Catena 158 (2017) 46–54

Contents lists available at ScienceDirect

Catena

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

Frequency dependence of magnetic susceptibility as a proxy for fine-grained iron minerals and aggregate stability of south Chilean volcanic ash soils

Marc-Oliver Goebel[a,*], Jiem Krueger[a], Heiner Fleige[b], Jan Igel[c], Rainer Horn[b], Jörg Bachmann[a]

[a] Institute of Soil Science, Leibniz Universität Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany
[b] Institute of Plant Nutrition and Soil Science, Christian-Albrechts-Universität zu Kiel, Hermann-Rodewald-Str. 2, 24118 Kiel, Germany
[c] Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hannover, Germany

ARTICLE INFO

Keywords:
Andosols
Iron oxides
Magnetic susceptibility
Mineral magnetism
Pedogenesis
Soil aggregate stability

ABSTRACT

Aggregate stability (AS) is an important property controlling erodibility of volcanic ash soils and is known to be strongly affected by fine-grained iron (Fe) and aluminum (Al) minerals. Assuming that frequency dependence of magnetic susceptibility (MS) is related to the amount of fine-grained Fe minerals and considering that formation of fine-grained Fe and Al minerals is closely coupled in volcanic ash soils, we hypothesized that the measurement of MS can be used to evaluate AS of these soils. To verify this, we investigated volcanic ash soils along a 120-km transect in southern Chile, reaching from the Andean Southern Volcanic Zone (SVZ) to the Pacific coastal range. Stability of 1-cm macroaggregates from topsoil (0–5 cm) and subsoil (20–25 cm) was determined by wet-sieving, combining long-term water immersion and subsequent ultrasonic treatment. MS was measured at 465 and 4650 kHz to calculate its frequency dependence. We found an increasing amount of organic matter, fine-grained Fe and Al minerals, and clay and decreasing bulk density with increasing distance from the SVZ, indicating progressing soil development along the transect. Likewise, AS increased with increasing distance from the SVZ and was found to be controlled primarily by soil organic matter and fine-grained Fe and Al minerals. While MS itself showed only slight variation, its frequency dependence continuously increased with increasing distance from the SVZ, indicating an increasing fraction of fine-grained ferrimagnetic particles. Accordingly, frequency dependence of MS was found to be linearly related to the amount of fine-grained Fe minerals as quantified by dithionite extraction, and moreover, due to the close linear relationship between fine-grained Fe and Al phases, it revealed to be suitable for estimating the total amount of both fine-grained Fe and Al minerals. Analysis of underlying material (60–65 cm) indicated that the increase in frequency dependence of MS with increasing distance from the SVZ was caused by fine-grained ferrimagnetic particles of pedogenic and lithogenic origin. Although overall organic matter content turned out to be more closely related to the stability of the investigated aggregates, we conclude that frequency dependence of MS can be used as an easily obtainable proxy for assessing the contribution of fine-grained Fe and Al minerals to AS.

1. Introduction

Large areas of southern Chile are covered by late-glacial and holocenic volcanic ash deposits originating from the Southern Volcanic Zone (SVZ) of the Andes (Bertrand and Fagel, 2008). The soils typically developed from these ashes are Andosols, which are usually characterized by large amounts of organic matter and reactive iron (Fe) and aluminum (Al) components (Shoji et al., 1993), low bulk density as well as high porosity, shrinkage potential and hydraulic conductivity (Beck-Broichsitter et al., 2016; Fleige et al., 2016). Despite their generally high resilience capacity (Dörner et al., 2011), south Chilean Andosols are progressively undergoing changes in structure and hydraulic properties due to increasing intensity and changes in land use during the last decades (Dec et al., 2012). The changes in mechanical and hydraulic properties make these soils particularly prone to degradation by water erosion. Hence, in order to take action to reduce the risk of Andosol degradation in southern Chile, there is a great need for information on the actual erodibility potential of these soils. Affordable methods that allow a rapid assessment of erodibility would therefore be highly desirable.

Soil aggregate stability (AS) is considered to be one of the most important controlling factors of soil erosion by water (e.g. Barthès and

Abbreviations: AS, aggregate stability; MS, magnetic susceptibility; SP, superparamagnetic; SVZ, Southern Volcanic Zone

* Corresponding author.
E-mail address: goebel@ifbk.uni-hannover.de (M.-O. Goebel).

http://dx.doi.org/10.1016/j.catena.2017.06.013
Received 27 March 2017; Received in revised form 31 May 2017; Accepted 9 June 2017
Available online 20 June 2017
0341-8162/

Roose, 2002; Cantón et al., 2009), rendering it particularly suitable for assessing soil erodibility. While most studies on this issue were carried out on arable soils under temperate climate, close negative relationships between erodibility and AS were also found for volcanic ash soils (e.g. Rodríguez Rodríguez et al., 2006; Zehetner and Miller, 2006). Several factors have been identified to play a crucial role in determining AS (Amezketa, 1999). Of these, organic matter content (Chenu et al., 2000; Regelink et al., 2015), soil wettability (Goebel et al., 2012; Zheng et al., 2016), cation exchange capacity (Dimoyiannis, 2012; Wang et al., 2016), clay content (Le Bissonnais, 1996), and the amount of fine-grained (pedogenic) Fe and Al minerals (Duiker et al., 2003; Goldberg et al., 1990) are considered to be most important.

Volcanic ash is a commonly unconsolidated, comminuted material containing large quantities of volcanic glass with generally weak resistance to chemical weathering (Shoji et al., 1993). A recent study by Botto et al. (2013) revealed that young volcanic ash deposits from the Puyehue-Cordon Caulle Volcanic Complex in the SVZ consist of Fe- and Al-rich volcanic glass fragments (70–80%) and, to a lesser extent, of crystals and crystal fragments of silicate phases and metal oxides (20–30%) such as hematite and magnetite. The weathering of volcanic ash produces large amounts of highly reactive Fe and Al phases, which are characteristic features of Andosols and occur essentially as Fe– and Al–humus complexes and fine-grained poorly crystalline Fe and Al minerals such as ferrihydrite, allophane and imogolite (Shoji et al., 1993). Accordingly, there is a great potential of aggregate stabilization by fine-grained Fe and Al minerals in soils developed from volcanic ash (Baumgarten et al., 2013; Churchman and Tate, 1987; Huygens et al., 2005).

An important characteristic of Fe-bearing minerals is their magnetic susceptibility (MS), which expresses the degree to which a material is magnetized under an external magnetic field. While antiferromagnetic minerals like hematite and ferrihydrite display only low MS, ferrimagnetic minerals such as magnetite and maghemite show very high MS and usually dominate the MS in soils and sediments even at low concentrations (Clark and Emerson, 1991). A typical feature of ferrimagnetic minerals is that their MS is strongly dependent on particle size (Liu et al., 2012). Below a certain size-threshold (ranging from 1 nm to some tens of nanometers), ferrimagnetic particles show so-called superparamagnetic (SP) behavior, characterized by considerably higher MS as compared to larger particles of the same composition (Dearing et al., 1996a). Thus, even at very low concentrations, SP ferrimagnetic particles can govern the MS of a sample (Thompson and Oldfield, 1986). The size threshold at which a particle displays SP behavior depends on the frequency of the magnetic field used for the MS measurement. By carrying out measurements at different frequencies, the frequency dependence of MS can be quantified, which in turn is related to the concentration of SP ferrimagnetic particles in the sample (Torrent et al., 2006). It is suggested that the frequency dependence of MS can be used as a semi-quantitative measure of the concentration of fine-grained pedogenic ferrimagnetic minerals (Dearing et al., 1996a); however, SP minerals may also originate from the parent rock (Igel et al., 2012; Knudsen et al., 2005), and the lithogenic overprint has to be taken into consideration.

The formation of fine-grained pedogenic ferrimagnetic minerals is closely linked to the presence of ferrihydrite, which acts as an important precursor phase (Maxbauer et al., 2016). Based on the close link between ferrimagnetic mineral formation in soils and ferrihydrite and the consideration that ferrihydrite formation in volcanic ash soils is often closely related to the formation of fine-grained Al phases such as allophane (Churchman and Tate, 1987; Shoji et al., 1993; Silva et al., 2015), we hypothesized that the frequency dependence of MS can be used to estimate the amount of both fine-grained Fe and Al minerals. Given the important role of fine-grained Fe and Al minerals in stabilizing aggregates, we further hypothesized that the frequency dependence of MS can be used as a proxy for AS.

While several studies have already used MS data for the exploration of soil redistribution in the field to identify erosional processes (e.g. de Jong et al., 1998; Dearing et al., 1986; Royall, 2001), there are only few studies that directly relate information from MS measurements to aggregation (Alekseeva et al., 2009; Jakšík et al., 2015; Rhoton and Duiker, 2008). These studies consistently reported a positive relationship between AS and MS. However, considering that MS depends on the total magnetic particle fraction of a soil, including fine-grained Fe minerals but also larger lithogenic Fe minerals, which are not likely to contribute to aggregate stabilization, we hypothesized that the frequency dependence of MS is more suitable to infer AS.

To test our hypotheses, we investigated AS and magnetic properties of volcanic ash soils along a 120-km transect in southern Chile. In order to account for other potentially important factors of AS, the impact of organic matter, clay content and cation exchange capacity was also considered. Previous experiments (unpublished) have shown that the AS of the investigated soils could not be distinguished on the basis of a commonly used wet-sieving procedure (see Le Bissonnais, 1996) as virtually no aggregate breakdown could be observed. We therefore applied a wet-sieving procedure that combined long-term water immersion and subsequent ultrasonic treatment to determine AS in the present study.

2. Materials and methods

2.1. Site description and soil sampling

Four sites, ranging from young volcanic ash soils to deeply weathered soils, were investigated along a 120-km SE–NW transect in southern Chile. The study area was located between 72° and 74°W and 39° and 41°S, reaching from the Andean SVZ across the Central Valley to the eastern slopes of the Pacific coastal range (Fig. 1 and Table 1). The sites were numbered consecutively according to their distance from the volcano the most recent ash material was derived from.

Site 1 (S1) was located in the SVZ at the base of the Puyehue volcano at an altitude of around 240 m a.s.l. The site was characterized by young volcanic deposits of the Puyehue (1960) and the Carrán (1955 and 1979) and by slightly developed soils. Here, soil samples were taken from a meadow plot which was used for extensive livestock farming. Site 2 (S2) was situated at the northern slopes of the Puyehue volcano at altitudes between 350 and 410 m a.s.l. Likewise, this site was characterized by slightly developed soils on young volcanic ash deposits of the Puyehue (1960) and the Carrán (1955 and 1979). Here, soil samples were taken from a meadow (used for extensive livestock farming) and a forest plot. Site 3 (S3) was located in the Central Valley between Río Coihue and Lago Ranco, about 6 km west of Futrono at an altitude of around 180 m a.s.l. The site was characterized by strongly weathered ash soils of varying thickness overlying moraine material, which were covered by natural and secondary forest or intensively used as cropland (under mechanized tillage). Site 4 (S4) was located at the eastern slopes of the Pacific coastal range, about 20 km north of Valdivia at an altitude of around 20 m a.s.l. The site was characterized by uniform soil development and a variety of land uses, ranging from extensive wood pasture to cropland (under mechanized tillage). No ash layers from recent eruptions were detectable in the profiles of S3 and S4, where soil material was sampled from meadow (used for extensive livestock farming), forest and cropland plots. At each site, disturbed material and undisturbed soil cores (100 cm^3) were collected from the topsoil (0–5 cm) and the subsoil (20–25 cm). In addition, disturbed samples from 60 to 65 cm depth were taken as a reference in order to estimate the magnetic properties of the parent material. Sampling was carried out during the southern hemisphere summer season (February–March) of 2011 and 2012. All soils were characterized by well-drained conditions without indications of waterlogging.