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Storage and depth distribution of organic carbon in volcanic soils as affected by environmental and pedological factors

J.L. Mora [a,*], J.A. Guerra [b], C.M. Armas-Herrera [c], C.D. Arbelo [d], A. Rodríguez-Rodríguez [d]

[a] Departamento de Ciencias Agrarias y del Medio Natural, Facultad de Veterinaria Universidad de Zaragoza, C/Miguel Servet 177, 50013 Zaragoza, Spain
[b] Gestión del Medio Rural de Canarias, C/Subida al Mayorazgo, 24, portal B, 38110 Santa Cruz de Tenerife, Spain
[c] INRA unité AgroImpact de Laon-Mons, Pôle du Griffon 180, rue Pierre-Gilles de Gennes, 02000, Barenton-Bugny, France
[d] Departamento de Biología Animal y Edafología y Geología, Facultad de Biología, Universidad de La Laguna, Avenida Astrofísico Francisco Sánchez, s/n, 38206 La Laguna, Spain

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ABSTRACT

It has been recognised that volcanic soils, particularly Andosols, can store large amounts of soil organic carbon (SOC). This study investigates the factors controlling the regional and vertical distributions of SOC in soils of volcanic origin. To this aim, we investigated the vertical distribution of SOC in a total of 212 soil profiles representing all combinations of soil-forming factors in a volcanic area with a high diversity of ecosystems and soil types. We analysed the SOC contents in relation to intrinsic (soil type and relevant soil properties: texture and pH) and extrinsic factors (climate, parent material, relief), and we studied the patterns of SOC distribution with depth by fitting the SOC contents to different curve models. Furthermore, we selected ten soil profiles for a more detailed study to assess the effect of vegetation by examining the relationships of the SOC storage and depth distribution to the amount and allocation of plant roots and litterfall.

SOC storage was controlled by the interaction of climatic (rainfall), time (substrate age), topographic (slope) and biotic (plant-mediated) factors. Our results indicate that under humid conditions, large organic inputs and the inhibition of microbial degradation due to low pH, Al-toxicity and persistent anaerobiosis within soil microaggregates largely contributed to SOC accumulation. Soil type was a poor predictor of SOC storage, most likely due to the co-occurrence of young and evolved Andosols and a certain andic character in many soils that did not qualify as Andosols. The distributions of root carbon and SOC appeared to be closely interrelated, suggesting a major role of roots in the supply of organic matter and the lack of significant bioturbation. The depth distribution of SOC was best fitted by the quadratic, cubic and power models, the latter being a feasible alternative that should be used to this aim in volcanic soils rather than the widely used exponential model.

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1. Introduction

Understanding the factors that control the storage of organic carbon in soils is crucial to predict and simulate the response of the carbon cycle to changes in climate and land use. Most research on soil organic carbon (SOC) has focused on the topsoil layer, where SOC is more abundant and sensitive to changes (Batjes, 1996; Rumpel and Kögel-Knabner, 2011). However, recent literature has emphasised the need to consider the SOC contained in the subsoil, as it contributes more than half of the total SOC stock (Batjes, 1996; Eswaran et al., 1993; Hiederer, 2010), can vary significantly in decadal time scales (Meersmans et al., 2009) and is even more sensitive to mid-term changes in temperature than the SOC in the topsoil (Fierer et al., 2003).

Nevertheless, regional databases often only include data from the topsoil (Jones et al., 2004; Mestdagh et al., 2004), and SOC measurements below a depth of one metre are rare (Hiederer, 2010; Lorenz and Lal, 2005). Analyses and modelling of the vertical distribution of SOC allows the storage of the SOC in the subsoil to be estimated from topsoil data (Mestdagh et al., 2004). Using this approach, the reservoirs of SOC at regional scales can be quantified and mapped (Minasny et al., 2006; Mishra et al., 2009; Sleutel et al., 2003). Several mathematical models have been used to describe the depth distribution of SOC in soils: exponential (Arrouays and Pélissier, 1994; Bernoux et al., 1998; Hilinski, 2001), power (Bernoux et al., 1998; Braakhekke et al., 2011; Jobbágy and Jackson, 2000), quadratic (Smith et al., 2000) and log (Hiederer, 2010; Jobbágy and Jackson, 2000), with the exponential model being the most widely accepted (Minasny et al., 2006).

Soil organic carbon (SOC) storage has long been known to depend on soil-forming factors, i.e., climate, parent material, organisms, relief and time (Jenny, 1980). At the global scale, the SOC contents increase with rainfall and decrease with temperature (Post et al., 1982). In general, the influence of climate on SOC contents is higher in the topsoil layer (0–30 cm) (Hiederer, 2010; Wang et al., 2004) than in the subsoil (below 30 cm), where other factors such as clay content are more influential. The ratio of the total SOC in the topsoil also increases with

* Corresponding author. Tel.: +34 876 554155; fax: +34 976762488.
E-mail address: jlmorah@unizar.es (J.L. Mora).

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precipitation and decreases with temperature (Batjes, 1996). However, tropical soils often show a deeper SOC distribution, which can be attributed to deep roots and deeper soil profiles, as well as to an intense bioturbation (Jobbágy and Jackson, 2000). At local scales, the life form and above- and belowground allocation of plants are considered the major determinants of the depth distribution of SOC (Jobbágy and Jackson, 2000). In general terms, deep distributions of SOC are expected to be less sensitive to fluctuations in climate than shallow distributions (Braakhekke et al., 2011) except for when changes in precipitation alter root density and the downward transport of SOC, particularly in shrink-swell soils (Chabbi et al., 2009; Marin-Spiotta et al., 2011).

Andosols are typically developed on volcanic ash materials and are considered to be amongst the soil types with the highest SOC storage, with approximately 30 kg C m^{-2} on average, second only to Histosols (Batjes, 1996; Eswaran et al., 1993). The high SOC storage in Andosols is mainly attributed to its stabilisation in aluminum (Al)–humus and allophane–humus complexes (Arnalds, 2008; Ugolini and Dahlgren, 2002). If such stabilisation does not occur, e.g., because of the scarcity of organic inputs, the andic character is transient and the Andosols evolve to other soil types (Peña-Ramírez et al., 2009; Ugolini and Dahlgren, 2002). Mineralogy (determined by soil weathering and age) appears to be very important in the accumulation and stabilisation of SOC in volcanic soils (Basile-Doelsch et al, 2007; Torn et al., 1997). Other factors used to explain the accumulation of SOC in Andosols include the occlusion of organic matter within highly stable micro- and macroaggregates (Mora et al., 2007; Tonneijck et al., 2010), possible inhibition of the microbial activity due to low pH and Al-toxicity (Tokashiki and Wada, 1977; Tonneijck et al., 2010) and the high productivity of ecosystems that are sustained by Andosols (Percival et al., 2000).

The response of SOC storage in Andosols to environmental gradients has not been fully established. For example, the SOC stocks in Andosols were found to be poorly correlated with climate by Percival et al. (2000) and Matus et al. (2006). In particular, research is needed on which factors control the vertical distribution of SOC in Andosols, which has been reported to be deeply distributed (Rumpel et al., 2012) and minimally influenced by root inputs; it is instead strongly affected by fauna bioturbation (Tonneijck and Jongmans, 2008).

The aim of this work is to provide a basic understanding of the extrinsic (biotic and abiotic) and intrinsic (pedological) factors that control the storage and depth distribution of the SOC of a trough of volcanic origin. To this aim, we investigated the SOC stocks and their vertical distribution in a large number of soil profiles in the Canary Islands (Spain), which is a suitable setting for this research because of its volcanic origin and high diversity of ecosystems and soils. We analysed the SOC contents in relation to: (i) abiotic factors (i.e., climate, type and age of parent material, relief); (ii) biotic factors (amount and allocation of plant roots and litterfall); and (iii) pedological features (soil type, texture, pH). In addition, we evaluated the performance of various curve models in predicting the depth distribution of the SOC contents under different soil types.

2. Materials and methods

2.1. Study area and sampling design

The Canary Islands are located in the Atlantic Ocean 100 km off the northwest coast of Africa. The islands are the result of a volcanism that dates back 30 Ma but is still active at present. The typical climate is subtropical maritime, but a variety of mesoclimates exist because of the complex interaction amongst the location at a subtropical latitude close to Africa, the influence of a cold ocean current, the effect of steep relief and the exposure to humid trade winds at the northern slopes of the islands. As a result, there is a high diversity of ecosystems (Del-Arco et al., 2006) and soils (Mora et al., 2009). The natural ecosystems on the Canary Islands are distributed according to vegetation belts, whose main types and characteristic soils are detailed in Table 1.

We designed a GIS-based sampling strategy with the aim of achieving a representative sample of the soils developed under the natural soil-forming conditions that are most common in each of the main ecosystems of the Canary Islands. The setting for this study was the island of Tenerife, which is the highest (3718 m a.s.l., Mt. Teide), largest (2038 km^2) and most ecologically diverse of the Canary Islands. Details on the sampling strategy can be found in Appendix A. In total, we analysed 212 soil profiles, whose locations are shown in Fig. 1.

In addition, with the aim to analyse the effect of plant-derived inputs on the storage and vertical distribution of SOC, we selected an additional set of ten soil profiles representative of the main habitat types in the Canary Islands in Tenerife and in the neighbouring island of La Gomera (Table 2). We selected two profiles (L1, L2) in the coastal scrubland ecosystem, five profiles (M1–M5) in the laurel forest ecosystem and three profiles (H1–H3) in the Canary pine forest ecosystem. Soils L1, M1, M2, H1 and H2 are located in nearly mature ecosystems; L2, M2, M3, M4 and H4 are located under secondary plant communities that are typical of disturbed areas; and M5 hosts a conifer plantation. Soils M1, M2, M3, M4, M5 and H3 show a marked andic character, although M4 does not qualify as an Andosol. Table 2 summarises the main characteristics of these ten sites and their soils. More detailed information on these study sites can be found in Armas-Herrera et al. (2012).

2.2. Field procedures

The soil profiles were opened to a 200 cm depth or to lithic contact. All the soil profiles and the general features of each site were extensively described following FAO (2006). From all the horizons, samples were collected for physical–chemical analysis, and core samples for bulk density measurement were taken at the midpoint of each horizon using cylinders with an 8 cm diameter and 5 cm height.

At the ten detailed study sites, we collected soil cores throughout the soil profiles for quantification of the carbon content in the form of plant roots. We also randomly placed four permanent litter traps (53 × 53 cm) to assess the aboveground carbon inputs via litterfall. As an exception, we did not place litter traps in the coastal scrub ecosystem because of the shrubby size of the vegetation; instead, we removed the surface litter from four 1 m^2 subplots. For two years, we seasonally collected (January, April, July and October) the litterfall residues in each trap or subplot.

2.3. Laboratory procedures

To quantify the SOC contents on a volume basis, we analysed the values of bulk density and the contents of coarse fragments and organic carbon in all the soil samples. Bulk density was determined by drying at 105 °C and weighing the soil core samples with known volume. Coarse fragments (>2 mm) were determined by wet sieving. Organic carbon was determined using the classic method by Walkley and Black (1934), consisting of oxidisation with 1 N sodium dichromate in acid and back-titration using 0.5 N ammonium ferrous sulphate. Saline soil samples were treated with a silver sulphate solution to eliminate interference by chlorides during analysis (Quinn and Salomon, 1964). We evaluated the consistency of the Walkley–Black method by calibrating it against the dry combustion method, as described in Appendix B.

Soil particle size distribution was determined by the Bouyoucos hydrometer method after dispersion with sodium hexametaphosphate and by sieving of the sand fraction. Soil pH was measured in 1:2.5 soil: water suspensions. Other soil properties were analysed when needed to classify the soils according to the WRB system (IUSS Working Group WRB, 2006).

Roots from the soils of the detailed study soils were separated from soil material using a 0.5-mm mesh sieve. Both the roots and litterfall samples from the detailed study sites were washed with deionised

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