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Soil organic carbon stocks controlled by lithology and soil depth in a Peruvian alpine grassland of the Andes

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A R T I C L E I N F O

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A B S T R A C T

The soil is the largest carbon (C) pool in the terrestrial ecosystem, and soil organic carbon (SOC) stocks play an important role in global C dynamics. Alpine grasslands of the Andes are characterized by high SOC stocks. Quantifying SOC stocks and unraveling key factors controlling SOC stocks, is necessary to obtain a better understanding of the dynamics of the large C stocks in this environment. However, most studies on C dynamics of the Andes focus on volcanic-ash soils, whereas information about non-volcanic ash soils in this region is scarce. Our objectives were: (i) to estimate SOC stocks in an alpine grassland of the Peruvian Andes (7° 11′S, 78° 35′W) with parent materials other than volcanic ash, and (ii) to identify the underlying soil formation and environmental (SFE) factors and soil properties explaining observed patterns of SOC stocks. We sampled 69 plots up to the parent material to measure soil properties and to calculate SOC stocks, in relation to lithology, land use, grazing intensity, slope angle, slope position and altitude. We applied linear models to identify key factors controlling SOC stocks. Our results showed that total SOC stocks had a mean value of 215 ± 21 T ha^{-1}, whereas SOC stocks of the upper 10 cm and 40 cm comprised 29.3% and 80.0% of total SOC stocks respectively. The variation of the total SOC stocks was mainly explained by soil depth and soil moisture. When soil depth and soil moisture were controlled as conditional variables, lithology became the key factor controlling the total SOC stocks. For the SOC stocks of the upper 10 cm, soil moisture explained a large part of the variation, whereas lithology, grazing intensity and altitude were also significant predictors. Our results also show that when soils are sampled with limited depths instead of the entire soil profile, SOC stocks can be underestimated, and the effects of the SFE factors on SOC stocks can be overestimated.

1. Introduction

Soil is one of the largest terrestrial carbon (C) pools, and plays an important role in global terrestrial C dynamics (Lal, 2004; Luo et al., 2016). Within the global terrestrial C pools, neotropical alpine grasslands of the Andes are characterized by high soil organic carbon (SOC) stocks (Buytaert et al., 2011; Sierra et al., 2007; Tonneijck et al., 2010). Previous studies of SOC in the Neotropical Andes focused on soils in recent volcanic-ash, especially being dominant in Ecuador (Farley et al., 2004; Minaya et al., 2016; Poulenard et al., 2003; Tonneijck et al., 2010). However, soils with parent materials other than volcanic ash also cover large areas of the Andean highland. In Peru about 27% of the Andean area is covered by Tertiary to Cretaceous volcanic rocks, mostly being ignimbrites in the northern half of Peru, and where active volcanism and recent ash deposits are absent (Buytaert et al., 2011; Geo GPS Perú, 2014). For these soils, only a limited number of studies have been reported (Muñoz García and Faz Cano, 2012; Segnini et al., 2011; Zimmermann et al., 2009). Apart from the importance with respect to the carbon cycle, Andean grasslands are characterized by their high soil water holding capacity, and act as water sources and regulate the provision of water to the arid coastal regions of the South American continent (Buytaert et al., 2011; Lineger et al., 1998). The high water holding capacity is partially attributed to the high SOC stocks (Buytaert et al., 2011). As such the management of these grasslands, including the soil, is crucial for maintaining ecosystems services especially for the western side of the Andean mountain range.

Soil formation and environmental (SFE) factors control SOC stocks and their persistence to a large degree, through complex interactions with organic matter (OM) and other factors, including mineralogy, physical properties, OM input and OM degradation (Luo et al., 2016; Schmidt et al., 2011). SOC stocks are to a large degree determined by the stabilization of OM, which is strongly affected by interactions

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between OM and soil minerals (Doetterl et al., 2015; Lutzow et al., 2006; Six et al., 2002). Contrasting mineralogical characteristics may cause differences in OM adsorption mechanisms on minerals, as well as physical stabilization related to the aggregate formation (Kögel-Knabner et al., 2008; Lutzow et al., 2006; Percival et al., 2000). Lithology (parent material) determines soil mineralogy and as such plays a role in controlling SOC stocks. In addition to lithology, effects of land use (change) and grazing are reported to be important. Generally, cropland has lower SOC stocks than natural forest and grassland, and land use shifting from natural forest or grassland to cropland has negative effects on SOC sequestration (Guo and Gifford, 2002; Poeplau et al., 2011). In addition, effects of land use (change) on SOC stocks are dependent on other factors (Leifeld et al., 2005; Powers et al., 2011), such as grazing. The effects of grazing on SOC stocks can be variable, ranging from positive to negative as summarized by Piñeiro et al. (2010) and Mcsherry and Ritchie (2013). This variability can be explained by the complex interaction between grazing, primary production, vegetation type and climate. Furthermore, topographic factors including altitude, slope angle and slope position, are also reported to have impacts on SOC accumulation, especially in mountainous regions (Ayoubi et al., 2012; Garcia-Pausas et al., 2007; Schwanghart and Jarmer, 2011).

SOC stocks are generally estimated using limited constant soil depths, generally with only the topsoil included (Doetterl et al., 2015; Du et al., 2014; Fernández-Romero et al., 2014; Minaya et al., 2016; Wang et al., 2014; Yang et al., 2008). However, soil depths are not always constant, and the subsoil may contain large amounts of SOC (Batjes, 2014). In addition, the persistence and stabilization of SOC may also differ between the topsoil and the subsoil (Schmidt et al., 2011). Studies may run a risk of inaccurate estimations of the SOC stocks as well as effects of external factors controlling the SOC stocks, when only limited constant soil depths instead of the entire soil profiles are examined (Harrison et al., 2011; Tonneijck et al., 2010; Wiesmeier et al., 2012). Therefore, Wiesmeier et al. (2012) recommended including entire soil profiles rather than sampling soils with constant depths when estimating SOC stocks.

In the present study, soil samples were collected with the entire soil profiles, from an Andean high altitude grassland with parent materials other than volcanic ash. The study area is characterized by heterogeneous SFE factors including lithology, land use, grazing intensity and topographical factors. The objectives of the study were: (1) to make an estimate of SOC stocks assessed to the C or R horizon, (2) to identify key factors controlling SOC stocks from the SFE factors as well as soil properties.

2. Materials and methods

2.1. Site description

The study area is located approximately 10 km to the west of the city Cajamarca in Peru (7° 11′S, 78° 35′W, Fig. 1), on the broad South American continental watershed between the Rio Jequetepeque (Pacific) and the Rio Cajamarca (Atlantic). The altitudes of the study area range from 3370 m to 3900 m above sea level. Mean annual temperatures were reported for two stations in or near the field area, based on 8–10 years of measurements: 8.2–10.8 °C for mean annual temperature, 12.0–14.7 °C for mean daily maximum temperature and 4.4–7.5 °C for mean daily minimum temperature for Porcon 2 (3510 masl) and Cumbe Mayo (3410 masl) stations. The temperature has small seasonal but large daily variations (Sánchez Vega and Dillon, 2006). The annual precipitations are between 616 and 1317 mm. The majority of precipitation falls in the wet season between October and April, but the amount is also strongly influenced by orographic effects (Sánchez Vega and Dillon, 2006).

The geological formations consist of a basement of folded Cretaceous marine sediments which are partly overlain or intruded by igneous bedrock. The sediments include the formations of Cajamarca, Chulec-Calizas, Pariatambo, Farrat and Yumagual, with limestone, shale, marl and quartzite lithologies. The igneous bedrocks that belong to the San Pablo formation include intrusive bedrock of granite and extrusive bedrock of ignimbrites (Geo GPS Perú, 2014; Reyes-Rivera, 1980).

Soil types are directly related to the parent materials and slope position. Going from the top position to the valley bottom we find for the successive lithologies the following dominant soil types (WRB, 2006): on quartzites: Leptosols and Regosols; on limestones and marls: Leptosols, Phaeozems and Luvisols; on ignimbrites: Leptosols, Andosols and (Vitric) Umbrisols, Alisols and Histosols; on granitic rocks: Leptosols and Umbrisols.

The area belongs to the Neotropical alpine grassland zone of the Jalca, which is seen as a transition between the wet Páramo in the north and the dry Puna in the south (Sánchez Vega et al., 2005). The most important grass species in the grasslands is especially *Calamagrostis tarmensis* Pilger, and *Calamagrostis trichopylla,* but also *Festuca huamachucensis* Infantes, *Agrostis tolucensis* Kunth and *Cortaderia sp.*. Land use is dominated by grazing of Jalca grasslands, small arable fields with regularly barley and wheat at lower locations and potatoes and potato-like crops (ocas) at higher positions, and some planted patches with pine (mostly *Pinus patula* and some *Pinus radiata*) and eucalypt (*Eucalyptus sp.*), which are exotic species, as well as replanting of *Polylepus racemosa* (endemic species). In this region, agriculture is shifting upwards with altitude because of climate change and population growth (Tovar et al., 2013). The land use of the agriculture fields is dynamic as it shows a rotation of cultivation, abandonment and grazing. Usually, the land is ploughed and cultivated for 2 years, followed by grazing or fallow for at least 1–5 years.

2.2. Sampling procedures

Fig. 1 shows the distribution of 69 sampling plots along three transect lines. The selection of the transect zones was based on lithology and altitude, with each zone containing contrasting bedrocks and wide ranges of altitude, as well as land use, grazing intensity, slope position and slope angle. Within the units the sample locations were selected at random. Lithology was classified into the classes of calcareous bedrocks (limestone and marl with thin shale intercalations) and acid bedrocks (granite, ignimbrite and quartzite). Land use was classified into 5 categories: grassland, cultivation, abandoned cultivation, cultivated grassland and forest, following the recommendation of Sánchez Vega et al. (2005). Grazing intensity was estimated in the field and was ranked into 4 levels: none, low, medium and high. The criteria to rank grazing intensity were based on the presence of physical indications of grazing, plant density, as well as the replacement of tall native tussock grasses (e.g. *Carex sp.*) with shorter invasive grass species and matted herbs including *Rumex* sp. as also applied by Verweij and Budde (1992). Slope position was classified into 3 groups: top, slope and valley bottom. Furthermore, slope angle and altitude were measured and recorded as numeric variables.

We took one complete soil profile per sampling point and divided these into sections of 10 cm, starting from the top until the C or R horizon was reached. Soil depth was defined from the ground level to the top of the C or R horizon and measured below the ground level. Undisturbed samples were collected from the representative layers with Kopecky rings (100 cm^{-3}) in order to determine bulk density using the core method (Blake and Hartge, 1986). Afterwards, all samples were weighted and transferred into sealed plastic bags before transportation.

2.3. Laboratory analysis

Soil bulk density was measured by weighing the intact ring samples after oven-drying at 105 °C, and calculated with the volume of 100cm^3. Field moisture contents were measured by weighing ring samples

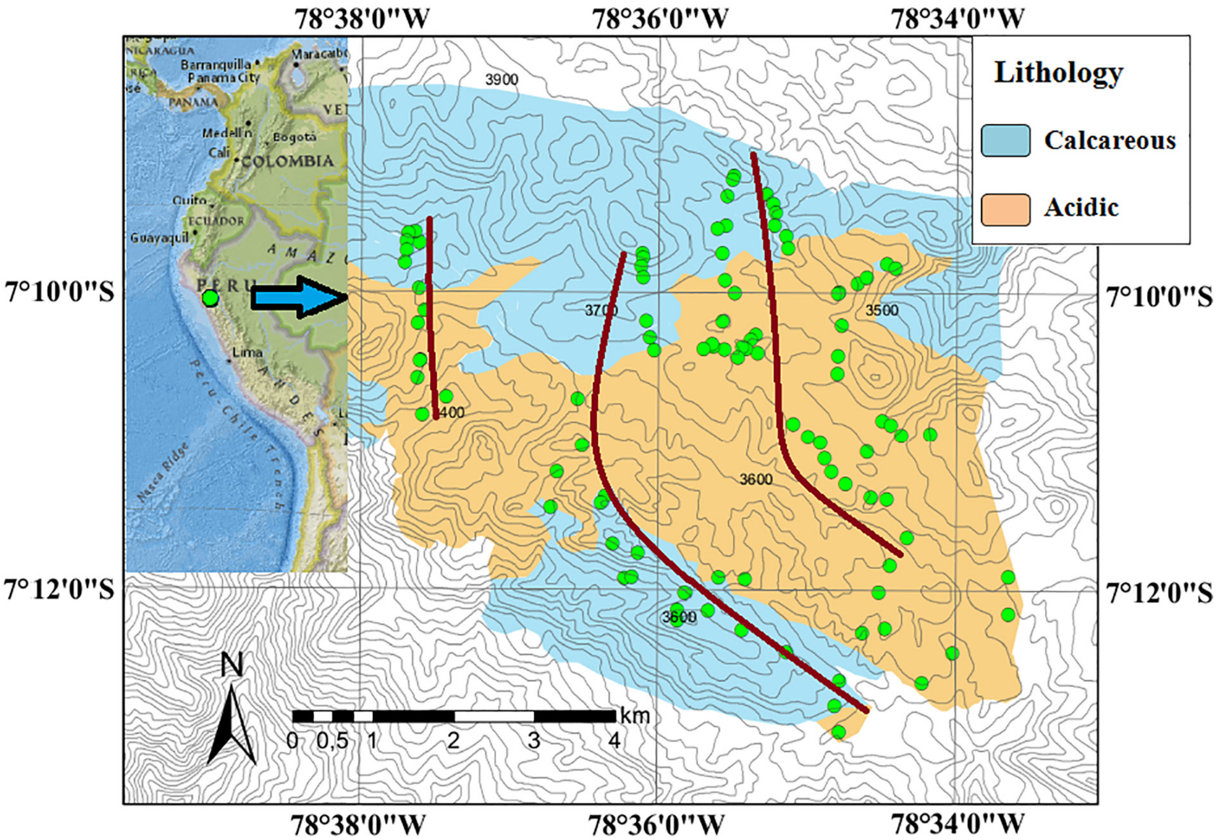

Fig. 1. Sampling sites in the study area. The picture on the left gives location of the study area, and green points on the main map indicate 69 sampling plots. The calcareous bedrocks are marked with blue background, and the acidic bedrocks are marked with yellow background. Bold red lines indicate transect lines. The distance between 2 adjacent contour lines is 50 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

before and after oven-drying. pH values were measured using a glass electrode with H_2O (w/v = 1:5) following the standard protocol of Bates (1973). Total carbon, nitrogen and inorganic carbon contents were measured with a VarioEL Elementar analyzer (Elementar, Germany) with an extension for inorganic carbon. Total organic carbon concentrations were calculated by subtracting inorganic carbon concentrations from total carbon concentrations.

Total SOC stocks were calculated by adding SOC stocks every 10 cm of the soil profile from the surface down to the C horizon using the equation:

$$SOC\ stock = \sum_{i=1}^{i=k} B_i C_i D_i$$

In which, B_i = bulk density (g cm^{-3}) of the layer i, C_i = C content (%) of the layer i; D_i = the thickness (cm) of layer i. Total SOC stocks and bulk densities were not corrected for gravel contents and gravel was negligible in most of the soil profiles.

2.4. Statistics

Linear models were used to test the effect of the SFE factors (lithology, land use, grazing intensity, slope position, altitude and slope angle) on total SOC stocks and SOC stocks of the upper 10 cm. We consider the soil properties (soil depth, moisture and pH) as potential conditional variables, because they may be important predictors for SOC stocks, although the SFE factors rather than soil properties are the focus of our study. The conditional variables were selected from soil properties, based on the criteria that the variables should be significantly related to SOC stocks and also be independent of the SFE factors. The criterion of independence aimed to avoid difficulties in interpretation that are introduced by interactions between the conditional variables and the SFE factors. The linear models were applied to identify the conditional variables (soil properties) that are linearly related to the SOC stocks and independent from the SFE factors. When the conditional variables were selected, we applied the linear models with all conditional variables and only one additional SFE factor to predict SOC stocks. These models are aimed at investigating the effects of individual SFE factors and to make comparisons with the linear models without conditional variables. We also conducted model selections by testing all combinations of conditional variables and SFE factors with up to 5 predictors included, and we selected the best model sets. Models with ΔAICc < 2 from the lowest AIC value were selected and presented with averaged standardized coefficients (Beta), R^2 and R^2 changed.

For each of the models that appeared as a suitable model (Based on AIC and significance of coefficients), a thorough visual check of the assumptions underlying the linear model was conducted (normality, homoscedasticity, independence of errors and absence of structural deviations from each of predictors and the response variable) and any apparent violations were reported with the other model results. The selection of best linear model sets was performed in R (R Core Team, 2017) using the MuMIn package (Barton, 2016), whereas other statistical analyses were performed with SPSS 22.0 (SPSS Inc., USA).

3. Results

3.1. Soil organic carbon (SOC) stocks and soil properties

Total SOC stocks ranged from 16.7 to 662.7 T ha^{-1} with a mean value of 215 ± 21 T ha^{-1} (mean ± S.E.), whereas SOC stocks of upper 10 cm and upper 40 cm had means values of 63 ± 4 and

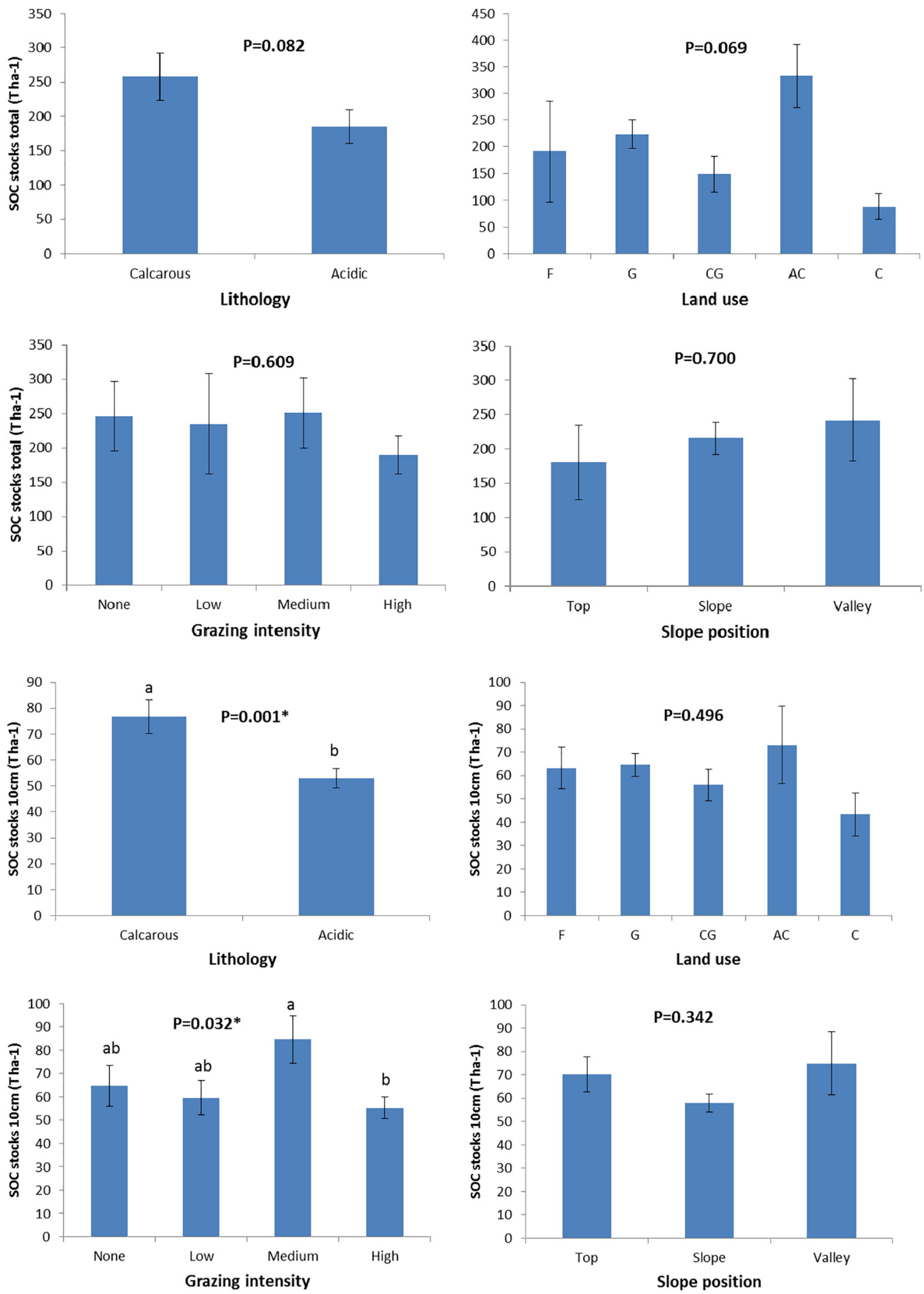

Fig. 2. Means and standard errors of total SOC stocks and SOC stocks of the upper 10 cm with different types of lithology, land use, grazing intensity and slope position. Means were compared using linear models (independent t-tests for lithology and one-way ANOVA for land us, grazing intensity and slope position) at a significance level of 0.05. F: forest, G: grassland, CG: cultivated grassland, AC: abandoned cultivation, C: cultivation.

$172 \pm 15\,\mathrm{T\,ha^{-1}}$. Total SOC stocks were not significantly ($P > 0.05$) different between any SFE factors, whereas SOC stocks of the upper 10 cm were significantly higher ($P < 0.05$) in calcareous bedrocks than in acidic bedrocks, and higher in medium grazing intensity than in other high grazing intensity (Fig. 2). Soil depth varied from 5 to 132 cm with a mean value of 41 ± 3 cm, whereas mean soil pH value was 5.58 ± 0.09 and mean soil moisture was $207.74 \pm 13.26\,\mathrm{g\,kg^{-1}}$ (Table 1).

3.2. Factors controlling soil organic carbon (SOC) stocks

Table 2 shows the linear models using only one SFE factor to predict the total SOC stocks and the SOC stocks of the upper 10 cm. No model predicting the total SOC stocks was significant ($P > 0.05$), although in the models with land use as the predictive variable (Table 2) soils under forest had significantly higher ($P = 0.010$) total SOC stocks than soils under cultivation. In contrast, models predicting SOC stocks of the

Table 1
Descriptions of SOC stocks, slope angles, altitudes and soil properties of the 69 sampling plots.

	Unit	Mean	Max	Min	SD	SE	95% confidence interval for means
SOC stocks total	$T\,ha^{-1}$	215	663	17	172	21	174–257
SOC stocks 10 cm	$T\,ha^{-1}$	63	190	14	31	4	55–70
SOC stocks 40 cm	$T\,ha^{-1}$	172	581	17	123	15	143–202
Slope angle	°	12	42	1	10	1	10–15
Altitude	m	3611	3901	3373	99	12	3588–3635
Soil depth	cm	41	132	5	25	3	35–47
pH Ave.		5.58	7.80	4.53	0.73	0.09	5.41–5.76
pH 10 cm		5.55	7.93	4.17	0.80	0.10	5.35–5.75
Moisture Ave.	$g\,kg^{-1}$	208	495	27	110	13	181–234
Moisture 10 cm	$g\,kg^{-1}$	206	654	27	136	17	173–239

pH Ave: average pH value, pH 10 cm: pH value of upper 10 cm, Moisture Ave.: average moisture content, Moisture 10 cm: moisture content of upper 10 cm. Sampling size n = 69 for each variable except for pH 10 cm (n = 66).

upper 10 cm were significant, when lithology, grazing intensity and altitude were the predictive variables in the models (Table 2). SOC stocks of the upper 10 cm were significantly higher with calcareous bedrocks than with acidic bedrocks (P = 0.001, Table 2), and were also significantly lower with high grazing intensity than with medium grazing intensity (P = 0.032, Table 2). Furthermore, altitude was a significant predictive variable that had a positive relationship with SOC stocks of the upper 10 cm (P = 0.007, Table 2). The model with lithology as the predictive variable explained the largest variation of SOC stocks of the upper 10 cm compared to other models (adjusted R^2 = 0.130, Table 2).

Fig. 3 and Table 3 give information about the selection of conditional variables from soil depth, soil moisture and pH (see Section 2.4). Soil depth was positively related to the total SOC stocks ($P < 0.001$) and explained 53.6% variation of the total SOC stocks individually. Average soil moisture had a positive relationship with total SOC stocks ($P < 0.001$) and explained 35.8% variation of the total SOC stocks (Fig. 3). Furthermore, soil moisture of the upper 10 cm also explained 37.0% variation of SOC stocks of the upper 10 cm with a positive linear relationship (Fig. 3). Soil depth and moisture were independent of all SFE factors, except for a significant relation between average soil moisture and altitude (Table 3). In contrast, soil pH was found to be dependent on lithology and land use (Table 3). Based on the criteria in Section 2.4, soil depth and average soil moisture were selected as conditional variables for total SOC stocks, whereas soil moisture of the upper 10 cm was the only conditional variables for SOC stocks of the upper 10 cm.

Table 4 gives the linear models with the conditional variables and only one SFE factor. Compared with linear models without conditional variables (Table 2), all models were highly significant ($P < 0.001$) and had higher values of R^2 and adjusted R^2 (Table 4). Within these models, lithology became the only significant SFE factor to predict the total SOC stocks when soil depth and average soil moisture were involved as the conditional variables (Table 4). The model with lithology and the

Table 2
Relation between SOC and single soil formation or environmental variable through linear regression, without any soil depth or moisture involved as conditional variable. The table lists standardized coefficients (Beta) with associated significance (P). Coefficients with $P < 0.05$ are shown in bold. The variable level within brackets under each soil formation or environmental variable means the category with Beta = 0. The P-values in the last column give the significance of the total model (i.e. resulting from an ANOVA of the regression model).

	Categorical variable										Numeric variables		R^2	Adjusted R^2	P value of the model
	Lithology (acid)	Land use (F)				Grazing intensity (none)			Slope position (top)		Altitude	Slope Angle			
	calcareous	G	CG	AC	C	Low	Medium	High	Slope	Valley					
SOC stocks total															
Beta	0.21												0.045	0.030	0.082
P	0.082														
Beta		0.09	−0.08	0.33	**−0.37**								0.125	0.071	0.669[a]
P		0.655	0.627	0.109	**0.010**										
Beta						−0.02	0.01	−0.16					0.028	−0.017	0.609
P						0.907	0.941	0.318							
Beta									0.10	0.14			0.011	−0.019	0.699
P									0.562	0.400					
Beta											0.11		0.011	−0.004	0.386
P											0.386				
Beta												−0.19	0.037	0.023	0.113
P												0.113			
SOC stock 10 cm															
Beta	**0.38**												**0.143**	**0.130**	**0.001**
P	**0.001**														
Beta		0.02	−0.08	0.13	−0.25								0.051	−0.009	0.496
P		0.924	0.662	0.555	0.095										
Beta						−0.04	0.25	−0.15					**0.125**	**0.085**	**0.032**[b]
P						0.745	0.097	0.331							
Beta									−0.19	0.06			0.054	0.025	0.161
P									0.257	0.717					
Beta											**0.32**		**0.102**	**0.089**	**0.007**
P											**0.007**				
Beta												−0.16	0.025	0.010	0.198
P												0.198			

F: forest, G: grassland, CG: cultivated grassland, AC: abandoned cultivation, C: cultivation.
[a] Soils under cultivation have significantly lower total SOC stocks than soils under forest, although the regression model as a whole is not significant.
[b] The multiple comparison shows that SOC stocks 10 cm are significantly different between medium and high grazing groups.

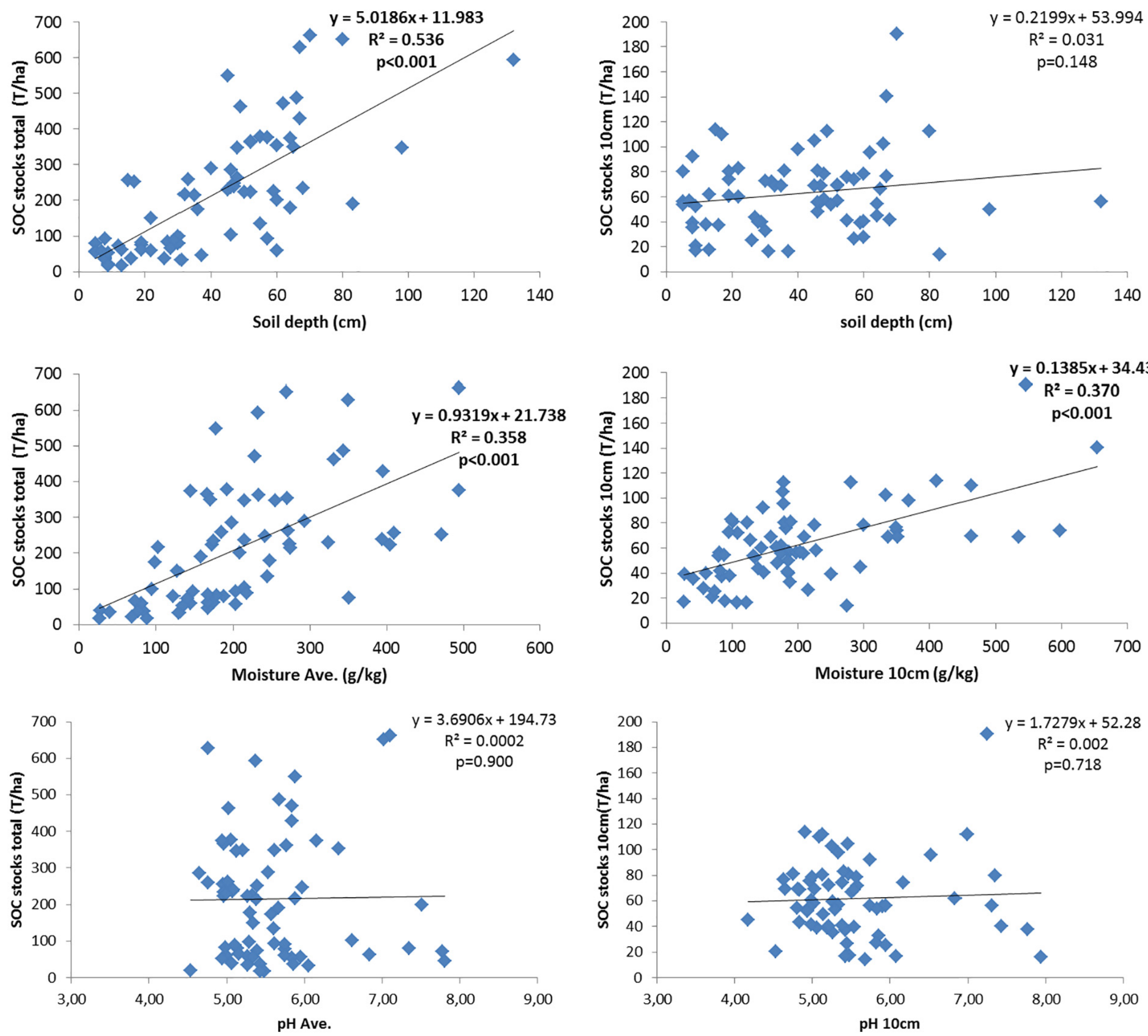

Fig. 3. Linear models (univariate linear regression) using soil depth, moisture and pH to predict total SOC stocks and SOC stocks of upper 10 cm. pH Ave: average pH value, pH 10 cm: pH value of upper 10 cm, Moisture Ave.: average moisture content, Moisture 10 cm: moisture content of upper 10 cm.

Table 3
Effects of soil formation or environmental factors on soil depth, moisture and pH using linear models (univariate regression). Significant factors ($P < 0.05$) are shown in bold.

	Categorical variable								Numeric variable			
	Lithology		Land use		Grazing intensity		Slope position		Slope angle		Altitude	
	R^2	P	R^2	P	R^2	P	R^2	P	R^2	P	R^2	P
Soil depth	0.002	0.692	0.087	0.204	0.007	0.931	0.052	0.175	0.002	0.733	0.043	0.089
Moisture Ave.	0.044	0.082	0.089	0.197	0.089	0.105	0.004	0.866	0.029	0.163	**0.094**	**0.010**
Moisture 10 cm	0.010	0.424	0.047	0.532	0.072	0.182	0.024	0.671	0.028	0.168	0.049	0.069
pH Ave.	**0.338**	**< 0.001**	**0.175**	**0.014**	0.030	0.577	0.021	0.492	0.001	0.770	0.044	0.085
pH 10 cm	**0.287**	**< 0.001**	0.118	0.101[a]	0.050	0.359	0.053	0.183	< 0.001	0.900	0.053	0.062

pH Ave: average pH value, pH 10 cm: pH value of the upper 10 cm, Moisture Ave.: average moisture content, Moisture 10 cm: moisture content of upper 10 cm.
[a] For this case the assumption of homogeneity of the variance is violated. A non-parametric analysis with a Kruskal-Wallis test leads to a significant effect of land use on pH 10 cm ($P = 0.035$).

conditional variables also explained the majority of the variation of the total SOC stocks (Table 4, adjusted $R^2 = 0.658$). For SOC stocks of the upper 10 cm, lithology, medium grazing intensity and altitude were significant SFE factors, when soil moisture of the upper 10 cm was involved as the conditional variable (Table 4). These models gave similar results as the linear models without the conditional variable (Table 2). The model with lithology and soil moisture of the upper 10 cm explained the largest part of the variation of the SOC stocks of the upper 10 cm (Table 4, adjusted $R^2 = 0.456$).

Table 5 shows the best linear model sets to predict the total SOC stocks and the SOC stocks of the upper 10 cm with all possible combinations of the SFE factors. The best predictive model for the total SOC

Table 4

Relation between SOC and single soil formation or environmental variable through multiple linear regression, with soil depth and/or moisture involved as conditional variables. The table lists standardized coefficients (Beta) with associated significance (P). Coefficients with a p-value < 0.05 are shown in bold. The bracket under each soil formation or environmental variable means the category with Beta = 0. The P-values in the last column give the significance of the total model (i.e. resulting from an ANOVA of the regression model).

	Categorical variable										Numeric variable		Conditional variable		R^2	Adjusted R^2	P value of the model
	Lithology (acid)	Land use (F)				Grazing intensity (none)			Slope position (top)		Altitude	Slope Angle	Soil depth	Moisture			
	calcareous	G	CG	AC	C	Low	Medium	High	Slope	Valley							
SOC stocks total																	
Beta	**0.18**												**0.61**	**0.31**	**0.673**	**0.658**	< **0.001**
P	**0.020**												< **0.001**	< **0.001**			
Beta		−0.08	−0.13	−0.06	−0.15								**0.57**	**0.35**	0.675	0.643	< **0.001**
P		0.534	0.217	0.670	0.091								< **0.001**	< **0.001**			
Beta						−0.03	0.06	−0.05					**0.60**	**0.34**	0.654	0.626	< **0.001**
P						0.726	0.517	0.654					< **0.001**	< **0.001**			
Beta									−0.12	−0.02			**0.61**	**0.36**	0.656	0.635	< **0.001**
P									0.240	0.860			< **0.001**	< **0.001**			
Beta											0.15		**0.65**	**0.29**	0.662	0.647	< **0.001**
P											0.071		< **0.001**	**0.002**			
Beta												−0.11	**0.59**	**0.34**	0.656	0.641	< **0.001**
P												0.140	< **0.001**	< **0.001**			
SOC stock 10 cm																	
Beta	**0.32**													**0.58**	**0.472**	**0.456**	< **0.001**
P	**0.001**													< **0.001**			
Beta		−0.07	−0.06	−0.04	−0.17									**0.61**	0.399	0.352	< **0.001**
P		0.699	0.689	0.823	0.147									< **0.001**			
Beta						0.02	**0.30**	0.04						**0.59**	**0.447**	**0.413**	< **0.001**
P						0.861	**0.013**	0.739						< **0.001**			
Beta									−0.23	−0.06				**0.60**	0.407	0.380	< **0.001**
P									0.087	0.671				< **0.001**			
Beta											**0.20**			**0.57**	**0.406**	**0.388**	< **0.001**
P											**0.049**			< **0.001**			
Beta												−0.06		**0.60**	0.373	0.354	< **0.001**
P												0.570		< **0.001**			

F: forest, G: grassland, CG: cultivated grassland, AC: abandoned cultivation, C: cultivation.

Table 5
Best linear models to predict SOC stocks with soil formation or environmental variables and soil properties. The table lists model-averaged standardized coefficients (Beta) with associated significance (P). The bracket under each soil formation or environmental variable means the category with Beta = 0. Coefficients with $P < 0.05$ are shown in bold. Averaging was done over the models that were within a ΔAICc value of 2 from the best model (all-subsets regression up to five predictors). R^2 denotes the range of R^2 values for the models used in the averaged model. ΔR^2 denotes the range of explained variance by the fixed factors for the models used in the averaged mode.

		Categorical variable						Numeric variable		Conditional variable		R^2	ΔR^2
		Lithology (acid)	Grazing intensity (none)			Slope position (top)		Altitude	Slope angle	Soil depth	Soil moisture		
		Calcareous	Low	Medium	High	Slope	Top						
SOC stocks total	Beta	**0.18**	–	–	–	**−0.20**	−0.14	0.16	−0.11	**0.65**	**0.26**	**0.68–0.71**	**0.04–0.07**
	P	**0.014**	–	–	–	**0.033**	0.177	0.098	0.113	**< 0.001**	**0.006**		
SOC stocks 10 cm	Beta	**0.30**	−0.01	**0.26**	0.02	−0.23	−0.07	0.17	–	–	**0.53**	**0.48–0.59**	**0.11–0.22**
	P	**0.001**	0.905	**0.020**	0.844	0.068	0.615	0.117	–	–	**< 0.001**		

stocks included lithology, slope position, altitude, slope angle and the conditional variables (soil depth and moisture), in which lithology, category slope of the slope position were significant predictive variables (Table 5). For the SOC stocks of the upper 10 cm, the best model included lithology, grazing intensity, slope position, altitude and the conditional variable (soil moisture), with lithology and medium grazing intensity as significant predictors (Table 5). With the SFE factors involved, the best models explained an extra 4% - 7% variation of the total SOC stocks and an extra 11% - 22% variation of SOC stocks of the upper 10 cm, comparing to the cases only conditional variables involved (Table 5).

4. Discussion

4.1. Soil organic carbon (SOC) stocks

The SOC stocks in our study area (215 ± 21 T ha^{-1} for the whole profiles, on average 41 ± 3 cm deep, Table 1) were higher than the global average levels (50 T ha^{-1} to 150 T ha^{-1} over 1 m; Lal, 2004). Our C-rich soils with acidic bedrocks correspond to Andosols, and dark soils with calcareous bedrocks correspond to Chernozems or Phaeozems (WRB, 2006). Batjes (2014) reported that SOC stocks assessed to 50 cm depth are 165 T ha^{-1} in Andosols, 86 T ha^{-1} in Chernozems and 105 T ha^{-1} in Phaeozems. When we compare our soils with acidic bedrocks (185 ± 25 T ha^{-1}) to Andosols and soils on calcareous bedrocks (258 ± 34 T ha^{-1}) to Chernozems or Phaeozems, our soils had higher average total SOC stocks (Fig. 2). Studies in other Andean alpine grassland soils showed either higher or lower SOC stocks compared to our results. Tonneijck et al. (2010) reported SOC stocks reaching 530 ± 40 T ha^{-1} in volcanic ash soils in Northern Ecuador, which are higher than our C stocks, due to high SOC concentrations (15 ± 5%) and deep soils (150–200 cm). Sarmiento and Bottner (2002) showed that SOC concentrations of Venezuelan Andean grassland were 10.54 ± 0.07% in the upper 20 cm, which is higher than our SOC concentrations in the upper 10 cm (7.61 ± 0.53%, Supplemental Table 1). Farley et al. (2004) showed that carbon stocks in the upper 10 cm soil in an Ecuadorian grassland were 50 T ha^{-1}, which is slightly lower than our SOC stocks in the upper 10 cm (63 ± 4 T ha^{-1}, Table 1). Zimmermann et al. (2009), Segnini et al. (2011), Muñoz García and Faz Cano (2012) and Rolando et al. (2017) reported lower SOC stocks in Puna grasslands from Bolivia to Central Peru when compared to our results (Table 1). Moreover, alpine or sub-alpine soils outside Andean regions were also reported to have lower SOC stocks compared to our results (Garcia-Pausas et al., 2007; Yang et al., 2008).

4.2. Effects of lithology and altitude

Our study area is characterized by heterogeneous parent materials (lithology), which should be distinguished from areas with homogeneous volcanic-ash soils (e.g. Buytaert et al., 2006; Tonneijck et al., 2010). In our results, lithology was the most important factor to predict SOC stocks when soil depth and soil moisture were involved as conditional variables, as indicated by the high Beta values, R^2 and adjusted R^2 compared to other SFE factors (Tables 4 and 5). Doetterl et al. (2015) highlighted the importance of soil mineralogy to predict SOC storage. This is consistent with our results, because soil mineralogy is closely related to the lithology. Similarly, Heckman et al. (2009) found that SOC distribution and stabilization is controlled by parent materials and soil mineralogy. Wagai et al. (2008) indicated that the interaction between lithology and climate had effects on the quality of SOC.

The lithology controlled SOC stock patterns can be explained by the lithology related stabilization mechanisms of soil organic matter (SOM). SOC stocks are controlled by the stabilization of SOM, and stabilization of SOM can be further explained by the occlusion of OM in soil aggregates and by the association of OM with the mineral surface (Lehmann and Kleber, 2015; Lutzow et al., 2006; Six et al., 2002). The association between OM and mineral surface is considered as a major mechanism contributing to long-term OM stabilization (Mikutta et al., 2006; Schrumpf et al., 2013). The OM-mineral association is largely controlled by soil mineralogy and climate (Van Breemen and Buurman, 2003). As climate conditions in our study are not much differentiated, lithology, which determines soil mineralogy, becomes a potential factor controlling SOC stocks. Evidence for this explanation is that soil pH values are significantly different between acidic and calcareous bedrocks ($P < 0.001$, Table 3). The differences in pH are potentially related to differences in the type of interaction of SOM with the soil mineral phase. In alkaline and neutral soils, organo-mineral associations are generally formed by polyvalent cation bridges, especially Ca^{2+} bridges; whereas in acidic soils, association of Fe and Al (hydr) oxides with OM and the formation of organo-metallic complexes are major ways for OM stabilization (Lutzow et al., 2006; Percival et al., 2000). Furthermore, soils rich in Ca are generally characterized by stable soil aggregates and good soil structure (Bronick and Lal, 2005). In our field observations, we found Iron pans(data not shown), which indicate high contents of iron oxides, in the soils formed on ignimbrite (an acidic bedrock). We also observed that soils with calcareous bedrocks have more stable aggregates and better structure than soils with acidic bedrocks. Our evidence indicates that the lithology related distribution of SOC stocks is in accordance with the consensus of the literature that described mineralogy related OM stabilization mechanisms.

Altitude also had significant effects on SOC stocks of the upper 10 cm, with generally higher SOC stocks at higher altitudes (Tables 2 and 4). Altitude is reported as a factor having positive, negative and no relation on SOC stocks (Garcia-Pausas et al., 2007; Leifeld et al., 2005; Schawe et al., 2007; Zimmermann et al., 2009). The positive relations between the altitude and the SOC stocks in our study may be explained by altitude related OM stabilization. de Koning et al. (2003) and Tsai et al. (2010) found amorphous Fe and Al fractions increasingly promote the OM stabilization with increasing altitude. It also can be explained by the low decomposition rate of OM at higher altitude (Du et al., 2014). Places with higher altitude generally have lower temperature, and in our study with high soil moisture contents (Table 3). As a result, soils at higher altitudes may have lower OM decomposition rates because of wet and cold climate, compared to soils at lower altitudes.

4.3. Effects of land use, grazing intensity and topography

Effects of land use (change) on SOC stocks have been intensively studied. Generally, SOC stocks are higher in grassland and forest soils than in cropland soils, and shifts from grassland or forest to cropland cause depletion of SOC (Guo and Gifford, 2002; Poeplau and Don, 2013). However, the direction and magnitude of the shifts depend on climate factors and soil mineralogy (Powers et al., 2011). Land use had very limited effects on SOC stocks in our study as we only find significant differences of the total SOC stocks between two land use types in a non-significant linear model (Table 2). In high Andean soils, Nierop et al. (2007), Zimmermann et al. (2009), Tonneijck et al. (2010) and Rolando et al. (2017) also reported no differences in SOC stocks between different land use patterns (generally grassland and forest). In our study, the limited effects on land use can be explained by the alternating land use patterns mentioned in the 2.1 site description part. The land use types alternate within a short period, and as a result, the C reserved in soils is likely in a dynamic balance. However, Rolando et al. (2017) observed shifts in SOC fractions between different land uses in a Peruvian high-Andes grassland, which suggested investigation on SOC fractions can be more effective than on bulk SOC.

Effects of grazing intensity on SOC stocks have been widely studied, in which positive, negative and neutral effects were reported (Cui et al., 2005; Piñeiro et al., 2010; Podwojewski et al., 2002). These inconsistent results can be explained by the variation of vegetation and SFE factors (Mcsherry and Ritchie, 2013; Piñeiro et al., 2010). Our results showed significant effects of grazing only on SOC stocks of upper 10 cm (Tables 2 and 4), which suggest that the topsoil may be more sensitive to grazing. Grazing activities influence SOC, by controlling net primary productivity and C decomposition pathways, and these pathways have more influence on the topsoil than the subsoil (Piñeiro et al., 2010).

SFE factors such as topography (slope position and slope angle) play limited roles in controlling SOC stocks, because we found that (1) slope position acted as a significant predictor only in the best linear model predicting total SOC stocks (Tables 2, 4 and 5); (2) slope angle was not the significant predictive variable (Tables 2, 4 and 5). This may be explained by the tropical location with low latitude (9° S), which indicates relatively homogeneous solar radiation and soil wetness in different aspects. This is supported by the independence of soil moisture from most of the topographical variables (except for altitude and average moisture, Table 3). In contrast, topographical factors such as aspect were reported to have strong effects on SOC in regions of higher latitudes with large annual variation of solar radiation (Garcia-Pausas et al., 2007; Schwanghart and Jarmer, 2011; van Hall et al., 2016).

4.4. Soil depth and moisture

Our results showed that soil depth was positively related to the total SOC stocks (Fig. 3), and explained a large part of variation of the total SOC stocks when compared with soil moisture and SFE variables ($R^2 = 0.536$ in Fig. 3, large Beta values in Tables 4 and 5). In addition, including soil depth as a conditional variable can largely improve the linear model to explain more variation of the SOC stocks (comparing R^2 and adjusted R^2 between Tables 2 and 4). The results indicate the importance of soil depth to predict the total SOC stocks. Similar to our results, Garcia-Pausas et al. (2007) and Zimmermann et al. (2009) also found positive correlations between SOC stocks and soil depth, whereas Yoo et al. (2006) concluded that soil depth is the key factor predicting the spatial SOC patterns. Furthermore, we found no relation between soil depth and SFE factors (Table 3), which indicates that soil depth is independent of any SFE factor in our study. Similarly, Garcia-Pausas et al. (2007) found that soil depth cannot be explained by any SFE factor including topographical factors. In contrast, Yoo et al. (2006) found that soil depth is controlled by geomorphic factors, and Zimmermann et al. (2009) found soil depth generally has positive correlations with altitude. The findings underpin the importance of including soil depth to predict SOC stocks, whereas the relation between soil depth and SFE factors need further study.

Our results showed that soil profiles with depths of 10 cm and 40 cm (average depths 41 cm) contained 29.3% and 80.0% of the total SOC stocks (Table 1). This indicates that sampling constant soil depths instead of the entire soil profiles can cause underestimations of SOC stocks, even assessed with average soil depths. Similarly, Tonneijck et al. (2010) found that the C stocks of Ecuadorian volcanic-ash soils assessed to 200 cm depth were 1.8 to 4.9 times of C stocks assessed to 30 cm depth. As many studies of SOC stock estimation only include soils with constant depths despite large potential SOC stocks in deep soils, SOC stocks can be generally underestimated (Batjes, 2014; Harrison et al., 2011; Wiesmeier et al., 2012). In order to avoid missing the information of the subsoil, SOC stocks are recommended being determined with the entire soil profile up to the C or R horizon, as the composition and stabilization of the deep soil C has distinguishing characteristics when compared to the topsoil C (Schmidt et al., 2011; Wiesmeier et al., 2012). Our results confirm the necessity to include the entire soil profile to avoid bias in the estimation of SOC stocks.

Another problem using constant soil depths, especially when only upper soil layers are involved, is that the effects of the SFE factors on SOC stocks can be overestimated (Harrison et al., 2011; Wiesmeier et al., 2012). Our results showed that models predicting the SOC stocks of the upper 10 cm had higher ΔR^2 values (0.11–0.22) than models predicting the total SOC stocks (0.04–0.07), which indicates SFE factors explained more variation of SOC stocks of the upper 10 cm than of the total SOC stocks (Table 5). This suggests the risk of overestimation of the effects of SFE factors when only using the upper soil layers. This can be further substantiated by our linear models without condition variables, which indicates that effects of lithology, grazing intensity and altitude were significant on the SOC stock of the upper 10 cm, but were not significant on the total SOC stocks (Table 2). The overestimated effects were also discussed by Poeplau et al. (2011), who found that the subsoil C varied less than the topsoil C with influences of land use change. Furthermore, Podwojewski et al. (2002) found that long-term intensive grazing stimulated soil erosion, which caused destruction of soil structure and C loss from the topsoil rather than the subsoil.

We found that soil moisture was positively related to the SOC stocks, and also explained a large part of the variation of the SOC stocks (Fig. 3 and Table 4). Other studies also found positive relationships between SOC and soil moisture, and the positive relationships are often explained by moisture related bio-degradation and/or OM stabilization (Farley et al., 2004; Krull et al., 2003; Yang et al., 2008). Based on the Beta values in the linear models, soil moisture explained less variation of total SOC stocks than soil depth, but explains more variation than lithology and grazing intensity (Tables 4 and 5). However, soil moisture data in our study may have limited power, because of the variation of soil moisture introduced by the cycle of dry and wet seasons. Nevertheless, the climate condition was stable throughout the sampling period, which means the soil moisture data of different plots are comparable.

5. Conclusions

Our results showed overall high SOC stocks of Andean grassland soils in the study area, when compared with global average levels as presented by Batjes (2014) and Lal (2004) with similar soil depths and soil groups (WRB, 2006). Total SOC stocks were largely controlled by soil depth, followed by soil moisture. When soil depth and moisture were controlled as conditional variables, lithology became the most important SFE factor for explaining the variation of the total SOC stocks. For SOC stocks of the upper 10 cm, soil moisture, lithology, grazing intensity and altitude were significant factors. Our results indicate that it is important to include the entire soil profile instead of a constant depth to avoid the underestimation of total SOC stocks. Alternatively, when soil samples are only collected from the top or with limited constant depths, effects of the SFE factors on SOC stocks can be overestimated. Therefore, when studying SOC stocks, we recommend sampling the entire soil profile up to the C or R horizon, instead of sampling with a limited constant depth.

In addition to soil depth and moisture, lithology was the most important factor to predict SOC stocks in our study area. As lithology is closely related to mineralogy linked OM stabilizations, further research on mineralogy related mechanisms of SOC sequestration and SOM stabilization may be useful to give applicable information for the management of this region. In addition, intensive grazing activities may be restricted, because these activities may increase risks of SOC loss and erosion induced topsoil material removal. Furthermore, the alternating land use pattern in our study region may be a good example to keep a dynamical balance of high SOC stocks.

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