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Changes in soil carbon inputs and outputs along a tropical altitudinal gradient of volcanic soils under intensive agriculture

Jorge Sierra*, François Causeret

ASTRO Agrosystèmes Tropicaux, INRA, 97170 Petit-Bourg, Guadeloupe, France

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ABSTRACT

Volcanic soils contain a large stock of soil organic carbon (SOC) which is highly vulnerable to changes in land use and climate warming. In this study we examine the changes of SOC stocks along a tropical elevation gradient (100 m–700 m; +437 mm yr^{-1} of rainfall and −0.7 °C every 100 m), which is subject to two intensive agricultural systems (banana monoculture and vegetable crops) characterised by the heavy use of fertilisers and pesticides. We hypothesise that in these systems SOC is mainly controlled by soil mineralogy, climatic factors and soil tillage. We used a process-based approach to determine soil C inputs and outputs along the elevation gradient. The banana monoculture systems (198 plots) are characterised by a temporal steady-state of SOC, and the vegetable crop systems (55 plots) present high annual SOC losses. The banana systems were used to determine for the first time the altitudinal change in the in situ rate constant of SOC mineralisation (k_{SOC}). Under banana monoculture, SOC stock increased by 218%, C input from crop residues decreased by 44%, and k_{SOC} decreased by 570% across the altitudinal gradient. These results indicated that the SOC gradient was mainly induced by changes in C outputs. Allophane content increased with altitude (R^2 = 0.61; 8 g kg^{-1} every 100 m) and was positively correlated with SOC content (R^2 = 0.51) and negatively correlated with k_{SOC} (R^2 = 0.53). We hypothesise that the physical protection of SOC within amorphous allophanic minerals was the main factor responsible for the k_{SOC} and SOC stock gradients. Strictly, the effects of allophane content and rainfall cannot be separated because soil mineralogy in the studied area is mainly determined by the level of rainfall. Our process-based analysis indicated that changes in temperature along the elevation gradient could only explain 22% of the observed change in k_{SOC}. SOC stocks under vegetable crops also increased with altitude; they were 57% lower than under banana at low altitude but only 9% lower at high altitude. This reflected simultaneously the higher C outputs under vegetable crops due to more intensive soil tillage, and the greater resilience to soil disturbance of protected SOC in altitude. The results suggested that neither soil nutrient content nor soil biological properties contributed to the SOC and k_{SOC} gradients under the intensive cropping systems analysed during this study. Overall, we conclude that SOC might be more vulnerable to soil tillage and warming in low-altitude soils.

1. Introduction

Although volcanic soils account for < 1% of Earth's land area, they store about 5% of the global stock of soil organic carbon (SOC) (Dahlgren et al., 2004). These soils have peculiar physical (e.g. very high water content at field capacity, high resilience to compaction and erosion), chemical (e.g. high SOC and basic cations contents), and physico-chemical properties (e.g. high P fixation, high anion exchange capacity), which are controlled by soil mineralogy, characterised by the presence of amorphous minerals such as allophane (Clermont-Dauphin et al., 2004). These soils are mostly found on the flanks of volcanic mountains and are occupied by forests and agricultural land, the latter mainly in the inter-tropical zone where altitude moderates climate (Legros, 2012). Volcanic soils have high agricultural productivity and are easy to work, but aluminium toxicity and P deficiency may occur in those that are more acidic (Dahlgren et al., 2004). Because of the high SOC stocks in these soils, conversion of the natural vegetation into farmland frequently induces SOC losses that can reach 2%–3% per year (e.g. Lemenih and Itanna, 2004; Sierra et al., 2015). However, some authors have reported that the proper management of cropping systems, including diversified production and reduced soil tillage, can be useful to preserving SOC stocks in volcanic soils (Segnini et al., 2011; Sierra et al., 2017). This is of crucial concern in tropical mountain systems where warming is likely to be particularly marked during coming decades and could contribute to increasing SOC losses (Nottingham et al., 2016).

* Corresponding author.
E-mail address: jorge.sierra@inra.fr (J. Sierra).

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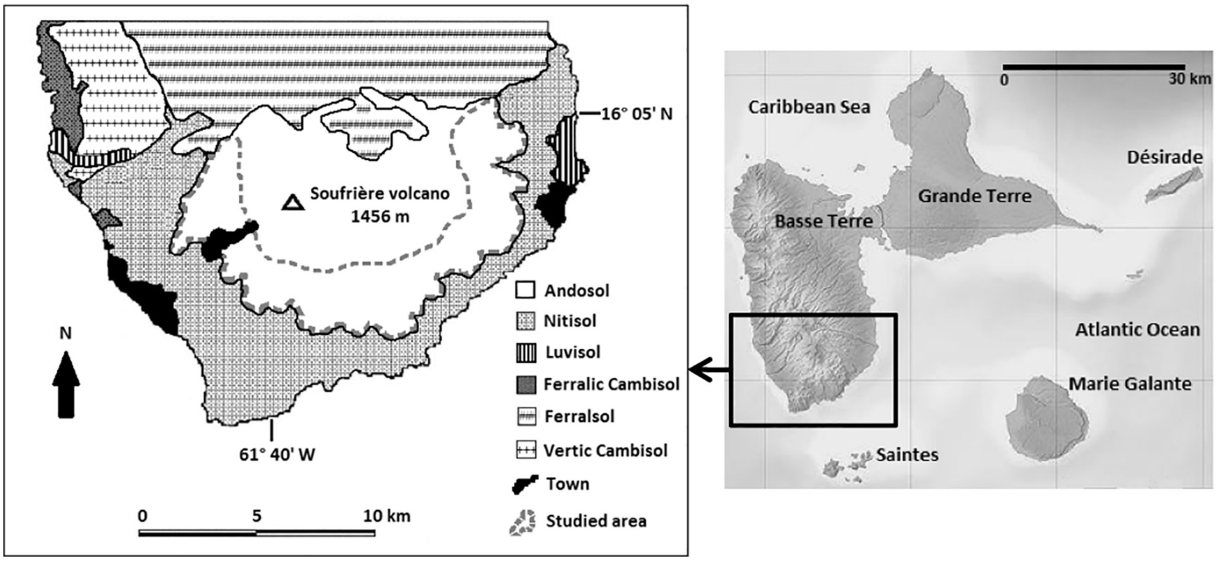

Fig. 1. Location of the studied area in the southern part of Basse-Terre Island in the Guadeloupe archipelago. The land occupied by andosols out of the area included in this study corresponds to the rainforest.

Most worldwide studies dealing with the dynamics of SOC in natural mountain systems have observed positive correlations between SOC stocks and altitude (Tashi et al., 2016, for a meta-analysis on this topic). A few exceptions did not demonstrate any such relationship (e.g. Tan and Wang, 2016) or an increase up to a given altitude and then a decrease (e.g. Djukic et al., 2010). Generally as altitude increases so does annual rainfall, while air temperature decreases, thus causing marked changes in vegetation, soil type and soil microbial activity across the elevation gradient, which in turn may affect the C cycle. Numerous factors and mechanisms have been proposed to explain the increase of SOC in line with elevation in each particular system; e.g. an improved physical protection of SOC because of the increase in the soil aggregate rate (Li et al., 2016), a reduction in SOC decomposition linked to the decline of soil temperature (Dieleman et al., 2013), or the increase of C humification associated with changes in vegetation and litter quality (Wang et al., 2016). This general pattern of increasing SOC with altitude is frequently masked in areas where forests have been replaced by agricultural systems which cause local decline in SOC stocks (Ozalp et al., 2016).

The high SOC stocks in mountain systems dominated by volcanic soils have generally been attributed to the physical protection of organic matter provided by allophanic minerals, together with a reduction in microbial activity breaking down SOC due to soil acidity, poor P availability and low soil temperature (Lemenih and Itanna, 2004; Naafs et al., 2004). As these factors co-vary with altitude, confounding effects may occur when the relationship between them and SOC is evaluated using correlation analysis (Körner, 2007). In this sense, although some authors have proposed that mountain areas – with their elevation gradients of temperature and rainfall – may be useful to assess the impact of climate changes similar to those observed across latitudes (Klimek et al., 2016; Wang et al., 2016), Nottingham et al. (2015) pointed out that careful consideration should be given to the effects of other soil and plant factors varying concomitantly with elevation. Undoubtedly, knowledge of the interactions between the factors that induce changes in SOC is necessary to assess the impact of projected warming in mountain areas. For example, if falling temperatures at higher altitudes is the main factor that controls rises in SOC, then studies addressing the temperature sensitivity of SOC decomposition (e.g. evaluation of the Q_{10} coefficient) are essential to predict the impact of warming. Indeed, several studies have focused on this topic (e.g. Zimmermann et al., 2009; Zimmermann and Bird, 2012). By contrast, more complex studies will be necessary if warming simultaneously affects C outputs (e.g. SOC decomposition) and C inputs (i.e. changes in vegetation and litter quality) (Nottingham et al., 2016), or if SOC changes are primarily controlled by the physical protection provided by soil structure, whose characteristics vary with altitude (Kramer and Chadwick, 2016).

The flanks of volcanic islands in tropical regions where the elevation gradient of climate is one of the strongest in the world present a wide range of soil types, with andosols on the summit and ferralsols, luvisols and nitisols on the footslopes (Legros, 2012). These regions therefore represent an interesting edaphic and climatic setting to determine the effects of the factors impacting SOC stocks. In this study we examine the changes of SOC stocks in an altitudinal gradient of a tropical volcanic island where the land is subject to two intensive agricultural systems (banana monoculture and vegetable crops), which are characterised by the heavy use of fertilisers and pesticides. We hypothesise that in these systems SOC is mainly controlled by soil mineralogy, climatic factors and soil tillage. We consider that the effects of other factors such as soil nutrient content and soil biological properties are of minor importance in our intensive agricultural systems. The aim of this study was therefore to assess the underlying mechanisms controlling SOC by focusing on the effect of the gradients of soil mineralogy (e.g. allophanic mineral content), climate (e.g. temperature and rainfall), and the intensity of soil tillage (low under banana, high under vegetable crops). The banana cropping systems are characterised by a temporal steady-state of SOC stocks and the vegetable crop systems present high annual SOC losses (Sierra et al., 2015). To reduce the impact of confounding effects caused by factors that co-vary with altitude, we used a process-based approach to estimate C outputs and C inputs and to assess their effects on the SOC balance along the elevation gradient. The study was carried out in Guadeloupe (French West Indies), which exhibits within a small area nearly every physical landscape and cropping system found in the Caribbean region. This study formed part of a larger project devoted to quantifying the impact of cropping systems, the pedoclimate and warming on SOC stocks, using Guadeloupe as a case study of the Caribbean (Sierra et al., 2017).

2. Materials and methods

2.1. Study location, soils and climate

The study was carried out in the uplands of south Basse-Terre, the main island of the Guadeloupe archipelago located in the eastern