol	(5, 5, 3)	2.7 ± 0.4 A	1.6 ± 0.5 A	1.0 ± 0.4 A	6.1 ± 0.3 AB	6.0 ± 0.3 ABC	5.8 ± 0.4 AB
Alisol	(18, 18, 8)	5.3 ± 2.7 A	2.8 ± 2.0 A	1.9 ± 1.3 A	5.4 ± 0.8 B	5.2 ± 0.7 B	5.0 ± 0.6 B
Acrisol	(30, 29, 19)	3.9 ± 2.1 A	2.6 ± 1.5 A	1.9 ± 1.0 A	5.4 ± 0.4 B	5.4 ± 0.6C	5.5 ± 0.5 B

[a] Numbers in the "N" column refer to the number of sites with values contributing to the mean of each depth increment (from left to right in the parenthesis, respectively) within each category.
[b] Numbers with different capital letters are significantly different (Tukey's HSD, $p < 0.05$) across ST Soil Order or WRB Reference Group categories within the same depth increment.

Acrisols in the 0–20 and 20–50 depth increments, while Gleysols had significantly higher pH values than Alisols at the 20–50 and 50–100 cm increments and Acrisols at the 50–100 cm depth increments.

3.5. Elevation – SOC relationship

Fig. 4a shows the relationship for 0–20 cm depth increment SOC concentrations with elevation. The results of multiple linear regression analysis of SOC with elevation and other factors are presented in Table 6. Because aspect did not have a significant effect across all sites after other terms were in the model we excluded it from our regression analysis. In each case, a summary of the model (selected by criteria described in Section 2.5) is shown.

For the 0–20 and 20–50 cm depth increments, elevation and land use emerged as the strongest predictors of SOC concentrations when pH was excluded. Landscape position was also a significant predictor of SOC for the 0–20 cm and 20–50 cm depth increments, but not for the 50–100 cm depth increments. The significance of these predictors remained even when pH was included in the model, and model fits were significantly improved (Table 6), however pH was the only significant predictor of SOC in the 50–100 cm depth increment when included in the model. An elevation-land-use interaction term was significant in all models for all three land use categories, implying that the slope of the relationship between SOC and elevation was significantly different between land use categories (Table 6). This can be visualized best in the 0–20 cm depth increment (Fig. 4), where this slope increased in magnitude by a factor of 2 from the Cultivated to Low Intensity land use categories (Fig. 4b and c). The slope was insignificant for Forest and

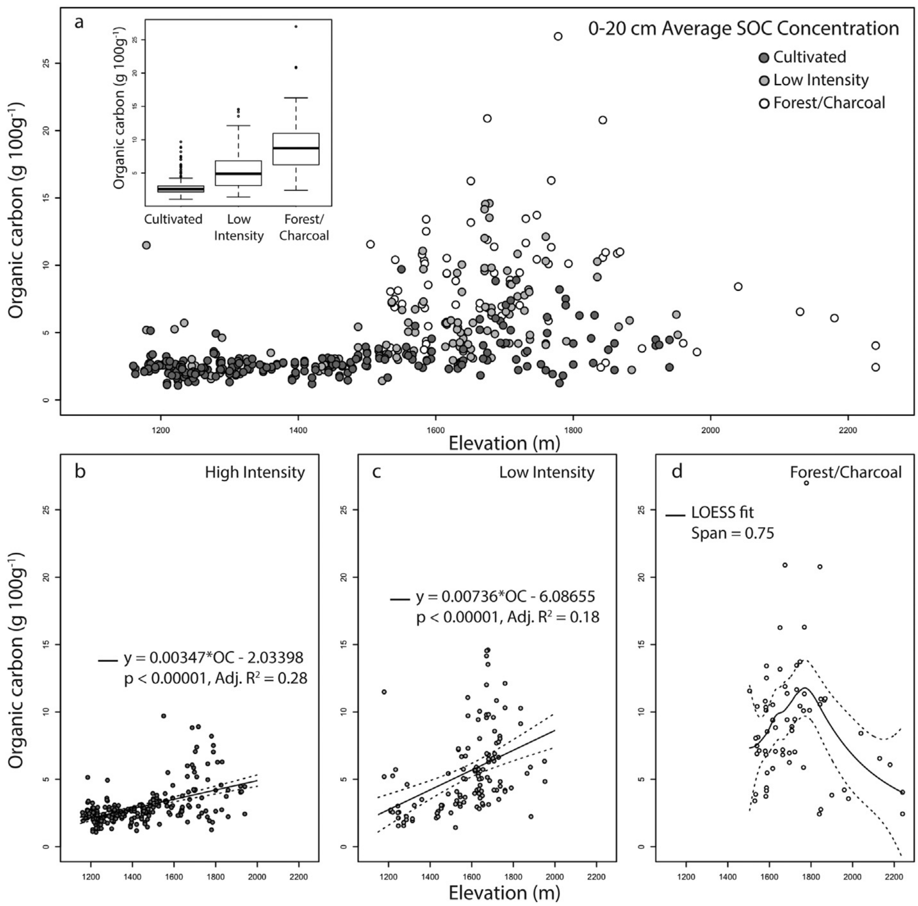

Fig. 4. Soil organic carbon (SOC) concentrations and Elevation. a) 0–20 cm average (slabbed) SOC concentrations and elevation across all sites. Inset: boxplot of 0-20 cm average SOC concentrations by Land Use. b) Linear relationship between 0 and 20 cm average (slabbed) SOC concentrations and elevation for Cultivated Land Use. c) Linear relationship between 0 and 20 cm average (slabbed) SOC concentrations and elevation for Low Intensity Land Uses. d) Non-linear relationship between 0 and 20 cm average (slabbed) SOC concentrations and elevation for Forest and Charcoal Land Uses – here the non-linear relationship is represented visually by a best-fit Locally Estimated Scatterplot Smoothing (LOESS) spline function.

Table 6
Summary results of multiple linear regression models for SOC and pH with Elevation, Land Use, and Landscape Position.

Dependent variable	Significant pedictors in final model	R^2	Most significant interaction term	Model R^2 w/interaction term
SOC models excluding pH				
0–20 cm SOC	Elevation (+)[a], Land Use, Landscape Position (Upper)	0.4739	Elevation × Land Use	0. 4998
20–50 cm SOC	Elevation (+), Land Use, Landscape Position (Upper)	0.3703	Elevation × Land Use	0.4214
50–100 cm SOC	Elevation (+), Land Use	0.1963	Elevation × Land Use	0.3016
SOC models including pH				
0–20 cm logSOC (w/pH)	Elevation (+), Land Use, pH (−), Landscape Position (Upper, Lower)	0.6567	Elevation × Land Use	0.6704
20–50 cm logSOC (w/pH)	Elevation (+), Land Use, pH (−), Landscape Position (Upper)	0.5449	Elevation × Land Use	0.5748
50–100 cm logSOC (w/pH)	pH (−)	0.4326	None	NA
pH models excluding SOC				
0–20 cm pH	Elevation (−), LandUse, Landscape Position (Valley)	0.4512	Elevation × Land Use	0.4842
20–50 cm pH	Elevation (−), Landscape Position (Valley), LandUse (Cultivated)	0.4632	Elevation × Land Use	0.486
50–100 cm pH	Elevation (−), Landscape Position (Valley)	0.262	None	NA
pH models including SOC				
0–20 cm pH (w/SOC)	logSOC (−), Elevation (−), Landscape Position (Valley)	0.542	None	NA
20–50 cm pH (w/SOC)	logSOC (−), Elevation (−), Landscape Position (Valley), Land Use (Cultivated)	0.5997	None	0.6048
50–100 cm pH (w/SOC)	logSOC (−), Elevation (−), Landscape Position (Valley)	0.431	None	NA

[a] Signs (+) or (−) next to covariates indicate whether or not the trend of the dependent variable was increasing (+) or decreasing (−) over the increasing values of the predictor. The name in parenthesis after categorical variables refers to the only significant categories at p < 0.05. If no name in paraentheses follows the categorical predictors Land Use and Landscape Position, then all categories were significant at $p < 0.05$.

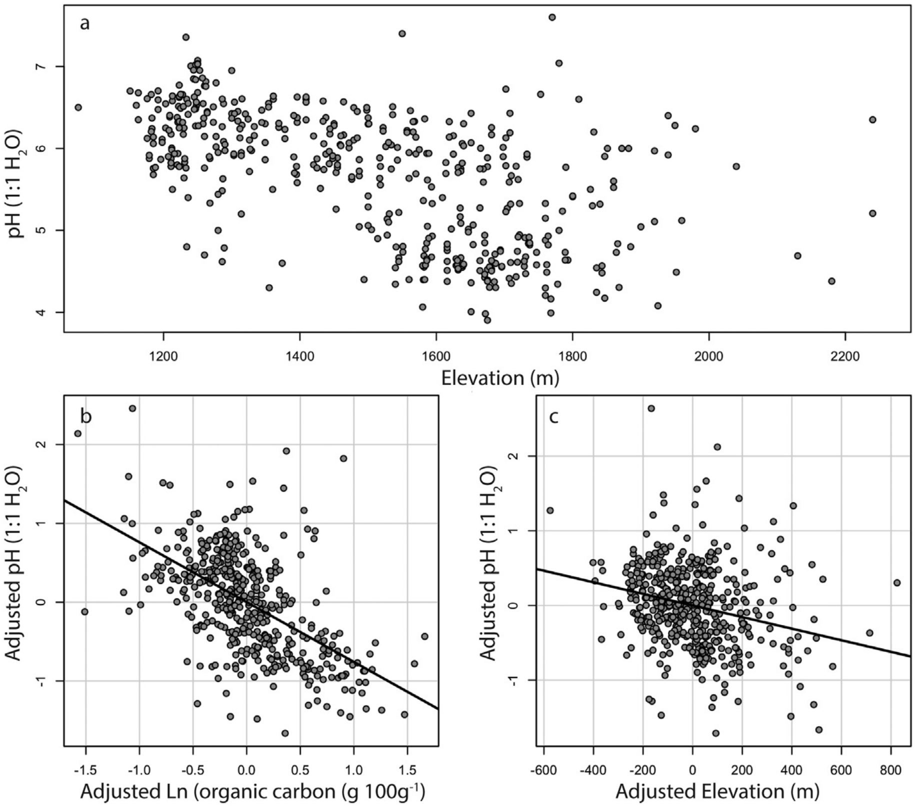

Fig. 5. pH (H_2O) and Elevation. a) 0–20 cm average (slabbed) pH (H2O) and elevation across all sites. b) Added variable plots of b) SOC and c) elevation for linear regression with 0–20 cm average (slabbed) pH (H_2O). Added variable plots show the effect of a single explanatory variable on a predictor when all other variables are in the model. These added variable plots therefore show the strength and significance of the effects of SOC and elevation on pH after other model variables have been accounted for.

Charcoal land uses across all elevations as the relationship was not linear (Fig. 4d), however for sites below 1800 m the relationship between SOC and elevation was linear and slope steeper (by a factor of 2.4 and 6.3, respectively) than for the Low Intensity and Cultivated land uses.

3.6. Elevation – pH relationship

For pH models including SOC, elevation and landscape position (significant for Valley sites) were significant predictors for 0–20 and 20–50 cm depth increments (Table 6). Land use was retained as a predictor in the 20–50 cm and 50–100 cm depth increments, while aspect was excluded because it did not have a significant effect across all sites after other terms were in the model (Table 6). Fig. 5a shows all 0–20 cm site average pH values plotted against elevation. No interaction factors were significant in these models when SOC was included, but an elevation- land use interaction term was significant when SOC was excluded. From these regression models (Table 6), evidence exists that (in addition to the landscape position factor at Valley sites) both SOC and elevation have a significant impact on pH: (1) first, both are retained in both forwards and backwards stepwise selection of multiple linear regression models; (2) adding elevation as a predictor along with SOC improves adjusted R^2 values in all depth increments; and (3) significant effects are observed in added variable plots (which show the effect of a single co-variate once all other predictors are in the model) (Fig. 5b and c) for both variables in all depth increments.

The slope of the added variable plots for SOC changes from a decrease of ~2.5 pH units across the elevation range (1040–2230 m) in the 0–20 cm depth increment (Fig. 5b) to a decrease of ~ 1 pH unit in the 50–100 cm depth increment. The slope of the added variable plot for elevation on pH remains constant with a decrease of approximately 1 pH unit across the elevation range for all depth increments (Fig. 5c).

3.7. Relationships between soil classification and topography

Five ST Orders and nine WRB Reference Groups were observed in the study area among the 69 sites with associated morphological and laboratory data allowing for definitive classification. Under the ST system, 48 of the 69 observed pedons classified as Ultisols (70%) (Table 7). Six pedons (9%) were classified as Alfisols, and 5 pedons each were observed for Entisols, Inceptisols and Mollisols (7% each) (Table 7). Under the WRB classification system, 30 of 69 pedons (43%) were classified as Acrisols, 18 as Alisols (26%), 5 each classified as Fluvisols and Lixisols (7% each), 3 each as Cambisols and Gleysols (5% each), 2 each as Regosols and Phaeozems (3% each) and 1 classified as a Luvisol (1%) (Table 7). There was strong evidence that the observed frequency distribution of ST Orders (Fisher's exact test, 2-sided, $p < 0.0001$) and WRB Reference Groups (Fishers exact test, 2-sided, $p < 0.0001$) differed between landscape positions, but not land use categories ($p = 0.1$ (U.S.) and $p = 0.5$ (WRB)). Fig. 6 shows several representative soil profiles across an elevation and land-use gradient.

Although Ultisols were the dominant ST Order observed, their distribution was highly dependent on landscape position (Table 7). At Valley positions, only Entisols, Inceptisols and Mollisols were observed, while at Crest positions only Ultisols were observed. Lower, Mid and Upper slope landscape positions had the highest diversity in terms of observed ST Orders, however Ultisols still made up 60–95% of the observed pedons at these positions (Table 7). Acrisols were the dominant WRB group observed (43%), but were less common than Ultisols because a number of Ultisol pedons classified as Alisols due to their high clay-normalized CEC values but low BS. At Valley positions, only Cambisols, Fluvisols and Gleysols were observed, while at Crest positions, only Acrisols and Alisols were observed (Fig. 6, Table 7).

Although the effect of slope aspect on soil properties across the entire dataset was not significant in regression models, there did appear to be an effect of aspect on soil classification. Alfisols were more abundant on west- and north facing slopes ($n = 5$) than on east- and south-facing slopes ($n = 1$), and Ultisols were more abundant on east-

Table 7
Distribution of U.S. Soil Orders and WRB Reference Groups by landscape position and slope aspect. Pedons in the aspect section include only soils on hillslope landscape positions (excluding Valley and Crest positions).

	Valley	Lower	Mid	Upper	Crest	Total	N&W Aspects	S&E Aspects	Total
U.S. soil order									
Entisol	2	2	1	0	0	5	0	3	3
Inceptisol	3	1	0	1	0	5	1	1	2
Mollisol	3	2	0	0	0	5	2	0	2
Alfisol	0	1	0	5	0	6	5	1	6
Ultisol	0	9	18	12	9	48	16	22	38
Total	8	15	19	18	9	69	24	27	51
WRB reference group									
Fluvisol	4	1	0	0	0	5	0	1	1
Gleysol	3	0	0	0	0	3	0	0	0
Cambisol	1	1	0	1	0	3	1	1	2
Regosol	0	1	1	0	0	2	0	2	2
Phaeozem	0	2	0	0	0	2	2	0	2
Luvisol	0	0	0	1	0	1	1	0	1
Lixisol	0	1	0	4	0	5	4	1	5
Alisol	0	2	7	6	3	18	10	4	14
Acrisol	0	7	11	6	6	30	6	18	24
Total	8	15	19	18	9	69	24	27	51

and south facing slopes (n = 22) than north- and west-facing slopes (n = 16). Among WRB Reference Groups groups, both Lixisols and Alisols were more abundant on north- and west-facing slopes (n = 4 and 1, respectively) than on south- and east-facing slopes (n = 1 and 4, respectively). Acrisols were 3 × more abundant on south- and east-facing slopes than north- and west-facing slopes (Table 7).

4. Discussion

4.1. Impact of land use on soil properties

In our dataset, land use emerged as the critical controlling factor on SOC concentrations, through which it influenced many other soil properties. SOC concentrations in all depth increments were significantly lower under Cultivated land use than any other land use category, while SOC concentrations in Low Intensity land uses were lower than Mature Forest and Charcoal Production Areas in the top 50 cm. Similarly, Kidanemariam et al. (2012) found that, in the Ethiopian Highlands, in high intensity cultivated systems, topsoil SOC was 25% and 35% lower than in low intensity pasture and forest lands, respectively. Winowiecki et al. (2016) also reported dramatically lower SOC under cultivated sites in the West Usambaras, indicating the need for sustainable land management practices, especially those that reduce erosion and build soil organic matter.

The central role that land use plays in influencing SOC concentrations in the West Usambara plateau is likely due to major changes in

Fig. 6. Profile pictures demonstrating representative diversity of West Usambaran plateau soils across an altitudinal transect. a) LUSH 11–4: Eutric Gleysol (Aric), Inceptisol, 1250 m; b) LUSH 1–2: Eutric Cambisol (Aric), Inceptisol, 1192 m; c) MBUZII 1A: Rhodic Lixisol (Aric, Humic), Alfisol, 1314 m; d) LUSH 7–7: Rhodic Acrisol (Aric, Humic), Ultisol, 1594 m; e) LUSH 7–1: Haplic Acrisol (Hyperhumic), Ultisol, 1616 m; f) LUSH 16–5: Leptic Acrisol (Hyperhumic), Ultisol, 1747 m.

soil and ecosystem carbon balances with land use and land cover changes. In a study on the southern slopes of Mt. Kilimanjaro, decay rates of the labile SOC pool were up to three times higher in intensified land use systems as compared to natural ecosystems (Mganga and Kuzyakov, 2014). Similarly, on the West Usambaran plateau, cultivated soils are prone to carbon loss relative to forested ecosystems due to increased decomposition, biomass removal, and erosion.

We found that Charcoal Production Areas were not significantly different from Mature Forest with regard to SOC and pH across all depth increments. This is surprising given the major change in land use associated with forest removal and charcoal production, however, from the narrow perspective of the soil carbon balance, intensive charcoal production may incorporate relatively recalcitrant carbon material deep in the profile (Sombroek et al., 2003). This may stabilize soil carbon losses in these systems, even though we note that ecosystem carbon losses would likely still be highly significant (Fearnside et al., 1993). In the West Usambaras, charcoal production is typically practiced on wood materials coming from very near to the site, and as the wood is being charcoalized it is covered in soil from the surrounding area. This results in intensive mixing of soil and charcoal fragments at these sites, and relatively homogenized soil profiles.

4.2. Impact of landscape position on soil properties

The impact of landscape position on soil properties across our dataset can primarily be conceptualized as the difference between receiving positions (Valley and Lower slope) and loss positions (Mid, Upper and Crest), with Valley sites most significantly different in chemical properties than all other landscape positions. pH values were significantly higher at Valley sites than any other landscape positions, regardless of depth. Our results therefore suggest that the surface and subsurface hydrologic redistribution of soil minerals and dissolved cations released from chemical weathering and leaching processes on adjacent hillslopes influences the pH, total exchangeable bases and base saturation at Valley sites, particularly at deeper depths (Supplementary material Section SM3).

SOC concentrations in the top 0–20 cm were lowest at Valley and Lower slope sites, while 0–20 cm SOC concentrations were highest at Mid, Upper and Crest landscape positions. Although a trend of decreasing SOC concentrations across successively lower hillslope positions may be surprising in other landscapes, there are several likely reasons for this trend in the West Usambaras. First, other authors have reported similar trends in tropical montane landscapes (Johnson et al., 2011) and suggested that important organo-mineral complexation and stabilization processes (particularly Fe- and Al-complexation) which occur in Upper slope soils are less prevalent in the poorly developed Lower slope or Valley soils. Second, on the plateau of the West Usambaras, land use varies significantly between Valley soils (where no sites were forested and which have a long history of high intensity cultivation of high value crops), and Upper slope soils, many of which are utilized less intensively or still under forest (Supplementary material Section SM1, Fig. SM2). Third, decomposition rates in Valley positions may be higher regardless of land use because of elevated pH, increased nutrient availability (Hayakawa et al., 2014; Souza et al., 2016; Min et al., 2014), and artificial drainage.

Lastly, we found that the effect of SOC and clay on CEC differed between Valley sites and all other landscape positions. At Valley sites, CEC was not significantly related to SOC, but was significantly related to clay content (Fig. 6). At hillslope sites, the opposite was true: CEC was not significantly related to clay content but was significantly related to SOC. Other meta-analyses that have examined the effects of SOC and Clay on CEC have shown that for soils dominated by 2:1 clays, the influence of organic carbon on CEC is 2–3 times lower in magnitude (and, conversely, the influence of clay on CEC is greater) in 2:1 phyllosilicate-dominated soils (Foth and Ellis, 1996; Seybold et al., 2005). This has interesting implications in light of previous work on generating local functions to estimate bulk and clay-normalized CEC. Widely utilized methods of estimating the clay contribution to CEC by applying a global function (Van Reeuwijk, 1995; Schad et al., 2001) would not be appropriate for these soils as a whole, a phenomena also observed by Kirsten et al. (2016) across 4 pedons on a neighboring block mountain plateau, the East Usambaras. Schad et al. (2001) also investigated this problem and developed individual regressions for CEC on based on vegetation classes. At least on the West Usambaran plateau, it appears that stratification by landscape position may enable underlying mineralogical differences in the soils to be captured, a local application of a successful global approach by Seybold et al. (2005).

Although there is no clay mineralogy information in our dataset, we consider these differences in the driving factors behind CEC to be preliminary evidence of mineralogical differences between hillslope and Valley soils in the West Usambara mountains. Testing this hypothesis would require information beyond what is available in our dataset, however the hypothesis matches field observations of greater shrink-swell behavior in Valley soils, and fits with a conceptual model of 2:1 phyllosilicate neosynthesis in the collecting landscapes of broad valleys in the West Usambaras. In this model, the intense weathering of saprolite on the hillslopes results in hydrologic inputs rich in cations to valley soils, which, with distinct wet and dry seasons, are subsequently under environmental conditions that would favor 2:1 phyllosilicate neoformation (Wilson, 1999).

4.3. Impact of elevation on soil properties

There are likely three major covariates associated with elevation change in the West Usambaras: temperature, precipitation and time since land-use conversion. Complexities regarding the use of elevation as a proxy for environmental variables have been extensively discussed in the literature (i.e. Körner, 2007). Nevertheless, some combination of these three major factors likely explains the residual patterns in SOC and pH with elevation observed in our data.

Temperature is the most ubiquitous and continuous change that occurs with elevation in mountainous landscapes (Minder et al., 2010). The environmental lapse rate (decrease in temperature with altitude) modeled by the AfriClim dataset (Platts et al., 2015) for the West Usambaras is approximately 0.56 °C per 100 m. Therefore, over the total elevation gradient in our dataset (approximately 1200 m), we would expect a decrease in Mean Annual Air Temperature (MAAT) of approximately 6.8 °C. The relationship of precipitation with elevation in the West Usambaras is considerably more complex due to a rainshadow effect on the plateau. Generally, the southeastern portions of the plateau experiences greater rainfall due to uplift of oceanic influenced weather systems approaching from the southeast (Hamilton, 1989). This creates, generally, a southeast to northwest trend in precipitation across the West Usambaran plateau, however it is important to note that this pattern is highly complex at larger scales, and confounded by changes in microclimate and so called “occult” precipitation (fog or dew condensation) at higher elevations (Munishi and Shear, 2005). Finally, the time since land use or land cover change also likely decreases with altitude. As post-colonial population pressure has increased, the conversion of forests to agricultural lands has moved upslope (Conte, 1999).

In our dataset, we found that average SOC concentrations in the top 0–20 and 20–50 cm increased with elevation, even after the effects of land use, landscape position, and pH were accounted for (Table 6). This suggests that SOC is responding to climatic variables (most likely temperature, which decreases as elevation increases), but may also be confounded by the recent nature of land use change (i.e. agricultural lands at higher elevations are more likely to have been recently converted) and higher levels of soil acidity at higher elevations, which may decrease decomposition rates.

Zech et al. (2014) found that SOC concentrations of topsoils increased along an elevation gradient on both the northern and southern slopes of Mt. Kilimanjaro, from < 5% at elevations below 1500 m to approximately 20% at elevations of 2200 m. In that study, topsoil SOC concentrations subsequently declined in the subalpine zone, at elevations above 2700 m. Similarly, at 5 sites along an elevational gradient on the southern slopes of Mt. Kilimanjaro, Blagodatskaya et al. (2016) found that SOC concentrations in topsoils increased from around 13% in forest at 950 m to 21% in forests at 2780 m, at which point SOC concentrations declined to 12% above 2700 m. In a mixed land-use study on Mt. Kilimanjaro, Pabst et al. (2013), found that 0–10 cm SOC concentrations increased from ∼3% in savanna at 950 m to 21% in forest at 2120 m. In contrast, out dataset showed a decline in SOC concentrations of the 0–20 cm increment above 2000 m, which we attribute to the confounding effects of differing moisture availability and lower precipitation in the northwestern portion of the plateau where these higher elevation sites were preferentially located.

In our dataset, we found that, even after accounting for the effects of SOC, landscape position, and land use, pH decreased approximately 1 unit in all depth increments across the range of elevation of our sites. The effect of elevation on pH reflected in these results may be due to the combined effects of increased leaching at higher altitudes (subsurface pH change) as well as soil acidification through reduced decomposition and the buildup of a high organic matter litter layer with organic acids.

These patterns have been observed in other locations in the Eastern Arc mountains. For a single land use (coffee plantation) along an elevational gradient in Uganda, De Bauw et al. (2016), found a strong linear decrease in pH with elevation from a pH of approximately 7.5 at 1000 m to a pH of approximately 4.9 at 2200 m. Hamilton (1998) also found that 0–10 cm soil pH values declined rapidly in the East Usambaras from a pH of 6.5 at 850 m to a pH of 4 at 1050 m. Studies in tropical soils have shown that soil pH is a major factor in controlling decomposition rate, and therefore may initiate a primary feedback loop by which initially more acidic conditions result in more extensive organic matter accumulation, which itself may contribute to maintaining acidic conditions (Motavalli et al., 1995).

4.4. Soil diversity and classification in the West Usambara mountains

Our dataset demonstrates that even at the ST Order and WRB Reference Group levels, soils are considerably more diverse on the West Usambaran plateau than has been previously reflected in small scale soil maps, which is consistent with the studies of Meliyo et al. (2001) and Massawe (2011). The highest levels of soil diversity were concentrated in Lower slope landscape positions (5 of 5 ST Orders and 7 of 9 WRB Reference Groups), followed by Upper slopes, Valleys, and Mid slopes. Crest positions were the least diverse, with only Ultisols (U.S.) or Acrisols and Alisols (WRB) present. In contrast, Mollisols, Inceptisols and Entisols (U.S.) and Cambisols, Gleysols and Fluvisols (WRB) dominated Valley positions.

Soil type was strongly influenced by landscape position but not by land use. Given the observed soil classifications and patterns in the distribution of soil types, it is not surprising that land use has little impact on soil classification in the West Usambaras. The greatest short-term impact of land use on soil classification is often reflected in impacts on the epipedon due to physical manipulation, erosion and deposition (Veenstra and Burras, 2012). Only Valley soils in our data had any soil types which were susceptible to epipedon change (Mollisols, Entisols and Inceptisols), while other landscape positions were dominated by soil types that are defined by subsurface diagnostic horizons and subsurface properties or features (such as the argillic horizon and BS requirements in Alfisols/Ultisols), making them less susceptible to classification changes through erosion or land-use change (Jelinski and Yoo, 2016).

The definitive classification of most tropical soils requires BS, CEC, and morphological data in both the U.S. ST and WRB systems (Soil Survey Staff, 2014a; IUSS Working Group WRB, 2015). This combination of properties is often laborious, costly and time consuming to collect. In contrast, pH, SOC and texture are much more commonly measured soil properties, and estimates of these properties can be rapidly determined by proximal soil sensing techniques such as MIR or NIR spectroscopy (Winowiecki et al., 2016). The locally derived pedotransfer functions we have developed for CEC and BS will allow pH, SOC and Clay to serve as reasonable proxies for CEC and BS for West Usambaran plateau soils. These values, in conjunction with information on landscape position (Valley positions in particular) and soil morphology may be used for rapid field identification and soil classification in the West Usambaras. Further validation and analysis of these relationships should be a focus of ongoing study.

4.5. Implications for soil management and land use planning

Patterns of SOC with land use and landscape position have been extensively described in sections above, however several aspects bear reviewing in the context of soil management. First, topsoil SOC concentrations are highest in mature forest and controlled primarily by land use. Continued land use conversion will inevitably lead to decreases in SOC, which will impact many other aspects of soil fertility. In particular, Total P is significantly correlated to SOC (Supplementary material Section SM2.5, Fig. SM4), which suggests that P is tightly biocycled in these montane forest systems and a significant portion is in organic form. Organic matter losses thus change P dynamics and may make P more susceptible to loss through erosion. Secondly, SOC is the major control on CEC in hillslope soils. With forest clearance and conversion to high intensity agriculture, these soils are particularly susceptible to CEC decreases due to organic matter loss, introducing further management challenges.

The continued upslope expansion of high intensity land use on the West Usambaran plateau will encounter soils with lower pH values and high initial carbon contents, and also with fertility parameters that are highly susceptible to losses by erosion and carbon loss. Therefore, agricultural expansion across the plateau must be paired with the implementation of aggressive soil conservation measures which build SOC on Upper slope soils and reduce erosion, while efforts aimed at increasing the sustainable intensification of rich and diverse Valley and Lower slope soils should continue.

5. Conclusions

In this synthesis, we have demonstrated the controlling factors on soil properties and classification in the plateau region of the West Usambara mountains of northeastern Tanzania. Our dataset shows that SOC is affected primarily by land use, and generally increases with elevation within land use categories due to the convergent effects of decreases in temperature, precipitation changes, acidification, and intactness of native ecosystems. Conversely, pH is affected both by land use and by landscape position, particularly at deep soil increments. Generally, pH decreases with elevation, likely due to increases in litter layer carbon content, organic acids in surface horizons, and increased leaching in the subsurface. In turn, these properties influence soil classification, which is strongly affected by topography. Nonetheless, soil properties varied more significantly by land use and topography than by soil type, suggesting that future mapping efforts in the region should focus primarily on soil property prediction and secondarily on soil classification. Local pedotransfer functions developed for BS and CEC from pH, clay content and SOC will prove useful for estimating these difficult to measure soil parameters. These conclusions can inform future mapping efforts by providing a conceptual understanding of critical variables and patterns affecting soil properties and classification on the West Usambaran plateau, other block mountain plateau regions in the Eastern Arc, and tropical montane systems around the world.

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