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A framework coupling farm typology and biophysical modelling to assess the impact of vegetable crop-based systems on soil carbon stocks. Application in the Caribbean

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ABSTRACT

Agricultural land devoted to vegetable crops in the Caribbean has strongly increased during the past twenty years, which raises major concerns regarding a reduction in soil organic carbon (SOC) stocks because of low C inputs and high SOC outputs from these cropping systems. The aim of this study was to assess the impact of farming practices on SOC stocks at the farm type level. We designed a framework which encompasses a farm typology describing the diversity of farm practices applied to vegetable crops and a model of SOC dynamics to estimate the impact of these practices on SOC stocks. The study was carried out in the Guadeloupe archipelago, which offers a good representation of the variability of Caribbean agriculture, in a context of transition from traditional sugarcane and banana monocultures for export to a more diversified agriculture including vegetable crops. A farm typology was developed from a survey of 71 farmers concerning their socio-economic characteristics and farming practices. The MorGwanik model of SOC dynamics was then used to assess the impact of farming practices on SOC at the farm type level, and to interpret the observed SOC changes. Five farm types were identified varying from traditional export agriculture with low diversification to monoculture of vegetable crops based on compost application and reduced soil tillage. The observed and simulated results indicated that systems with a fallow/vegetables cycle ratio > 2 and the monoculture of vegetables including compost applications at ≥10 Mg ha^{-1} yr^{-1} presented C sequestration corresponding to SOC increases of 10% and 3% of the initial stock, respectively. The monoculture of vegetables with a compost rate < 10 Mg ha^{-1} yr^{-1} and systems including vegetables in rotation with export crops and a short fallow cycle presented a reduction in SOC that ranged from 10% to 18%. Pedoclimatic conditions had a lower impact on SOC changes. Similar socio-economic profiles of farmers were observed for farm types including very different cropping systems. The model well described SOC changes for each farm type and offered valuable insights about the factors affecting SOC losses and C sequestration. The framework proposed in this study was helpful to identify improved managements that can maintain or increase SOC stocks under tropical conditions.

1. Introduction

Farmers in the small island states of the Caribbean must respond to crucial food security challenges because of the reduction in traditional export agriculture due to market liberalisation (e.g. sugarcane and banana) (United Nations, 2013). Moreover, because of the overuse of chemical fertilizers and pesticides (Kendall and Petracco, 2009), export agriculture in the Caribbean is often blamed for the pollution of soils and water resources (Castillo et al., 2006), so that a transition towards diversified agriculture should promote more environmentally-friendly production. Some local governments have prioritized the development of horticulture (e.g. tropical fruits and vegetables) to diversify export agriculture and to reduce poverty (Van den Broeck and Maertens, 2016), and the FAO (2013) recommended that a large fraction of Caribbean agriculture should be diversified and committed to the local market in order to ensure food security. Indeed, the questions about the transition from the current export agriculture to a more diversified agriculture devoted to the local markets also arises in other tropical regions of Africa (e.g. Sotamenou and Parrot, 2013) and Asia (e.g. Ullah et al., 2015). In the Caribbean, agricultural land devoted to vegetables has increased markedly during the past twenty years, raising major agro-environmental concerns about the impact of these systems on soil organic carbon (SOC) stocks (IFAD, 2014). A recent study performed in the Caribbean indicated that most soils cultivated with vegetables present SOC losses that range from 0.5 to 2 Mg C ha^{-1} yr^{-1}, depending on the cropping system (Sierra et al., 2015). These SOC losses were associated

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with the small quantities of residues from these crops (low C input; Lal, 2008), and with the intensive soil tillage required to obtain uniform soil conditions at planting, which favours SOC mineralization (high C output; Bajgai et al., 2015). The same was reported by Bhattacharyya et al. (2007) with respect to vegetable crop systems in the Indo-Gangetic Plains. On the other hand, when studying vegetable farms in Uruguay, Dogliotti et al. (2005) reported that reducing the area used for vegetable crops by introducing long crop rotations with pastures and green manure during the inter-crop periods could decrease or stop SOC losses over the entire rotation cycle.

Caribbean agriculture is characterized by a mosaic of soils, climates and cropping systems, which vary considerably at a small scale. This variability, together with that concerning the socio-economic traits of farmers, is responsible for the marked heterogeneity of cropping systems. This heterogeneity has generally been assessed by means of typological analysis, such as that performed by Blazy et al. (2009) for banana systems in Martinique, Meylan et al. (2013) for coffee-based agroforestry systems in Costa Rica, and Chopin et al. (2015) for farming systems in Guadeloupe. From these studies, it can be concluded that the biophysical and socio-economic contexts strongly affect the performance of cropping systems. We hypothesize that the same occurs regarding the impact of vegetable crop-based systems on SOC stocks. To test this kind of proposal, the first step is typically to construct a farm typology so as to identify groups of farmers with common practices and/or similar socio-economic characteristics which might correspond to the different performances of the cropping systems (Blazy et al., 2009). Differences between these groups can then be assessed in order to identify those factors which affect the performance of the system for each farm group. This has frequently been carried out using conceptual models that include a functional representation of the interactions between biophysical and socio-economic factors (e.g. Le Gal et al., 2010). These models were useful to analyse the trade-offs involved in the management of the system and in farmer decisions, and to assess their impacts on the system's performance (Meylan et al., 2013). Concerning SOC dynamics, numerical models are needed to obtain quantitative indicators for the impact of farming practices on SOC stocks (Saffih-Hdadi and Mary, 2008). Combining such models in a framework with a farm typology could facilitate communication with extentionists and policy makers, which should assist with the design of more sustainable cropping systems at the farm type scale (Blazy et al., 2015). If adequately parameterized and validated for the local biophysical context, models of SOC dynamics could constitute a powerful tool to interpret differences between farm types in terms of SOC changes.

Sierra et al. (2015) designed the MorGwanik model of SOC dynamics adapted to the pedoclimatic conditions of the Caribbean, which was successfully applied to assessing the impact of export and diversified agriculture on SOC stocks at the level of the agro-ecological region (AER). During the present study, this model was combined with a farm typology in order to identify the factors affecting SOC stocks in vegetable cropping systems at the level of the farm type. The aim of this study was therefore to determine the impact of farming practices on SOC dynamics at the farm type scale, in a context of transition from traditional sugarcane and banana monocultures to a more diversified agriculture including vegetable crops. We first developed a farm typology using the information obtained from a survey of farmers performed for this study. The model of SOC dynamics was then applied in order to assess the changes in SOC stocks for each farm type using the information on farming practices obtained during the first step. The novelty of this study relies in the combination of these two approaches to identify relevant farming practices responsible for the maintaining and the increase of SOC stocks. To our knowledge this is the first study that couples a farm type approach with a model of SOC dynamics to propose improved management that could maintain SOC stocks at the farm type scale in tropics. The study was carried out in Guadeloupe, which offers a good representation of the spatial variability of Caribbean agriculture, in terms of their pedoclimatic conditions and of cropping systems.

2. Materials and methods

2.1. Study location, soils and climate

The study was carried out in Guadeloupe in the eastern Caribbean (Fig. 1). Guadeloupe is an archipelago consisting of two main islands (Basse-Terre: 848 km^2; Grande-Terre: 586 km^2) and several smaller islands. Vegetables are mainly cultivated on the two main islands, so the smaller islands were not included in this study. Although Grande-Terre is characterized by a gently undulating surface, northern, eastern and southern Basse-Terre presents elongated hills with convex slopes. There are two protected areas where agriculture has been excluded: the tropical rainforest and the coastal wetland forest (Fig. 1).

During this study we considered the AERs defined by Sierra et al. (2015). Only four of these AERs are concerned by the cultivation of vegetables (Fig. 1):

- AER 1: the soils are calcic vertisols (FAO classification) characterized by high clay content (80%) dominated by smectite. SOC stocks in the 0–0.25 m layer range from 60 to 75 Mg ha^{-1}. The mean air temperature is 26.5 °C and the mean annual rainfall is 1100 mm.
- AER 2: the soils are acid ferralsols with a clay content of 70% dominated by kaolinite. SOC stocks range from 50 to 65 Mg ha^{-1}. The mean air temperature is 25.4 °C and the mean annual rainfall is 2300 mm.
- AER 3: the soils are acid andosols characterized by high allophanic clay content (75%). SOC stocks range from 90 to 110 Mg ha^{-1}. The mean air temperature is 23.9 °C and the mean annual rainfall is 3800 mm.
- AER 4: the soils are acid nitisols with a clay content of 70% dominated by halloysite. SOC stocks range from 40 to 55 Mg ha^{-1}. The mean air temperature is 25.0 °C and the mean annual rainfall is 2200 mm.

In all of the AERs there is a dry season from December to May, but it is very slight in AERs 2, 3 and 4 (i.e. about 45% of the annual rainfall). The dry season is more important in AER 1, with only 30% of the annual rainfall.

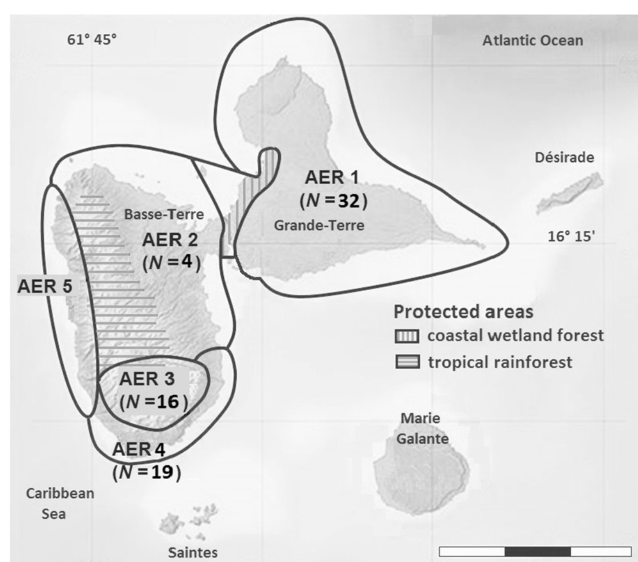

Fig. 1. The archipelago of Guadeloupe and the four agro-ecological regions (AER) studied during this work. AER 5 was not studied because the area occupied by vegetable crops is negligible. Values in brackets indicate the number of farms surveyed in each AER. The soils are vertisols in AER 1, ferralsols in AER 2, andosols in AER 3 and nitisols in AER 4. The annual mean rainfall is 1100 mm in AER 1, 2300 mm in AER 2, 3800 mm in AER 3, and 2200 mm in AER 4.