Reduced tillage and organic amendments can offset the negative impact of climate change on soil carbon: A regional modelling study in the Caribbean

Pierre Chopin, Jorge Sierra

Reduced tillage and organic amendments can offset the negative impact of climate change on soil carbon: A regional modelling study in the Caribbean

Pierre Chopin[a,b,*], Jorge Sierra[b]
[a] Swedish University of Agricultural Sciences, Department of Crop Production Ecology, Uppsala, Sweden
[b] ASTRO Agrosystèmes Tropicaux, INRA, 97170, Petit-Bourg, Guadeloupe, France
* Corresponding author. E-mail address: pierre.chopin@inra.fr (P. Chopin)

ABSTRACT

Climate change and the ongoing development towards agriculture for the local market in the Caribbean could contribute to soil degradation in coming decades. This study assessed the potential impacts of climate change (A1B IPCC scenario), land use (local market crops vs. export crop production based on pluriannual sugarcane and banana), alternative cropping practices (reduced tillage and organic amendments) and pedoclimatic conditions on soil organic carbon (SOC) changes in the period 2015–2045. The study was carried out in the Guadeloupe archipelago, which offers a good representation of the diversity of Caribbean agriculture. Our modelling approach coupled a biophysical model of SOC dynamics with three databases accounting for land use, cropping practices and soil properties at the territory scale. The results indicated that cropping practices and land use were more important than climate change and pedoclimatic conditions in affecting SOC stocks. Despite this, in absolute terms climate change increased SOC losses at the territory scale by 29-fold, and up to 30% of these losses were linked to pluriannual sugarcane monoculture, due to the negative impact of climate change on plant growth. Most scenarios tested gave a variable degree of SOC losses (0.01−0.32% yr−1 of the initial territory SOC stock). However, some cropping systems for the local market exhibited small SOC losses or slight C sequestration, mainly when reduced tillage was applied in regions characterised by high use of organic amendments. These results suggest that soil resilience to climate change under crop production for local market could be reinforced by adopting reduced soil tillage and improved organic amendment management.

Keywords: Carbon sequestration Compost Crop diversification Reduced soil tillage Sugarcane Tropical soils

1. Introduction

Small changes in the SOC pool can significantly affect atmospheric carbon dioxide concentrations, and therefore climate change (Chen et al., 2019). Changes in SOC stocks are strongly affected by farming practices and, in particular, SOC in the tropics is more sensitive to changes in land use and tillage practices than SOC in temperate regions (Ogle et al., 2005). Indeed, these authors observed that SOC losses 20 years after conversion of native ecosystems (forests and grassland) into cropland were about 15% higher in tropical than in temperate systems. On the other hand, most previous studies dealing with the impact of climate change on SOC at the regional scale (e.g. Sierra et al., 2010) and global scale (e.g. Peng et al., 2014) agree on the negative impact of warming on SOC stocks in the tropics, as an effect of greatly accelerated microbial decomposition induced by rising temperature.

There is now increasing evidence to suggest that the small island states of the Caribbean region are experiencing diminished food security because of agricultural losses and ecosystem degradation induced by climate change (IPCC, 2014; Shah and Dulal, 2015). Moreover, Caribbean agriculture is undergoing a shift in production towards domestic markets, which includes a transition towards cropping systems based on annual crops (e.g. annual vegetables, tuber and root crops), because of declining demand on global markets for the major agricultural exports from the region (e.g. sugar, bananas, cocoa) (Saint Ville et al., 2015). Sierra et al. (2015) have shown that development of agriculture for the local market can seriously reduce SOC stocks because the mass of crop residues recycled back to soil is smaller and soil tillage is more intensive for annual crops than for pluriannual export crops (i.e. sugarcane, banana). However, some recent studies have reported that adoption of improved management practices (e.g. reduced tillage, organic amendments) are still relevant in meeting the challenges of food security and adaptation to climate change in the tropics (Fujisaki et al., 2018; Gonzalez-Sanchez et al., 2019). To our knowledge, there is no available information concerning the impact of climate change on stocks of SOC in the Caribbean at the regional scale.

Several approaches have been proposed for assessing the effect of climate change on SOC. Modelling SOC dynamics is one of the most effective tools to evaluate trends in SOC over time and the impact of changes in cropping practices under a climate change scenario (Muñoz- Rojas et al., 2017). However, it should be borne in mind that the effect of climate change on SOC remains uncertain to some extent, because of uncertainties in climate projections and in the underlying mechanisms included in SOC models. Model uncertainties can be reduced by using simple models of SOC balance calibrated and tested locally, which require minimal data inputs and few parameters and are therefore better suited than more complex models of SOC dynamics to situations with scarce agricultural data, such as the Caribbean (Sierra et al., 2015; Muñoz-Rojas et al., 2017). In this study, we hypothesize that the current trend of Caribbean agriculture towards the replacement of export crops by local market crops will be detrimental to SOC stocks particularly under a climate change scenario, but that adaptation strategies, including implementation of reduced tillage and the use of organic amendments, can reduce SOC decrease.

The present study was carried out in the Guadeloupe archipelago, which contains within a small area nearly every physical landscape and cropping system found in the Caribbean. This archipelago covers a large range of land uses from monoculture for export to local market crops including vegetable, roots and tuber crops, orchards, and livestock (Chopin et al., 2015). The objectives of this study were therefore: i) to assess the impact of climate change and agriculture change towards local market on SOC stocks and ii) to test scenarios concerning changes in land use and in cropping practices in order to identify climate change-resilient cropping systems.

2. Materials and methods

We here detail each step of the modelling approach (Fig. 1).

2.1. Study site

The study was carried out in Guadeloupe in the eastern Caribbean Sea (Fig. 2). Guadeloupe is an archipelago consisting of three main islands (Basse-Terre: 850 km^2; Grande-Terre: 590 km^2 and Marie- Galante: 160 km^2). (Fig. 2). Guadeloupe includes five agro-ecological regions (AERs) (Fig. 2), characterised by very different pedoclimatic conditions. Some characteristics of these AERs are presented in Table 1. All the AERs have very clayey soils (i.e. > 70% clay content).

2.2. Land use and cropping systems

Data on land use were obtained from farm surveys performed by the Board of Food, Agriculture and Forestry of Guadeloupe (Table A.1 in Appendix A). Sugarcane and banana, which are the two main export crops, occupy 70% and 12%, respectively, of agricultural land on Guadeloupe. Sugarcane is mainly cultivated in the two largest areas, AERs 1 and 2. Banana is the dominant crop in the more humid AERs 3 and 4. Local market crops include vegetable crops, water yam, melon, pineapple and orchards (mainly citrus). The proportion of the land area occupied by these crops varies from 12% in AER 2–80% in AER 5. In this study, we excluded areas occupied by natural grasslands devoted to livestock production, because few data on SOC stocks and dynamics are currently available for these systems and the rate of conversion from grassland to cropland is negligible.

Information on the rotations and cropping practices in each AER was taken from a survey carried out by Sierra et al. (2015) (Table A.2). The main difference between crop production systems of export crops and local market crops is soil tillage. Sugarcane and banana are pluriannual crops where tillage is applied every 5–6 years, just before planting. In contrast, soil tillage for annual local market crops is rather intensive, with at least four passes of tillage implements per year. After harvest, crop residues in all systems are left on the soil surface or buried to 0.1−0.2 m depth. Several organic amendments are applied by farmers (e.g. manure, sugar scum, sewage sludge, vinasse and compost), with the application rate varying widely between cropping systems and AERs (Table A.2). To simplify the calculations and presentation of the results, in this study all organic amendments used by farmers were assessed as compost, using the application rate of each amendment and the amount of humified soil C derived from the amendments compared with that from compost.

2.3. Soil data

Soils in this study are described in terms of their initial SOC content in each AER (determined with a C analyser), their bulk density (core method) and their rate constant (k) of SOC mineralisation. The values of these parameters were obtained from the soil-crop database developed for the TropEmis Project performed in Guadeloupe (Sierra et al., 2015), which contains information on the 0-0.25 m soil layer in all AERs. For modelling purposes, we classified the values of SOC content observed in each AER into 3–4 classes to be used separately during model simulations (see section 2.7). Table A.3 summarises the classes of SOC content observed in each AER, while Table A.4 shows the mean bulk density of soil in each AER. SOC stocks were calculated using Eq. (B.1) in Appendix B.

2.4. Model of SOC dynamics

We used the MorGwanik model, which has been calibrated, tested and validated for the soils, climates and cropping systems present in the Caribbean and successfully applied to assess SOC dynamics at cropping system scale in many AER×cropping systems including tillage type in Guadeloupe (Sierra et al., 2015, 2017). The MorGwanik model simulates SOC balance at plot scale as a function of annual C inputs and outputs. Carbon inputs comprise crop residues (aboveground and roots) and organic amendments. Carbon outputs are calculated using two coefficients: the mineralisation rate constant kAER (yr^{-1}), which is specific to each AER and reflects the impact of soil type and climate on SOC dynamics, and kcrop (unitless), which affects kAER and is specific to each crop. Coefficient kcrop reflects mainly the frequency and intensity of soil tillage (i.e. lower for pluriannual crops such as sugarcane and banana than for annual crops). The values of model parameters are presented in Tables A.4 (kAER), A.5 (kcrop), A.6 (yield of sugarcane and banana), A.7 (characteristics of crop residues), A.8 (amount of crop residues for sugarcane) and A.9 (characteristics of the compost). The yields of export crops were used in the model to estimate the amount of crop residues. Data on the yield of local market crops were unavailable, so for these crops we assumed that the amount of residues varies only as a function of climate change (see section 2.5). Further details on the model can be found in Appendix B.

2.5. Climate change scenario

The temporal change in SOC stocks in the period 2015–2045 was analysed using the climate change scenario elaborated by Météo France for the Guadeloupe archipelago, which is based on the A1B IPCC-SRES climate emissions scenario in the 21st century (Brisson and Levrault, 2011). The scenario predicts an increase in mean air temperature of 0.7 °C during the study period and no change in mean annual rainfall. Therefore, in this study we assumed that only the temperature increase affected SOC dynamics within the study period.

We accounted for two impacts linked to the increase in temperature: 1) an increase in kAER due to accelerated mineralisation of SOC and 2) a change in the amount of crop residues associated with the impact of warming on plant growth. The increase in kAER was assessed using a Q10 approach (rate of change in the system on increasing the temperature by 10 °C) and assuming a linear increase in temperature rate of 0.023 °C yr^{-1} (i.e. 0.7°C/30 yr) within the study period. Calculation of kAER is described in Appendix B (Eq. (B7)) and the kAER values obtained for the period 2015–2045 are presented in Table A.10. The impact of the increase in temperature on the amount of crop residues was estimated from results reported by Sierra et al. (2010) for Guadeloupe. Those authors found that, under the A1B scenario, crop residues would increase by 3.7% for C3 crops and decrease by 7.5% for C4 crops within the period 2015–2045, in accordance with values found in the tropics (e.g. Galindo et al., 2015; Korres et al., 2016). As done for the increase in temperature, the change of the amount of crop residues was assumed linear over time. Table A.11 shows the relative impact of climate change on the amount of crop residues for the C3 and C4 crops studied. The calculations are described in Appendix B (Eq. (B8)).

2.6. Design of the scenarios of changes in land use and cropping practices

The scenarios were built by changing three of the input parameters detailed in Fig. 1:

1) The land area occupied by local market crops in each AER was increased by 50%, which corresponds to the present trend in Caribbean agriculture and the area occupied by monocultures of sugarcane and banana in each AER was reduced by 50%(Table A.2).
2) The land area fertilised with organic amendments was increased by 50%. This increase included all cropping systems with the same initial rate of application. When the initial area receiving organic amendments was zero (e.g. sugarcane in AER 4), the value was set to 20% of the area (Table A.2).
3) The conventional deep tillage applied for local market crops was changed to reduced tillage, which implied a reduction of 21% in kcrop for these crops (Table A.5). For this, we assumed that the mouldboard ploughing used for land preparation was replaced by disc harrowing. The reduction in kcrop was assumed to be linked to fuel consumption of each tillage implement and estimated from data reported by Vigier et al. (2012) for clayey soils. This assumption is supported by the results reported by Pratibha et al. (2019) concerning the relationship between fuel consumption of several

tillage implements and CO_2 emissions following soil tillage in a tropical soil of India. Details on calculation of fuel consumption are presented in Table A.12. A change in soil tillage method was not considered for export crops, because conventional tillage in these systems, which is applied only once every five years, is necessary to restore soil macroporosity in the clayey soils of the Caribbean (Cruz and Guillaume, 1999).

Based on the above, we tested eight scenarios of land use change, comprising two levels (current vs. modified situations) for each of three parameters analysed. The reference scenario (business-as-usual) was the current situation without any change in the parameters analysed. The scenarios are summarised in Table A.13.

2.7. Model simulations and calculations

Simulations for a given cropping system × AER × scenario situation were performed for each SOC class and each level of organic amendment use (i.e. with/without). The rate of SOC change for each situation was then calculated as the pooled mean over the 30-year simulation period by taking into account the frequency of each SOC class and area with and without organic amendments. This value was used to calculate total SOC changes at system and AER scale, based on their land area. In a first set of simulations, we assessed the impact of climate change on SOC changes by using the business-as-usual scenario with and without the impact of climate change on model parameters. A second set of simulations was performed to test the scenarios of land use change under the impact of climate change. Differences in the effects of climate change, cropping systems, AERs and the scenarios of land use on SOC changes were assessed by ANOVA under a factorial design using the XLSTAT™ 2018.5 program.

2.8. Sensitivity analysis

We performed a sensitivity analysis to determine the effect of uncertainties in the assessment of model parameters on SOC changes and to assess the relative impact of biophysical parameters compared with the information obtained from farmer surveys. For this, we analysed four biophysical parameters (yield of sugarcane, effect of climate change on sugarcane residues, kcrop of sugarcane and Q10 value) and two parameters obtained from farm surveys (area occupied by sugarcane monoculture and amended area of each cropping system). Four parameters were linked to sugarcane, which is the most frequent crop, so it might control SOC changes at the AER scale (Table A.1). For the same reason, the analysis focused on AER 1, which is the largest AER on Guadeloupe (Table A.2). In assessing the effect of climate change on sugarcane residues, the negative impact considered in the initial simulations (see Section 2.5) was compared with no impact and with a positive impact. For the other parameters analysed, the sensitivity analysis consisted of decreasing and increasing by 10% the value used in the initial simulations.

3. Results and discussion

3.1. Effects of climate change, crop production system and agro-ecological region on SOC changes

Crop production system (i.e. export vs. local market) contributed to more than two-thirds of the total variance in the ANOVA, followed by AER and climate change. As described above, export systems include banana and sugarcane crops, and systems for the local market involve annual crops such as vegetables and tubers. The impact of the individual factors represented 97% of the total variance, and thus the effect of interactions between factors was rather negligible (Table 2). Most export crop systems showed positive changes, indicating C sequestration over the study period, while most crop systems for the local market production showed negative values, indicating C losses (Fig. 3). The exceptions to this general trend were export crop systems in AERs 1 and 2 under climate change (slight negative values) and crop systems for local market production in AER 5 (slight positive values). The effect of AER was reflected by an increase in C sequestration under export crop systems and a decrease in SOC losses under local market crops from AER 1 to AER 5. Finally, climate change induced a decrease in C sequestration under export crop production and an increase in SOC losses in crop systems for the local market (Fig. 3). More interesting, climate change caused a shift in SOC in export crop systems in AERs 1 and 2, from a net increase in SOC stocks without climate change to a net decrease.

The rates of SOC change under climate change observed in the present study were similar to those reported for the Mediterranean region (e.g. Muñoz-Rojas et al., 2015, 2017) and for the tropical regions (Cerri et al., 2007; Minasny et al., 2017). In the present study, the rate of SOC change under climate change was equivalent to -0.15% yr^{-1} in relation to the initial stock at the territory scale, and varied from -0.20% yr^{-1} in AER 1 to +0.28% yr^{-1} in AER 5. While the effect of climate change was smaller than that of crop production system or AER (Table 2), in absolute terms climate change increased SOC changes at the territory scale 29-fold (Table 3). Only AER 4, due to amended banana and orchard systems, and AER 5, due to amended orchard systems, showed net C sequestration at the regional scale (Table 3). This agrees with results reported by Castellano et al. (2015) concerning the importance of C inputs in soils with relatively small SOC stocks, as in AERs 4 and 5. Despite the slight negative rate observed for monoculture of sugarcane under climate change, 30% of SOC losses at the territory scale derived from this cropping system in AERs 1 and 2 (Table 3), which was principally due to its relatively large cultivated area in these AERs. These results suggest that even small uncertainties in model parameters concerning sugarcane (e.g. impact of climate change, cultivated area) could affect strongly the estimated SOC changes at the cropping system, AER and territory scale. This is discussed in Section 3.3.

The results of this study are in line with Luo et al. (2010) that also observed that SOC changes were mainly driven by crop management, rather than by climate or soil type in the tropics. In our study, the crop production system affected SOC stocks in two ways: 1) local market production based on vegetable and tuber crops is characterised by a smaller mass of crop residue recycling in soil compared with export crop production (i.e. smaller C input; Luo et al., 2010), and 2) the intensity of soil tillage is higher in local market production, which enhances C outputs (Bhattacharyya et al., 2007; Sierra et al., 2017). While the use of organic amendments is more frequent for local market crops and the impact of climate change on their amount of residues is positive, these effects were not large enough to offset C losses from these systems. This indicates that C outputs induced by intensive tillage were the major factor affecting SOC stocks in these systems. This confirms results reported by Mangalassery et al. (2015) on the strong impact of soil perturbation associated with conventional tillage on the rate of SOC decomposition in the tropics. In our approach, this effect is indicated by kcrop, which was much higher for most local market crops than for export crops (Table A.5).

In a detailed review dealing with SOC changes, Ogle et al. (2005) observed that SOC losses were higher in moist than in dry tropics, but concluded that it was not possible to determine the reason for this pattern because of the many interactions between C inputs and outputs under each climate. In the present study, the highest SOC losses were found for the sub-humid AER 1 (Table 3, Fig. 3). Analysis of model outputs (data not shown) indicated that the lower sugarcane yield in AER 1 (Table A.6), which affected the amount of crop residues, was the main factor responsible for the higher SOC losses under export crop production in this AER. For local market production, however, the highest SOC losses observed in AER 1 were mainly driven by conventional tillage acting on soils with high initial SOC stock (Table 1) and kAER value (Table A.4). Minasny et al. (2017) also found that high SOC stocks frequently favour SOC losses under conventional tillage. As pointed out by Ogle et al. (2005) and others (e.g. Wan et al., 2011), precise assessment of the impact of AER on SOC changes is extremely difficult, since a number of model parameters (kAER, initial SOC stocks, crop yield, proportions of export and local market crops, area receiving organic amendments and application rate of organic amendments) differ simultaneously between AERs as a function of their pedoclimatic conditions and cropping practices.

3.2. Impact of changes in land use and cropping practices on SOC stocks under climate change

At the territory scale, SOC changes were negative for all combinations of cropping practices, but some of them limited SOC losses (Fig. 4). Reduced tillage was the major factor affecting SOC changes, followed by land use and area receiving organic amendments (Table 4). On average, SOC losses were 4.3-fold lower for reduced than for conventional tillage. SOC losses decreased 1.5-fold when the area receiving organic amendments was increased by 50% and increased 2.2-fold when the area occupied by local market production was increased by 50%. The impact of reduced tillage was higher under the scenario with an increase in local market production (4.8-fold reduction in SOC losses compared with conventional tillage) than for the current land use scenario (3.5-fold reduction). This result reflects the significant land use × tillage interaction shown in Table 4, which contributed about 12% to total variance.

Expressed in terms of the initial SOC stocks at the territory scale, SOC losses represented 0.05% yr^{-1} for reduced tillage (-1.5% over the 30-year study period) and 0.21% yr^{-1} for conventional tillage (-6.3% over 30 years). More interestingly, a change in soil tillage practices from conventional to reduced tillage induced a shift in AERs 3 and 4 from a decrease in SOC stocks to slight C sequestration (Fig. 5). Model outputs indicated that this effect was linked to the shift caused by reduced tillage in vegetable crop systems, in monoculture or in rotation with long-term fallow, which resulted in C sequestration in these AERs. This agrees with field data reported by Sierra et al. (2017) for farms in the Caribbean using reduced tillage to produce vegetable crops. In the present study, vegetable crop systems, in monoculture or in rotation with sugarcane, also showed C sequestration in AER 1, but the relatively small area occupied by these systems was not enough to compensate for SOC losses from sugarcane monoculture in this AER. Similarly, the small amount of C sequestration under reduced tillage in AERs 3, 4 and 5 did not compensate overall for the SOC losses from the largest AERs (1 and 2) at the territory scale (Figs. 4 and 5). Despite this, in absolute terms the main effect of reduced tillage at AER scale was observed in AER 1 (3.0-fold reduction in SOC losses compared with conventional tillage), followed by AER 2 (2.1-fold reduction) (Fig. 5). These results suggest that reduced tillage may partly counteract SOC losses caused by the conventional tillage routinely used in cropping systems for local market production, even under a scenario of increasing area occupied by these systems. In this context, the small C sequestration observed in AERs 3, 4 and 5 should be regarded as an improvement in soil resilience, rather than as a significant contribution to climate change mitigation as suggested by Powlson et al. (2016) for tropical conditions.

In our results, scenarios involving changes in C outputs showed a higher effect on SOC changes than scenarios involving changes in C inputs (i.e. increased area receiving organic amendments) (Table 4). This confirms the importance of C outputs for driving SOC changes under a tropical climate (Peng et al., 2014; Mangalassery et al., 2015). Ogle et al. (2005) also concluded that reduced tillage was more relevant than increasing C inputs via the use of organic amendments in preserving SOC stocks in the tropics, but the opposite was found by Minasny et al. (2017). However, the relative effect of organic amendments depends on the application rates, which were relatively low in our study. For example, in a modelling study, Oliveira et al. (2017) reported that application of organic amendments at a rate equivalent to 6 Mg C ha^{-1} yr^{-1} induced C sequestration in tropical soils cropped with sugarcane in Brazil. Such a rate would be equivalent to about 35 Mg of compost ha^{-1} yr^{-1}, which is 4- to 5-fold higher than our observed annual rates of application (Table A.2). A recent study carried out in Guadeloupe indicated that the current availability of organic amendments is about 24 000 Mg yr^{-1}, which could increase to 40 000 Mg yr^{-1} with better management of organic wastes derived from agro-industrial factories and water treatment plants (Paul, 2017). However, an application rate of 35 Mg of compost ha^{-1} yr^{-1} would need a compost production of 55 000 Mg yr^{-1}, which is currently unrealistic to attain.

The importance of reduced soil tillage or no-till in preserving SOC stocks in the tropics has already been pointed out by several authors (e.g. Mangalassery et al., 2015; Powlson et al., 2016). In our study, we simulated reduced tillage by replacing mouldboard ploughing, a very intensive practice that inverts and thoroughly mixes the soil, leading to high SOC decomposition (Miller et al., 2019), with a less intensive practice based on disc harrowing. Our results suggest that fostering the adoption of reduced tillage and, secondarily, the use of organic amendments can significantly decrease the negative impact of climate change on SOC stocks in the study area under the scenario of increase of the local market production. Reduced tillage should primarily be promoted in AER 1, which was found to have the highest SOC losses and the greatest impact of this practice, which could help to reduce significantly overall C emissions at the territory scale. From a modelling point of view, Kollas et al. (2015) point out that most current crop models do not simulate the effect of ploughing on SOC turnover, which makes it difficult to use them to assess the impact of changes in soil tillage practices. In the Century model, which is adapted to the conditions of Southern Brazil, soil tillage is represented by an empirical coefficient operating as a multiplier to increase the mineralisation rate constant of SOC during the two months following tillage operations (Bortolon et al., 2011). However, it may be difficult to extrapolate this empirical approach based on local information to other tropical regions such as the Caribbean, where tillage practices vary considerably as a function of the orientation of crop production; e.g. export crop vs. local market crops. In the present study, we opted to apply a more mechanistic approach based on the fuel consumption of tillage implements. The advantage of our approach is that it permits assessment of the impact of tillage practices under different pedoclimatic conditions.

3.3. Sensitivity analysis

Among the parameters analysed, the greatest impacts were observed for kcrop of sugarcane, the effect of climate change on sugarcane growth and sugarcane yield (Table 5). Changes in the other three parameters (i.e. area occupied by sugarcane in monoculture, amended area and Q10) had a smaller effect on the variation in SOC losses. These results imply that model outputs are very sensitive to the biophysical parameters associated with sugarcane.

The highest impact of kcrop was associated with the fact that the initial rate of SOC change under monoculture of sugarcane was very low (-0.07 Mg C ha^{-1} yr^{-1}), so even a small change in C outputs, represented by kcrop, strongly affected SOC changes in relative terms. Despite the great reduction in SOC losses observed by decreasing kcrop (i.e. decreasing tillage intensity), implementation of reduced tillage is problematic for sugarcane, because conventional tillage applied every five years just before planting is necessary to restore macroporosity in the clayey soils of the Caribbean (Cruz and Guillaume, 1999). From a modelling point of view, kcrop is rather robust because it was estimated from observed SOC stocks in 43 plots under sugarcane monoculture in Guadeloupe (Sierra et al., 2015). This led us to conclude that uncertainties associated with kcrop of sugarcane were of minor importance in our study.

In contrast, the impact of sugarcane yield and of climate change on the amount of crop residues may be two major factors affecting model outputs via their effects on C inputs (Table 5). For example, sugarcane monoculture showed small C sequestration when the impact of climate change on sugarcane growth was considered to be positive. In that case, the rate of SOC change was +0.08 Mg C ha^{-1} yr^{-1}, compared with -0.07 Mg C ha^{-1} yr^{-1} under a negative impact of climate change. A 10% increase in crop yield strongly decreased SOC losses from sugarcane monoculture, but did not induce C sequestration (-0.01 Mg C ha^{-1} yr^{-1}). Moreover, the impact of climate change and crop yield could vary easily with a change in the cultivars used and in crop management. Many modelling studies have assessed the impact of climate change on sugarcane production in the tropics, but there is significant variation in results concerning the sign of the impact, which is reported to range from positive (e.g. Marin et al., 2013) to negative (e.g. de Carvalho et al., 2015) or variable depending on site and cultivar (e.g. Singels et al., 2014). On the other hand, it has been proposed that the increase in crop yield through improved management of nitrogen fertilisers can help to increase soil resilience under a climate change scenario in the tropics (Bhattacharyya et al., 2007; Powlson et al., 2016).

The low impact of changes in coefficient Q10 (Table 5) is in line with the smaller effect of climate change than of crop production system and AER (Table 2). In fact, the increase in temperature in the study period (i.e. 0.7°C) was not large enough to cause a great impact on Q10. The sensitivity analysis indicated that model outputs would be more affected by uncertainties in the biophysical parameters of sugarcane than in those identified from farm surveys. Besides, the results suggested that, for a cropping system such as sugarcane monoculture with near-steady state SOC stocks and occupying a large land area, a change in the impact of climate change via a change of the cultivars used could affect greatly the magnitude and sign of SOC changes at the system and regional scale.

4. Conclusions

The overall effects of land use and cropping practices will be more important in determining SOC changes in the next three decades than those linked to climate change and pedoclimatic conditions. SOC losses at regional were driven by pluriannual sugarcane systems, in which SOC stocks are currently near steady state. This was mainly caused by the slight negative impact of climate change on this C4 crop, which was magnified by the large land area occupied by these cropping systems. Further work is needed to determine the precise effect of changes in crop cultivars and management (e.g. N fertiliser) in reducing the impact of climate change on sugarcane.

Declaration of interest

None.

Acknowledgements

This study formed part of the TropEmis Project funded by the Reacctif Programme of the French Environment and Energy Management Agency (ADEME) (grant 410-00159), the European Regional Development Fund (FEDER) (grant 410-00160) and the Regional Council of Guadeloupe (grant no. 410-00161). The first author received funding from the Cropping System Platform from the Swedish University of Agricultural Sciences (SLU).We would like to thank Mary McAfee for reviewing the English manuscript.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at

References

Bhattacharyya, T., Pal, D.K., Easter, M., Batjes, N.H., Milne, E., Gajbhiye, K.S., Chandran, P., Ray, S.K., Mandal, C., Paustian, K., Williams, S., Killian, K., Coleman, K., Falloon, P., Powlson, D.S., 2007. Modelled soil organic carbon stocks and changes in the Indo- Gangetic Plains, India from 1980 to 2030. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales, pp. 84–94 Agric. Ecosyst. Environ. 122.

Bortolon, E.S.O., Mielniczuk, J., Tornquist, C.G., Lopes, F., Fernandes, F.F., Bergamaschi, H., 2011. Validation of the century model to estimate the impact of agriculture on soil organic carbon in Southern Brazil. Geoderma 167-168, 156–166.

Brisson, N., Levrault, F., 2011. Green Book of the CLIMATOR Project: Climate Change, Agriculture and Forests in France: Simulations of the Impacts on the Main Species. ADEME, Paris, France.

Castellano, M.J., Mueller, K.E., Olk, D.C., Sawyer, J.E., Six, J., 2015. Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. Glob. Change Biol. Bioenergy 21, 3200–3209.

Cerri, C.E.P., Easter, M., Paustian, K., Killian, K., Coleman, K., Bernoux, M., Falloon, P., Powlson, D.S., Batjes, N., Milne, E., Cerri, C.C., 2007. Simulating SOC changes in 11 land use change chronosequences from the Brazilian Amazon with RothC and Century models. Agric. Ecosyst. Environ. 122, 46–57.

Chen, S., Arrouays, D., Angers, D.A., Martin, M.P., Walter, C., 2019. Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept. Soil Till. Res. 188, 53–58.

Chopin, P., Blazy, J.M., Doré, T., 2015. A new method to assess farming system evolution at the landscape scale. Agron. Sustain. Dev. 35, 325–337.

Cruz, P., Guillaume, P., 1999. Growth and mineral nutrition of sugarcane under planting or ratoon cropping conditions. Cah. Agric. 8, 101–107 (in french).

de Carvalho, A.L., Menezes, R.S.C., Silva Nobrega, R., de Siqueira Pinto, A., Balbaud Ometto, J.P.H., von Randow, C., Giarolla, A., 2015. Impact of climate changes on potential sugarcane yield in Pernambuco, northeastern region of Brazil. Renew. Energ. 78, 26–34.

Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y.B., Chotte, J.L., 2018. Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: a synthesis. Agric. Ecosyst. Environ. 259, 147–158.

Galindo, L.M., Bremont, J.E.A., Martinez, O.R., 2015. Adaptation of climate change through the selection crop in Peru. Trimestre Económico 82, 489–519.

Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Conway, G., Moreno-Garcia, M., Kassam, A., Mkomwa, S., Ordoñez-Fernandez, R., Triviño-Tarradas, R., Carbonell-Bojollo, R., 2019. Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. Soil Till. Res. 190, 22–30.

IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Kollas, C., Kersebaum, K.C., Nendel, C., Manevski, K., Müller, C., Palosuo, T., Armas- Herrera, C.M., Beaudoin, N., Bindi, M., Charfeddine, M., et al., 2015. Crop rotation modelling-A European model intercomparison. Eur. J. Agron. 70, 98–111.

Korres, N.E., Norsworthy, J.K., Tehranchian, P., Gitsopoulos, T.K., Loka, D.A., Oosterhuis, D.M., Gealy, D.R., Moss, S.R., Burgos, N.R., Miller, M.R., et al., 2016. Cultivars to face climate change effects on crops and weeds: a review. Agron. Sustain. Dev. 36, 12.

Luo, Z., Wang, E., Sun, O.J., 2010. Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: a review and synthesis. Geoderma 155, 211–223.

Mangalassery, S., Sjögersten, S., Sparkes, D.L., Mooney, S.J., 2015. Examining the potential for climate change mitigation from zero tillage. J. Agric. Sci. 153, 1151–1173.

Marin, F.R., Jones, J.W., Singels, A., Royce, F., Assad, E.D., Pellegrino, G.Q., Justino, F., 2013. Climate change impacts on sugarcane attainable yield in southern Brazil. Clim. Change 117, 227–239.

Miller, G.A., Rees, R.M., Griffiths, B.S., Ball, B.C., Cloy, J.M., 2019. The sensitivity of soil organic carbon pools to land management varies depending on former tillage practices. Soil Till. Res. 189, 236–242.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S., et al., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86.

Muñoz-Rojas, M., Doro, L., Ledda, L., Francaviglia, R., 2015. Application of CarboSOIL model to predict the effects of climate change on soil organic carbon stocks in agrosilvo- pastoral Mediterranean management. Agric. Ecosyst. Environ. 202, 8–16.

Muñoz-Rojas, M., Abd-Elmabod, S.K., Zavalad, L.M., De la Rosa, D., Jordán, A., 2017. Climate change impacts on soil organic carbon stocks of Mediterranean agricultural areas: a case study in Northern Egypt. Agric. Ecosyst. Environ. 238, 142–152.

Ogle, S., Jaybreidt, F., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72, 87–121.

Oliveira, D.M.S., Williams, S., Cerri, C.E.P., Paustian, K., 2017. Predicting soil C changes over sugarcane expansion in Brazil using the DayCent model. Gcb Bioenergy 9, 1436–1446.

Paul, J., 2017. Le compostage et la fertilisation organique à l'échelle du territoire en Guadeloupe: conditions d'émergence d'une filière de recyclage des déchets en agriculture. PhD These. University Paris Sarclay. Abstract available at: http://www. theses.fr/s156506 (Accessed 14.12.18.). (in french).

Peng, J., Dan, L., Huang, M., 2014. Sensitivity of global and regional terrestrial carbon storage to the direct CO2 effect and climate change based on the CMIP5 Model Intercomparison. PLoS One 9 (4), e95282. https://doi.org/10.1371/journal.pone. 0095282.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jate, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174.

Pratibha, G., Srinivas, I., Rao K, V., Raju, M.K., Shanker, A.K., Jha, A., Uday Kumar, M., Srinivasa Rao, K., Sammi Reddy, K., 2019. Identification of environment friendly tillage implement as a strategy for energy efficiency and mitigation of climate change in semiarid rainfed agro ecosystems. J. Clean. Prod. 214, 524–535.

Saint Ville, A., Hickey, G., Phillip, L., 2015. Addressing food and nutrition insecurity in the Caribbean through domestic smallholder farming system innovation. Reg. Environ. Change 15, 1325–1339.

Shah, K.U., Dulal, H.B., 2015. Household capacity to adapt to climate change and implications for food security in Trinidad and Tobago. Reg. Environ. Change 15, 1379–1391.

Sierra, J., Brisson, N., Ripoche, D., Déqué, M., 2010. Modelling the impact of thermal adaptation of soil microorganisms and crop system on the dynamics of organic matter in a tropical soil under a climate change scenario. Ecol. Modell. 221, 2850–2858.

Sierra, J., Causeret, F., Diman, J.L., Publicol, M., Desfontaines, L., Cavalier, A., Chopin, P., 2015. Observed and predicted changes in soil carbon stocks under export and diversified agriculture in the Caribbean. The case study of Guadeloupe. Agric. Ecosyst. Environ. 213, 252–264.

Sierra, J., Causeret, G., Chopin, P., 2017. 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. Agric. Syst. 153, 172–180.

Singels, A., Jones, M., Marin, F., Ruane, A., Thorburn, P., 2014. Predicting climate change impacts on sugarcane production at sites in Australia, Brazil and South Africa using the Canegro model. Sugar Tech 16, 347–355.

Vigier, F., Lacour, S., Benzaï, S., Dieudé-Fauvel, E., 2012. Comment déterminer la consommation des automoteurs agricoles? Sciences Eaux Territoires 7, 46–53 (in french).

Wan, Y., Lina, E., Xiong, W., Li, Y., Guo, L., 2011. Modeling the impact of climate change on soil organic carbon stock in upland soils in the 21st century in China. Agric. Ecosyst. Environ. 141, 23–31.

Table 1

Some pedoclimatic characteristics of the agro-ecological regions (AER) of the archipelago of Guadeloupe.

AER	Mean air temperature	Mean annual rainfall	Soil type[a]	Main clay type	Cation exchange capacity	SOC stock	Soil pH
	°C	mm yr^{-1}			cmol kg^{-1}	Mg C ha^{-1}	
1	26.5	1100	calcic vertisol	smectite	50-70	60-75	7.0-8.4
2	25.4	2300	ferralsol	Fe and Al hydrous-oxides	10-20	50-60	4.5-5.5
3	23.9	3800	andosol	allophane	30-50	90-120	5.0-6.5
4	25.0	2200	nitisol	halloysite	15-35	40-55	5.0-6.5
5	26.6	900	calcisol	smectite	40-50	45-55	7.0-8.0

[a] FAO classification.

Table 2

Analysis of variance of the impacts of climate change, agro-ecological region and crop production system on SOC changes estimated using the business-asusual scenario.

Source of variation	DOF	Contribution to total variance %	F	Level of significance
Climate change (CC)[1]	1	1.4	102	< 0.01
Agro-ecological regions (AER)	4	26.6	476	< 0.01
Crop production system (AS)[2]	1	68.9	4944	< 0.01
CC × AER	4	0.1	3	0.20
CC × AS	1	0.1	1	0.30
AER × AS	4	2.8	51	< 0.01
Error	4	0.1		

[1] With and without the impact of climate change.
[2] Export vs. Local crop production systems.

Table 3

SOC changes at the agro-ecological region (AER) scale estimated using the business-as-usual scenario. CC, refers to climate change.

AER	SOC change	
	Without CC Mg C yr^{-1}	With CC
1	–342	–1685
2	21	–459
3	–10	–65
4	181	99
5	79	66
Total	–71	–2044

Table 4

Analysis of variance of the effect of the scenarios of change in land use and cropping practices under the impact of climate change.

Source of variation	DOF	Contribution to total variance %	F	Level of significance
Land use (LU)[1]	1	21.0	2244	0.01
Tillage (TIL)[2]	1	60.4	6448	0.01
Amended area (AM)[3]	1	6.7	718	0.02
LU × TIL	1	11.5	1232	0.02
LU × AM	1	0.2	24	0.13
TIL × AM	1	0.1	4	0.29
Error	1	0.1		

[1] Current distribution of export and diversified crop production vs. 50% of increase in the area occupied by local crop production.

[2] Conventional vs. reduced tillage.

[3] Current amended area vs. 50% of increase in this area.

Table 5

Impact of the change in the initial values of the model parameters analysed in the sensitivity analysis. The values within the table represent the relative variation of SOC losses at the AER 1 scale in relation to that estimated for the business-as-usual scenario under the impact of climate change (1685 Mg C yr^{-1}, Table 3). Positive and negative values correspond to an increase and a decrease of SOC losses, respectively.

Parameter	Change in the initial value	
	+ 10%	–10%
Yield of sugarcane[1]	–35%	+35%
Area occupied by sugarcane monoculture[2]	–7%	+7%
k_{crop} of sugarcane[3]	+79%	–85%
Q_{10}[4]	+5%	–3%
Amended area[5]	–3%	+3%
	Change in the initial impact	
	nil	positive
Impact of climate change on sugarcane[6]	–37%	–73%

[1] Initial value: 60 Mg ha^{-1}.
[2] Initial value: 69% of the AER 1 area.
[3] Initial value: 0.85.
[4] Initial value: 3.0.
[5] Initial value: 17% of the AER 1 area.
[6] Initial impact: negative.

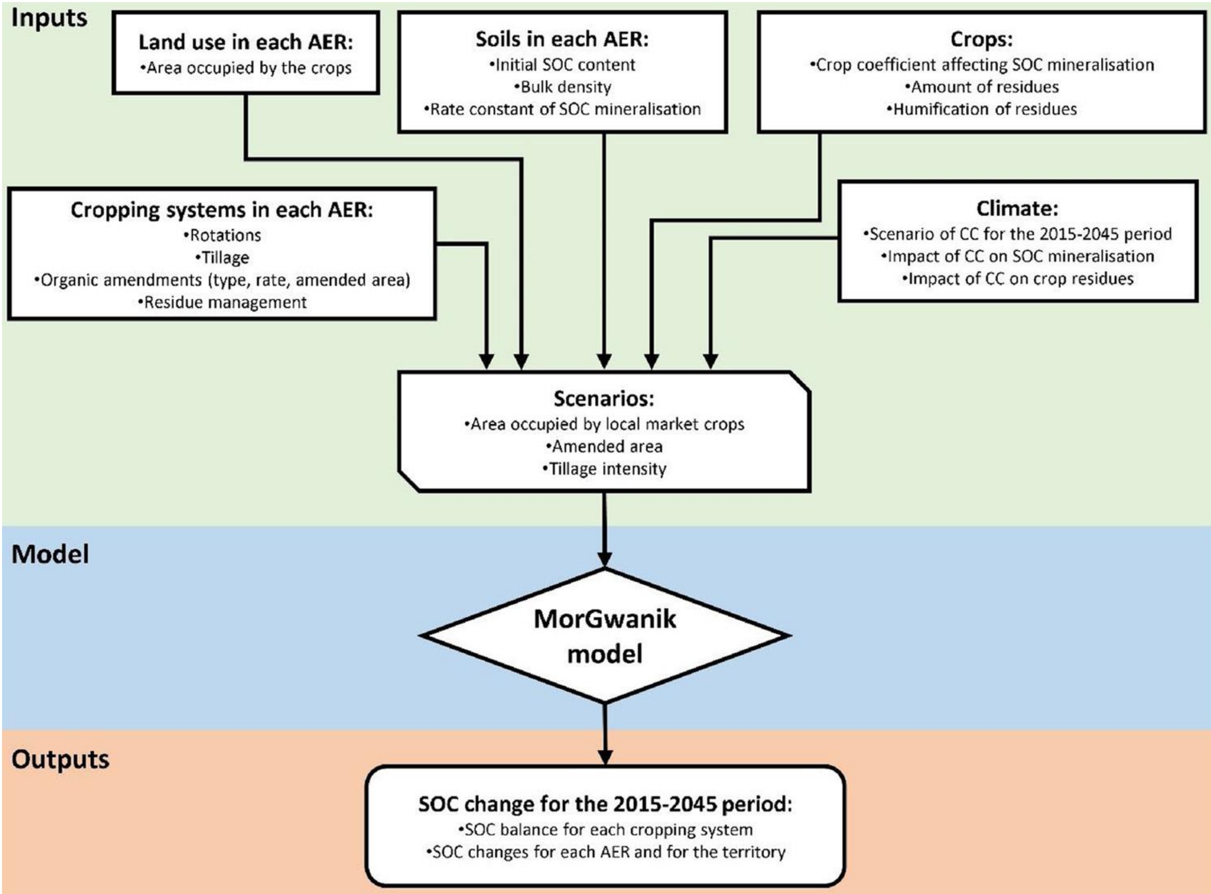

Fig. 1. Overview of the modelling approach applied to assess soil organic carbon (SOC) changes under the impact of climate change.

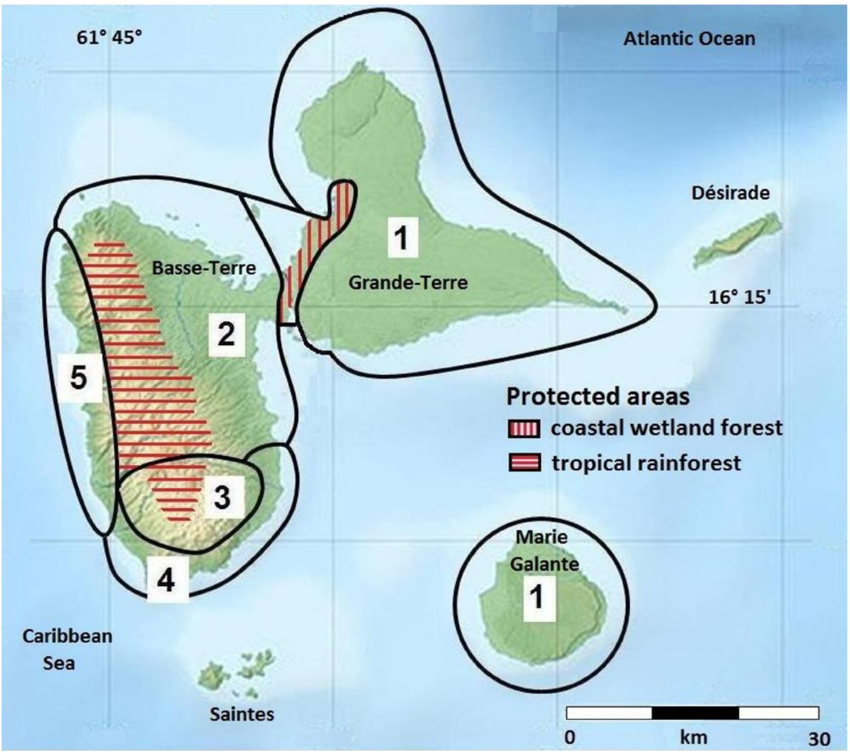

Fig. 2. The archipelago of Guadeloupe in the Caribbean and its five agro-ecological regions (AER). The pedoclimatic characteristics of the AERs are detailed in Table 1.

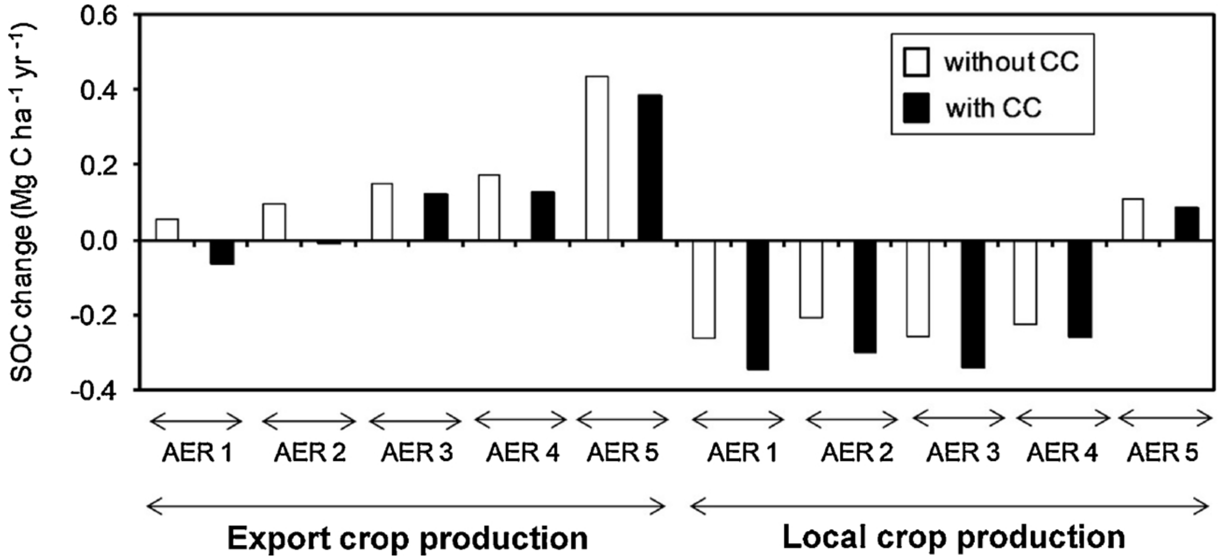

Fig. 3. Annual soil organic carbon (SOC) changes estimated using the business-as-usual scenario with and without the impact of climate change (CC) at the agroecological region (AER) scale for export crop and diversified crop production systems.

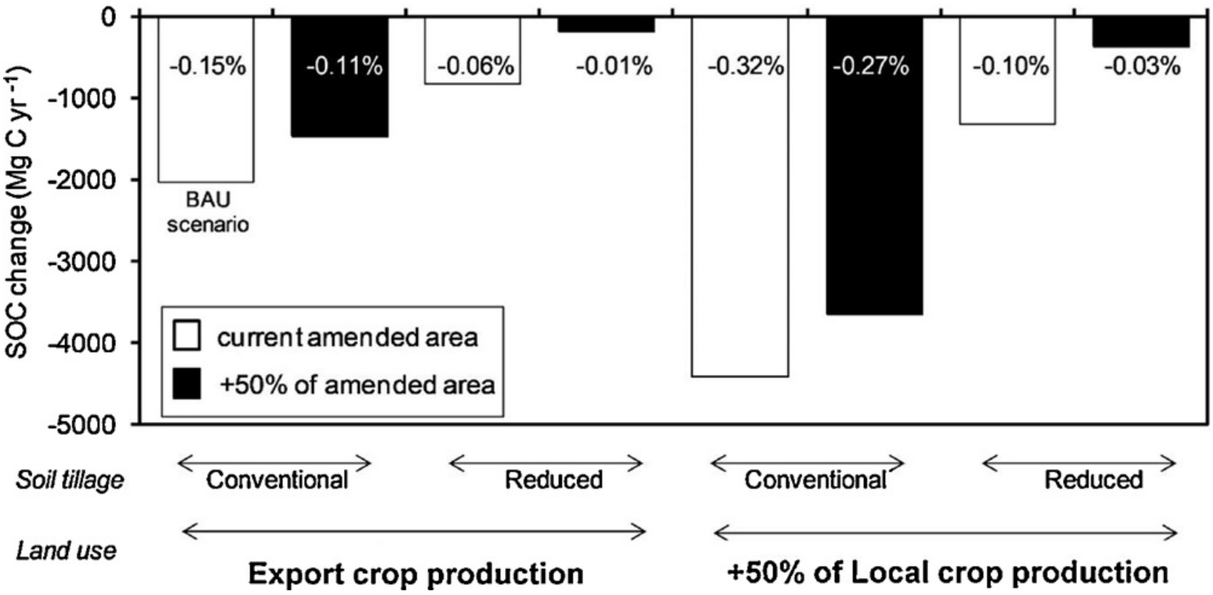

Fig. 4. Annual soil organic carbon (SOC) changes at the territory scale under scenarios of change in land use and farming practices and the impact of climate change. The values within the bars indicate the annual change in SOC stocks in relation to the initial stock. BAU refers to the business-as-usual scenario (see Table 3).

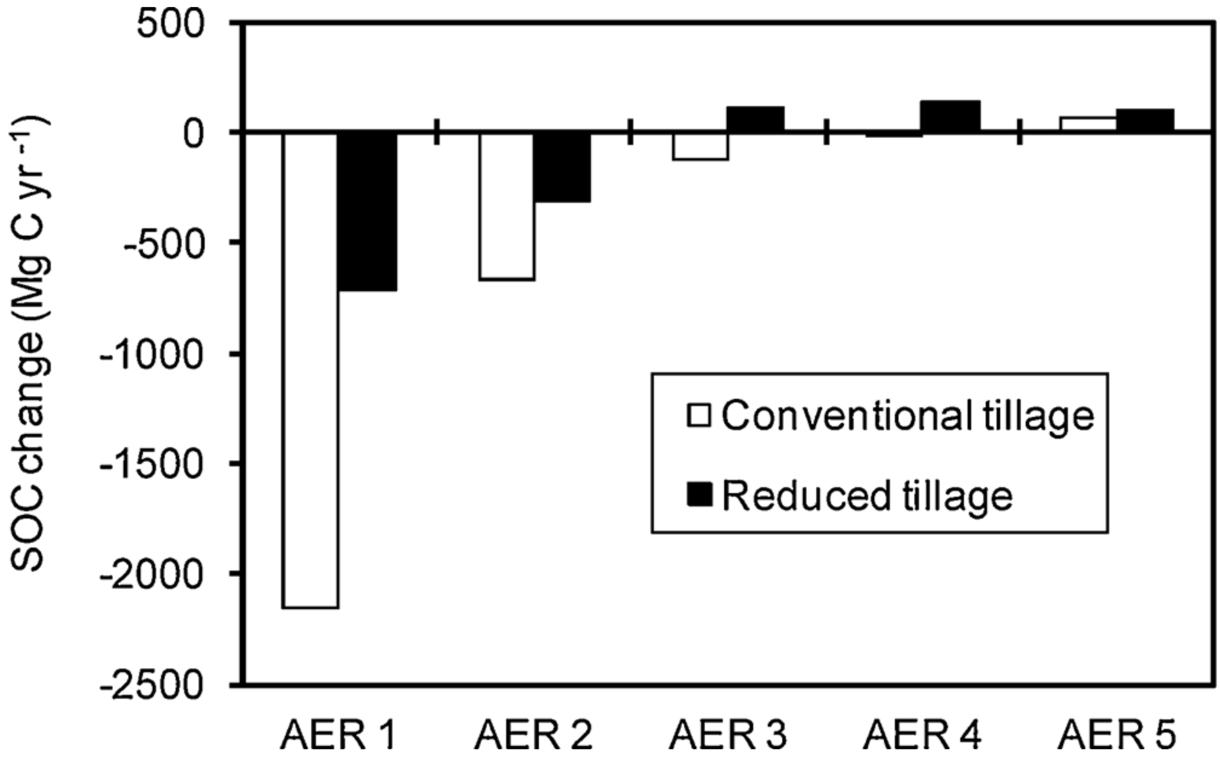

Fig. 5. Impact of conventional and reduced tillage on the annual rates of soil organic carbon (SOC) changes at the agro-ecological region (AER) scale. The rates correspond to the mean annual SOC changes in the scenarios involving conventional and reduced tillage, respectively (n=4).