Catena 171 (2018) 11–21

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

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

Songyu Yang[a,*], Erik Cammeraat[a], Boris Jansen[a], Michael den Haan[a], Emiel van Loon[a], Jorge Recharte[b]

[a] Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, Science park 904, 1098 XH Amsterdam, the Netherlands
[b] Instituto de Montaña, Calle Ricardo Palma 100, Huaraz, Ancash, Peru

ARTICLE INFO

Keywords:
Entire profile SOC stocks
Soil moisture
Grazing
Topography
Linear model

ABSTRACT

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

* Corresponding author.
E-mail address: s.yang@uva.nl (S. Yang).

https://doi.org/10.1016/j.catena.2018.06.038
Received 29 January 2018; Received in revised form 28 June 2018; Accepted 30 June 2018

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