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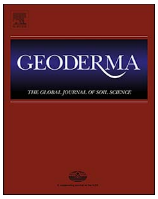

Understanding carbon storage in volcanic soils under selectively logged temperate rainforests

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ABSTRACT

A disturbance due to selective logging causes the release of carbon from forest soils. Here, we examine this effect under *Nothofagus* stands in Andisols of southern Chile (39°38′S, 72°02′W, > 4000 mm yr^{-1}). We postulate that soil carbon destabilization caused by forest management is counteracted by two contrasting carbon stabilization mechanisms linked to pedogenic processes: (1) the formation of allophane-imogolite-like materials (i.e., short-range ordered aluminosilicate particles with a specific Al/Si molar ratio, for example in the present study 3.8) and (2) formation of Al- and Fe-carbon complexes. The aim of this study was to compare the effects of selective logging on the organic carbon storage of forest Andisols. We estimated that carbon storage occurred in the uppermost 1 m of soils under evergreen (EGF) and secondary growth mixed deciduous forests (DMF). The selective dissolution method was used to estimate the mechanisms of soil carbon storage. The soil carbon storage under the unmanaged EGF did not differ significantly from that of the stands measured 10 or 50 years after selective logging. Likewise, the soil carbon storage under DMF was similar to that under stands measured 2, 6 or 50 years after selective logging. Overall, soil carbon storage was 24% lower under DMF than under EGF, which was attributed to the faster decomposition of organic matter produced by deciduous forests. The soil pH of the Ah-horizon was significantly lower (4.5–5.1) than that of the subsoil (5.5–6.0) due to the leaching of cations, leading to the development of less allophanic properties (i.e., an aluandic horizon). This effect increased the formation of organo-mineral complexes and reduced the content of allophane-imogolite-like precursors (e.g., non-crystalline Si and Al). As a result, an inverse relationship was found between metals (Al, Fe) complexed with carbon and the content of non-crystalline Si and Al, both of which were within single horizons and the entire soil profile in general. We conclude that disturbances caused by forest management did not alter carbon storage in these Andisols, which can be explained by (1) the potential mechanisms of carbon stabilization studied here and (2) humid climate, which protected the bare horizon from irreversible drying after the management of these ecosystems, thus preventing potential carbon loss.

1. Introduction

It is well known that historical land use and the inappropriate management of forest soils have had negative impacts on soil carbon, the nitrogen cycle and forests' community structures. Although this has been documented in tropical habitats (Kolbe et al., 2016), the effects of these activities on carbon pools in temperate rainforests in the southern latitudes remain understudied (Ordoñez et al., 2015).

Management is one of the most common causes of changes in soil carbon and has often been proposed as a method for sequestering carbon from rising atmospheric CO_2 levels (Post and Kwon, 2000). However, earlier studies have shown that harvesting produces no

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Abbreviations: EGFU, unmanaged evergreen forest (pristine); EGF10, evergreen forest managed 10 years; EGF50, evergreen forest managed 50 years prior to the present study; DMF2, secondary growth deciduous mixed forest managed 2 years; DMF6, deciduous forest managed 6 years; DMF50, deciduous forest managed 50 prior to the present study; SOC, soil organic carbon; BD, bulk density; N, nitrogen; Al_p, Aluminium pyrophosphate extractable; Fe_p, Iron pyrophosphate extractable; Al_o, Aluminium acid oxalate extractable; SOM, soil organic matter; POM, particulate organic matter

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significant change (± 10%) in the organic matter of bulk soil, since its stabilization in the soil partly depends on soil properties (e.g., soil texture), which are little affected by stand management (Johnson, 1992; Johnson and Curtis, 2001).

Litterfall on the surface and deep rooting provide biogeochemical connections with deep soil through nutrient uptake as well as root exudates and turnover (Maeght et al., 2013). An improved understanding of surface and deep soil processes is necessary to predict the environmental changes that may induce the mineralization of stable carbon or increase the carbon storage in the soil of a managed ecosystem.

Most Chilean temperate rainforests stand on volcanic soils (i.e., Andisols, Soil Survey Staff, 2014) and have largely been managed or burned, except in protected areas where pristine ecosystems can still be found. Selective clearing and biomass removal are common forest practices in Chile that have been shown to affect the status of soil nutrients in surface horizons (e.g., Armesto et al., 1998). Very little research has focused on the effects of forest management practices in temperate rain forest ecosystems on soil carbon storage in the top and subsurface soil (Guo and Gifford, 2002). Consequently, avoiding soil disturbance is important for the formation of stable organo-mineral complexes, which in turn is a central concept in the process of soil carbon sequestration (Jandl et al., 2007).

Two types of Andisols are known (e.g., Dahlgren et al., 2004): non-allophanic and allophanic Andisols. The latter, which contains amorphous materials such as allophane, imogolite (or imogolite-like allophane) and ferrihydrite, has a pH between 5 and 7 and low soil organic matter (SOM) contents. In contrast, non-allophanic Andisols have pH < 5.0 and high SOM contents due to the formation of large organo-mineral complexes, which inhibit the polymerization of Al-hydroxides needed for allophane formation (see below) (Tonneijck et al., 2010). Vegetation is also often reported to cause more acidification in forests than in grassland volcanic soils due to the slower recycling and higher leaching of base cations under high rainfall conditions (Tonneijck et al., 2010).

Analyses of pedogenic processes in volcanic soils are usually performed using wet chemical methods, such as Al pyrophosphate and Al acid oxalate extraction. Al extracted by acid oxalate (Al_o) is considered to represent the sum of Al in organic and amorphous complexes in non-crystalline hydrous oxides, such as allophane and imogolite (Matus et al., 2006). However, the usefulness of pyrophosphate at pH 10, which is the commonly used extraction agent for organic carbon-bound Al, has been questioned (Kaiser and Zech, 1996). Not only can it dissolve Al hydroxide and some interlayered Al and labile forms of surface-precipitated Al (Page and de Kimpe, 1989), but it can also enhance peptisation (Kaiser and Zech, 1996). Nonetheless, Bardy et al. (2007) demonstrated that Na–pyrophosphate effectively removes Al bound to soil carbon, as determined by studies of ^{27}Al NMR spectra in Amazonian podzols.

In allophanic Andisols (i.e., imogolite-like minerals and ferrihydrite) carbon stabilizes when reacting with the surfaces of amorphous minerals to form tight bonds with low turnover rates, thus preventing the further mineralization of carbon (Levard et al., 2012; Parfitt, 2009; Sollins et al., 2006). In allophanic Andisol, stabilized carbon is also found in Al- and Fe-oxide complexes and precipitates. This carbon, however, appears to be derived from the microbial by-products of plant material transformations rather than from recalcitrant plant material itself (Buurman et al., 2007; Parfitt, 2009). In addition to this chemical stabilization, the physical protection of SOM by soil plays an important role in SOM decomposition. Pores and soil particles control SOM accessibility and the availability of water and oxygen to decompose organisms (Baldock and Skjemstad, 2000). Decomposition is inhibited at larger proportions of small pores (i.e., pores with a radius of < 0.1 μm) because the exclusion of decomposer organisms and the associated large water retention capacity facilitate anaerobic conditions (Baldock and Skjemstad, 2000). Upon weathering, the microporosity of Andisols generally increases markedly, but this may be accompanied by less accessible pore sizes after shrinkage and carbon losses caused by irreversible drying due to land-use change (for example, a change from grassland to agriculture) (Poulenard et al., 2002).

In the rainforest of Chile's southern latitudes, amorphous minerals (e.g., Al- and Fe-oxides, allophane and imogolite) or organo-mineral complexes are the key prevailing agents of soil carbon stabilization (Matus et al., 2008). These soils often contain several times the amount of carbon of non-volcanic soils (Matus et al., 2014). They display unique chemical, morphological and physical Andic properties (Soil Survey Staff, 2014) attributed to the compositions of their mineral phases, which consist of short-range ordered (SRO) materials that lack long-range crystal atomic order, such as allophane clay. Because allophane has a large degree of hydration (which is a key factor in the stability of its tridimensional structure), it features a highly reactive surface area of variable charge and high phosphate retention. The rate of allophane and imogolite formation in volcanic-ash soils is largely regulated by macro and microenvironmental factors, including pH, Al, silicic acid in soil solution, rainfall, leaching regime, and reactions with organic matter (Parfitt, 2009). Allophane in Andisol is generally formed in situ (Dahlgren et al., 2004) in tephra at pH values > 4.5 (Neculman et al., 2013). According to Parfitt (2009), a pH of at least 4.8 is required for allophane to precipitate.

Chilean Andisols are derived from coloured basaltic volcanic ash from the Holocene and/or Late Pleistocene. Buried and rejuvenated horizons are frequently found in recent ash deposits. In mature allophanic Andisols under humid climate conditions, such as those prevailing in southern Chile, the composition of the colloidal fraction (< 2 μm) comprises a continuum between Al–humus complexes and allophane, depending on the pH of the soil and the characteristics of its organic matter (Mizota and van Reeuwijk, 1989).

Most studies of anthropogenic disturbances in Chile have been performed on nitrogen in the coastal range at a very southern latitude (e.g., Pérez et al., 2009). However, few studies have examined these effects on soil carbon storage in the lowland of the Andean range (Staelens et al., 2011; Neculman et al., 2013). Staelens et al. (2011) determined that the litterfall, leaf litter losses and nutrient dynamics (e.g., C, N, K, Ca, Mg and P) in evergreen and deciduous managed *Nothofagus* spp. strongly affect nutrient turnover and alter the species composition and forest structure. Neculman et al. (2013) analysed the contributions of several chemical parameters to soil carbon stabilization in an evergreen forest. They determined that allophane content is directly proportional to soil pH and inversely proportional to soil carbon complexes and the age of the soil. However, none of these studies has examined the effect of anthropogenic disturbances on potential carbon losses and pedogenic changes in the topsoil and subsoil associated with the long-lasting effects of 50 years of the selective cutting of temperate rainforests.

This study presents the first in situ experiment performed across temperate rain forests at a southern latitude that explores the underlying processes of carbon stabilization in the surface and deep soils of managed volcanic forest soil ecosystems. We hypothesize that carbon destabilization caused by forest management is counteracted by two carbon stabilization mechanisms mediated by pedogenic processes: the formation of allophane and imogolite-like allophane, which is directly proportional to soil pH, and the formation of Al- and Fe-carbon complexes, which is inversely proportional to pH (Neculman et al., 2013). Therefore, an inverse relationship between these two mechanisms is expected within a humid climate, where the irreversible drying of the surface soil is less likely.

The objective of this investigation is to determine the effect of forest management on soil properties that regulate soil organic carbon storage and pedogenic processes in the top and deep volcanic soils of temperate rainforest ecosystems.