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► To cite this version:

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. *Soil and Tillage Research*, 2019, 192, pp.113-120. 10.1016/j.still.2019.05.009 . hal-02627066

HAL Id: hal-02627066

<https://hal.inrae.fr/hal-02627066v1>

Submitted on 14 Jul 2023

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

3
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10

11 ABSTRACT

12

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

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

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35

36 **1. Introduction**

37

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

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

63 Several approaches have been proposed for assessing the effect of climate change on SOC.
64 Modelling SOC dynamics is one of the most effective tools to evaluate trends in SOC over time and
65 the impact of changes in cropping practices under a climate change scenario (Muñoz-Rojas et al.,
66 2017). However, it should be borne in mind that the effect of climate change on SOC remains
67 uncertain to some extent, because of uncertainties in climate projections and in the underlying
68 mechanisms included in SOC models. Model uncertainties can be reduced by using simple models of
69 SOC balance calibrated and tested locally, which require minimal data inputs and few parameters
70 and are therefore better suited than more complex models of SOC dynamics to situations with scarce
71 agricultural data, such as the Caribbean (Sierra et al., 2015; Muñoz-Rojas et al., 2017). In this study,
72 we hypothesize that the current trend of Caribbean agriculture towards the replacement of export
73 crops by local market crops will be detrimental to SOC stocks particularly under a climate change
74 scenario, but that adaptation strategies, including implementation of reduced tillage and the use of
75 organic amendments, can reduce SOC decrease.

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

83

84

85 **2. Materials and methods**

86

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

88

89 **2.1. Study site**

90

91 The study was carried out in Guadeloupe in the eastern Caribbean Sea (Fig. 2). Guadeloupe is
92 an archipelago consisting of three main islands (Basse-Terre: 850 km²; Grande-Terre: 590 km² and
93 Marie- Galante: 160 km²). (Fig. 2). Guadeloupe includes five agro-ecological regions (AERs) (Fig. 2),
94 characterised by very different pedoclimatic conditions. Some characteristics of these AERs are
95 presented in Table 1. All the AERs have very clayey soils (i.e. > 70% clay content).

96

97 **2.2. Land use and cropping systems**

98

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

109 Information on the rotations and cropping practices in each AER was taken from a survey
110 carried out by Sierra et al. (2015) (Table A.2). The main difference between crop production systems
111 of export crops and local market crops is soil tillage. Sugarcane and banana are pluriannual crops
112 where tillage is applied every 5–6 years, just before planting. In contrast, soil tillage for annual local
113 market crops is rather intensive, with at least four passes of tillage implements per year. After

114 harvest, crop residues in all systems are left on the soil surface or buried to 0.1–0.2 m depth. Several
115 organic amendments are applied by farmers (e.g. manure, sugar scum, sewage sludge, vinasse and
116 compost), with the application rate varying widely between cropping systems and AERs (Table A.2).
117 To simplify the calculations and presentation of the results, in this study all organic amendments
118 used by farmers were assessed as compost, using the application rate of each amendment and the
119 amount of humified soil C derived from the amendments compared with that from compost.

120

121 2.3. Soil data

122

123 Soils in this study are described in terms of their initial SOC content in each AER (determined
124 with a C analyser), their bulk density (core method) and their rate constant (k) of SOC mineralisation.
125 The values of these parameters were obtained from the soil-crop database developed for the
126 TropEmis Project performed in Guadeloupe (Sierra et al., 2015), which contains information on the 0-
127 0.25 m soil layer in all AERs. For modelling purposes, we classified the values of SOC content
128 observed in each AER into 3–4 classes to be used separately during model simulations (see section
129 2.7). Table A.3 summarises the classes of SOC content observed in each AER, while Table A.4 shows
130 the mean bulk density of soil in each AER. SOC stocks were calculated using Eq. (B.1) in Appendix B.

131

132 2.4. Model of SOC dynamics

133

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

150

151 2.5. Climate change scenario

152

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

159 We accounted for two impacts linked to the increase in temperature: 1) an increase in kAER
160 due to accelerated mineralisation of SOC and 2) a change in the amount of crop residues associated
161 with the impact of warming on plant growth. The increase in kAER was assessed using a Q10
162 approach (rate of change in the system on increasing the temperature by 10 °C) and assuming a
163 linear increase in temperature rate of 0.023 °C yr⁻¹ (i.e. 0.7°C/30 yr) within the study period.
164 Calculation of kAER is described in Appendix B (Eq. (B7)) and the kAER values obtained for the period
165 2015–2045 are presented in Table A.10. The impact of the increase in temperature on the amount of
166 crop residues was estimated from results reported by Sierra et al. (2010) for Guadeloupe. Those
167 authors found that, under the A1B scenario, crop residues would increase by 3.7% for C3 crops and
168 decrease by 7.5% for C4 crops within the period 2015–2045, in accordance with values found in the
169 tropics (e.g. Galindo et al., 2015; Korres et al., 2016). As done for the increase in temperature, the
170 change of the amount of crop residues was assumed linear over time. Table A.11 shows the relative
171 impact of climate change on the amount of crop residues for the C3 and C4 crops studied. The
172 calculations are described in Appendix B (Eq. (B8)).

173

174 2.6. Design of the scenarios of changes in land use and cropping practices

175

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

177

178 1) The land area occupied by local market crops in each AER was increased by 50%, which
179 corresponds to the present trend in Caribbean agriculture and the area occupied by monocultures of
180 sugarcane and banana in each AER was reduced by 50%(Table A.2).

181 2) The land area fertilised with organic amendments was increased by 50%. This increase included all
182 cropping systems with the same initial rate of application. When the initial area receiving organic
183 amendments was zero (e.g. sugarcane in AER 4), the value was set to 20% of the area (Table A.2).

184 3) The conventional deep tillage applied for local market crops was changed to reduced tillage, which
185 implied a reduction of 21% in kcrop for these crops (Table A.5). For this, we assumed that the
186 mouldboard ploughing used for land preparation was replaced by disc harrowing. The reduction in
187 kcrop was assumed to be linked to fuel consumption of each tillage implement and estimated from
188 data reported by Vigier et al. (2012) for clayey soils. This assumption is supported by the results
189 reported by Pratibha et al. (2019) concerning the relationship between fuel consumption of several

190 tillage implements and CO₂ emissions following soil tillage in a tropical soil of India. Details on
191 calculation of fuel consumption are presented in Table A.12. A change in soil tillage method was not
192 considered for export crops, because conventional tillage in these systems, which is applied only
193 once every five years, is necessary to restore soil macroporosity in the clayey soils of the Caribbean
194 (Cruz and Guillaume, 1999).

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

199

200 2.7. Model simulations and calculations

201

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

213

214 2.8. Sensitivity analysis

215

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

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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 $-0.15\% \text{ yr}^{-1}$ in relation to the initial stock at the territory scale, and varied from $-0.20\% \text{ yr}^{-1}$ in AER 1 to $+0.28\% \text{ yr}^{-1}$ 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.

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

278 In a detailed review dealing with SOC changes, Ogle et al. (2005) observed that SOC losses
279 were higher in moist than in dry tropics, but concluded that it was not possible to determine the
280 reason for this pattern because of the many interactions between C inputs and outputs under each
281 climate. In the present study, the highest SOC losses were found for the sub-humid AER 1 (Table 3,
282 Fig. 3). Analysis of model outputs (data not shown) indicated that the lower sugarcane yield in AER 1
283 (Table A.6), which affected the amount of crop residues, was the main factor responsible for the
284 higher SOC losses under export crop production in this AER. For local market production, however,
285 the highest SOC losses observed in AER 1 were mainly driven by conventional tillage acting on soils
286 with high initial SOC stock (Table 1) and k_{AER} value (Table A.4). Minasny et al. (2017) also found that
287 high SOC stocks frequently favour SOC losses under conventional tillage. As pointed out by Ogle et al.
288 (2005) and others (e.g. Wan et al., 2011), precise assessment of the impact of AER on SOC changes is
289 extremely difficult, since a number of model parameters (k_{AER} , initial SOC stocks, crop yield,
290 proportions of export and local market crops, area receiving organic amendments and application
291 rate of organic amendments) differ simultaneously between AERs as a function of their pedoclimatic
292 conditions and cropping practices.

293

294 3.2. Impact of changes in land use and cropping practices on SOC stocks under climate change

295

296 At the territory scale, SOC changes were negative for all combinations of cropping practices,
297 but some of them limited SOC losses (Fig. 4). Reduced tillage was the major factor affecting SOC
298 changes, followed by land use and area receiving organic amendments (Table 4). On average, SOC
299 losses were 4.3-fold lower for reduced than for conventional tillage. SOC losses decreased 1.5-fold
300 when the area receiving organic amendments was increased by 50% and increased 2.2-fold when the
301 area occupied by local market production was increased by 50%. The impact of reduced tillage was
302 higher under the scenario with an increase in local market production (4.8-fold reduction in SOC

303 losses compared with conventional tillage) than for the current land use scenario (3.5-fold
304 reduction). This result reflects the significant land use × tillage interaction shown in Table 4, which
305 contributed about 12% to total variance.

306 Expressed in terms of the initial SOC stocks at the territory scale, SOC losses represented
307 0.05% yr⁻¹ for reduced tillage (-1.5% over the 30-year study period) and 0.21% yr⁻¹ for conventional
308 tillage (-6.3% over 30 years). More interestingly, a change in soil tillage practices from conventional
309 to reduced tillage induced a shift in AERs 3 and 4 from a decrease in SOC stocks to slight C
310 sequestration (Fig. 5). Model outputs indicated that this effect was linked to the shift caused by
311 reduced tillage in vegetable crop systems, in monoculture or in rotation with long-term fallow, which
312 resulted in C sequestration in these AERs. This agrees with field data reported by Sierra et al. (2017)
313 for farms in the Caribbean using reduced tillage to produce vegetable crops. In the present study,
314 vegetable crop systems, in monoculture or in rotation with sugarcane, also showed C sequestration
315 in AER 1, but the relatively small area occupied by these systems was not enough to compensate for
316 SOC losses from sugarcane monoculture in this AER. Similarly, the small amount of C sequestration
317 under reduced tillage in AERs 3, 4 and 5 did not compensate overall for the SOC losses from the
318 largest AERs (1 and 2) at the territory scale (Figs. 4 and 5). Despite this, in absolute terms the main
319 effect of reduced tillage at AER scale was observed in AER 1 (3.0-fold reduction in SOC losses
320 compared with conventional tillage), followed by AER 2 (2.1-fold reduction) (Fig. 5). These results
321 suggest that reduced tillage may partly counteract SOC losses caused by the conventional tillage
322 routinely used in cropping systems for local market production, even under a scenario of increasing
323 area occupied by these systems. In this context, the small C sequestration observed in AERs 3, 4 and
324 5 should be regarded as an improvement in soil resilience, rather than as a significant contribution to
325 climate change mitigation as suggested by Powlson et al. (2016) for tropical conditions.

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

340 application rate of 35 Mg of compost $\text{ha}^{-1} \text{yr}^{-1}$ would need a compost production of 55 000 Mg yr^{-1} ,
341 which is currently unrealistic to attain.

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

363

364 3.3. Sensitivity analysis

365

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

371 The highest impact of kcrop was associated with the fact that the initial rate of SOC change
372 under monoculture of sugarcane was very low ($-0.07 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$), so even a small change in C
373 outputs, represented by kcrop, strongly affected SOC changes in relative terms. Despite the great
374 reduction in SOC losses observed by decreasing kcrop (i.e. decreasing tillage intensity),
375 implementation of reduced tillage is problematic for sugarcane, because conventional tillage applied
376 every five years just before planting is necessary to restore macroporosity in the clayey soils of the
377 Caribbean (Cruz and Guillaume, 1999). From a modelling point of view, kcrop is rather robust

378 because it was estimated from observed SOC stocks in 43 plots under sugarcane monoculture in
379 Guadeloupe (Sierra et al., 2015). This led us to conclude that uncertainties associated with kcrop of
380 sugarcane were of minor importance in our study.

381 In contrast, the impact of sugarcane yield and of climate change on the amount of crop
382 residues may be two major factors affecting model outputs via their effects on C inputs (Table 5). For
383 example, sugarcane monoculture showed small C sequestration when the impact of climate change
384 on sugarcane growth was considered to be positive. In that case, the rate of SOC change was +0.08
385 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%
386 increase in crop yield strongly decreased SOC losses from sugarcane monoculture, but did not induce
387 C sequestration (-0.01 Mg C ha⁻¹ yr⁻¹). Moreover, the impact of climate change and crop yield could
388 vary easily with a change in the cultivars used and in crop management. Many modelling studies
389 have assessed the impact of climate change on sugarcane production in the tropics, but there is
390 significant variation in results concerning the sign of the impact, which is reported to range from
391 positive (e.g. Marin et al., 2013) to negative (e.g. de Carvalho et al., 2015) or variable depending on
392 site and cultivar (e.g. Singels et al., 2014). On the other hand, it has been proposed that the increase
393 in crop yield through improved management of nitrogen fertilisers can help to increase soil resilience
394 under a climate change scenario in the tropics (Bhattacharyya et al., 2007; Powlson et al., 2016).

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

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406 **4. Conclusions**

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

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417 **Declaration of interest**

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419 None.

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422 **Acknowledgements**

423

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

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432 **Appendix A. Supplementary data**

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

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547 **Table 1**

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

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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

556 ^a FAO classification.

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558 **Table 2**

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

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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		

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¹ With and without the impact of climate change.

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² Export vs. Local crop production systems.

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575 **Table 3**

576 SOC changes at the agro-ecological region (AER) scale estimated using the business-as-usual scenario.

577 CC, refers to climate change.

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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

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591 **Table 4**

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

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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.

606 **Table 5**

607 Impact of the change in the initial values of the model parameters analysed in the sensitivity analysis.
 608 The values within the table represent the relative variation of SOC losses at the AER 1 scale in
 609 relation to that estimated for the business-as-usual scenario under the impact of climate change
 610 (1685 Mg C yr⁻¹, Table 3). Positive and negative values correspond to an increase and a decrease of
 611 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%

621 ¹ Initial value: 60 Mg ha⁻¹.

622 ² Initial value: 69% of the AER 1 area.

623 ³ Initial value: 0.85.

624 ⁴ Initial value: 3.0.

625 ⁵ Initial value: 17% of the AER 1 area.

626 ⁶ Initial impact: negative.

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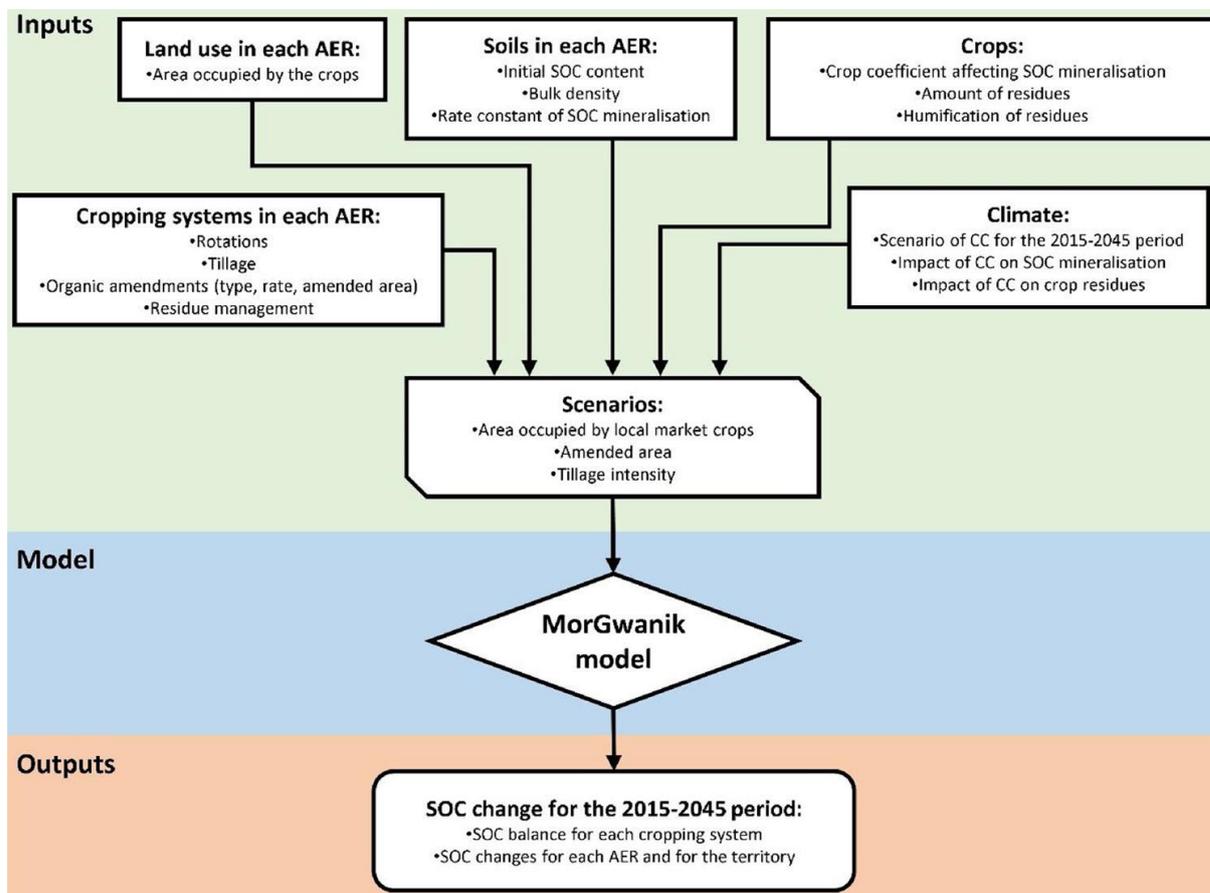


Fig. 1. Overview of the modelling approach applied to assess soil organic carbon (SOC) changes under the impact of climate change.

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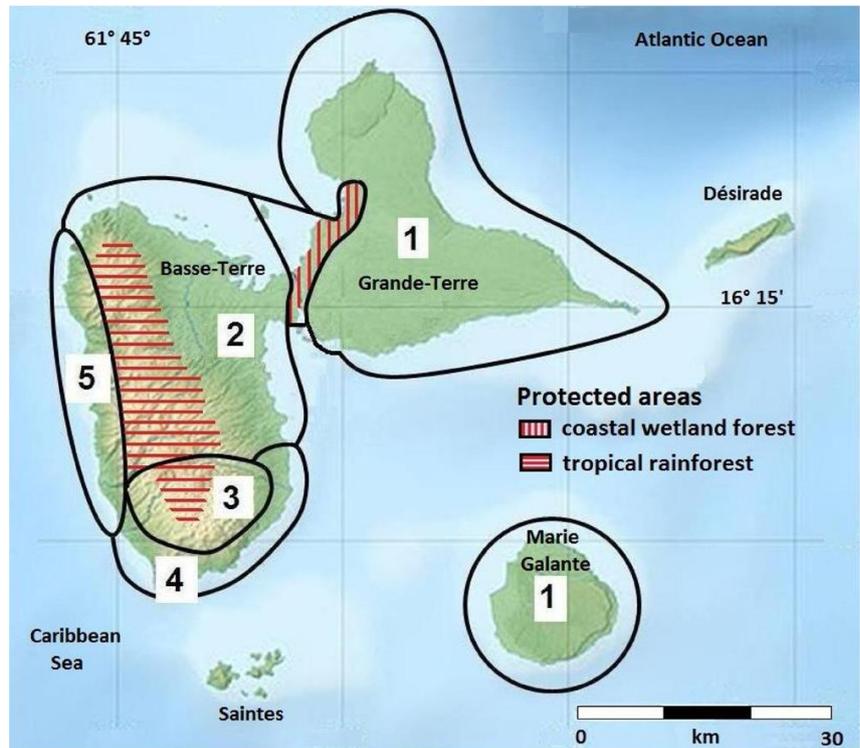


Fig. 2. The archipelago of Guadeloupe in the Caribbean and its five agro-ecological regions (AER). The pedoclimatic characteristics of the AERs are detailed in Table 1.

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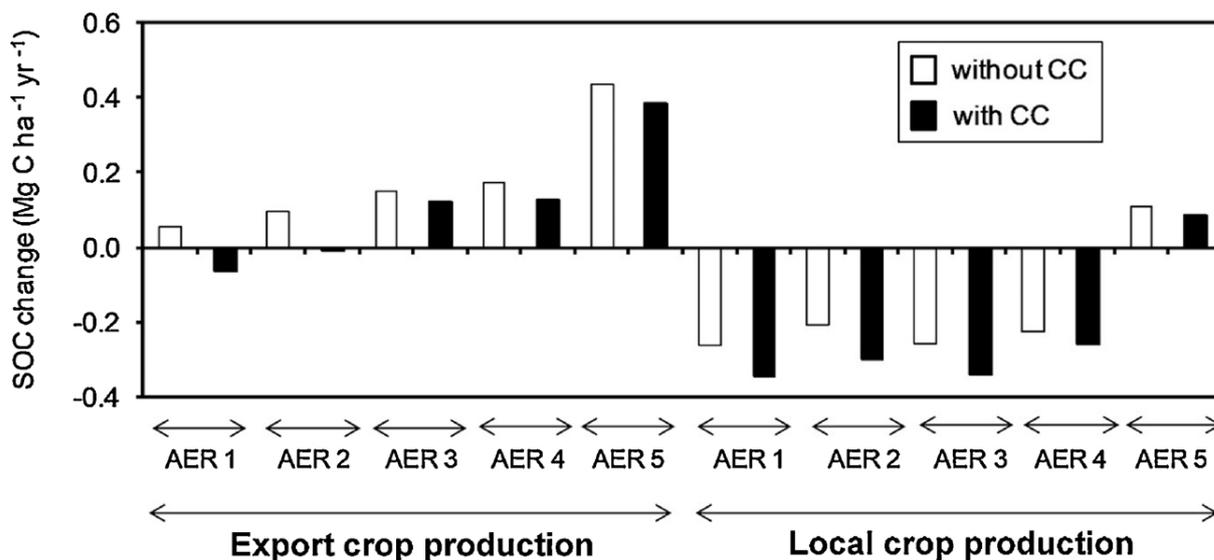


Fig. 3. Annual soil organic carbon (SOC) changes estimated using the business-as-usual scenario with and without the impact of climate change (CC) at the agroecological region (AER) scale for export crop and diversified crop production systems.

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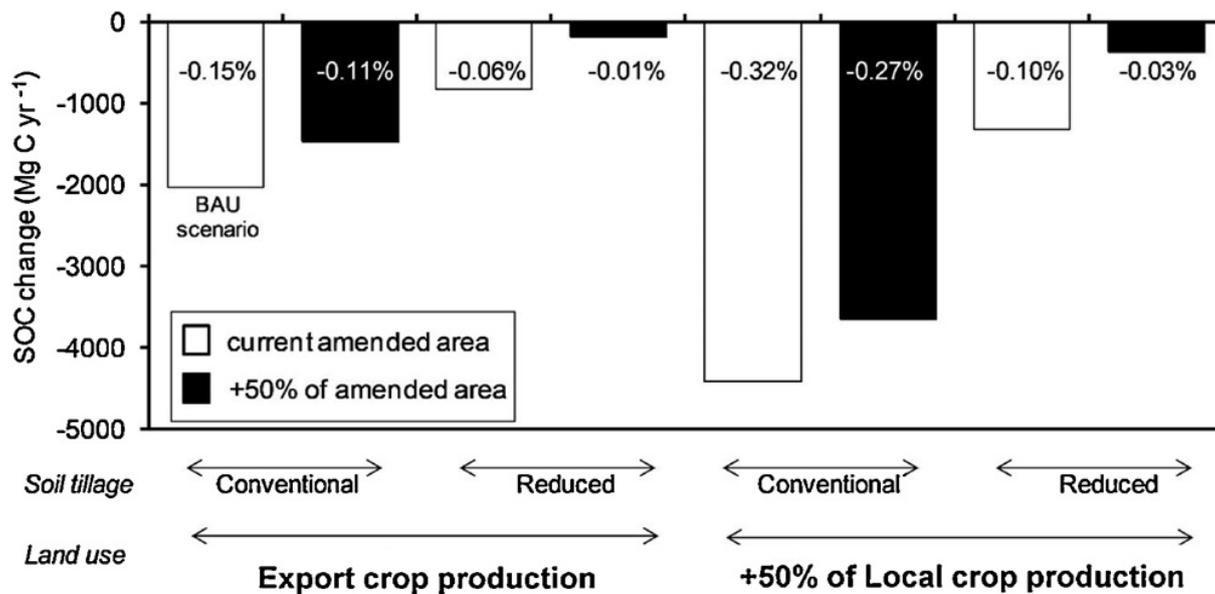


Fig. 4. Annual soil organic carbon (SOC) changes at the territory scale under scenarios of change in land use and farming practices and the impact of climate change. The values within the bars indicate the annual change in SOC stocks in relation to the initial stock. BAU refers to the business-as-usual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

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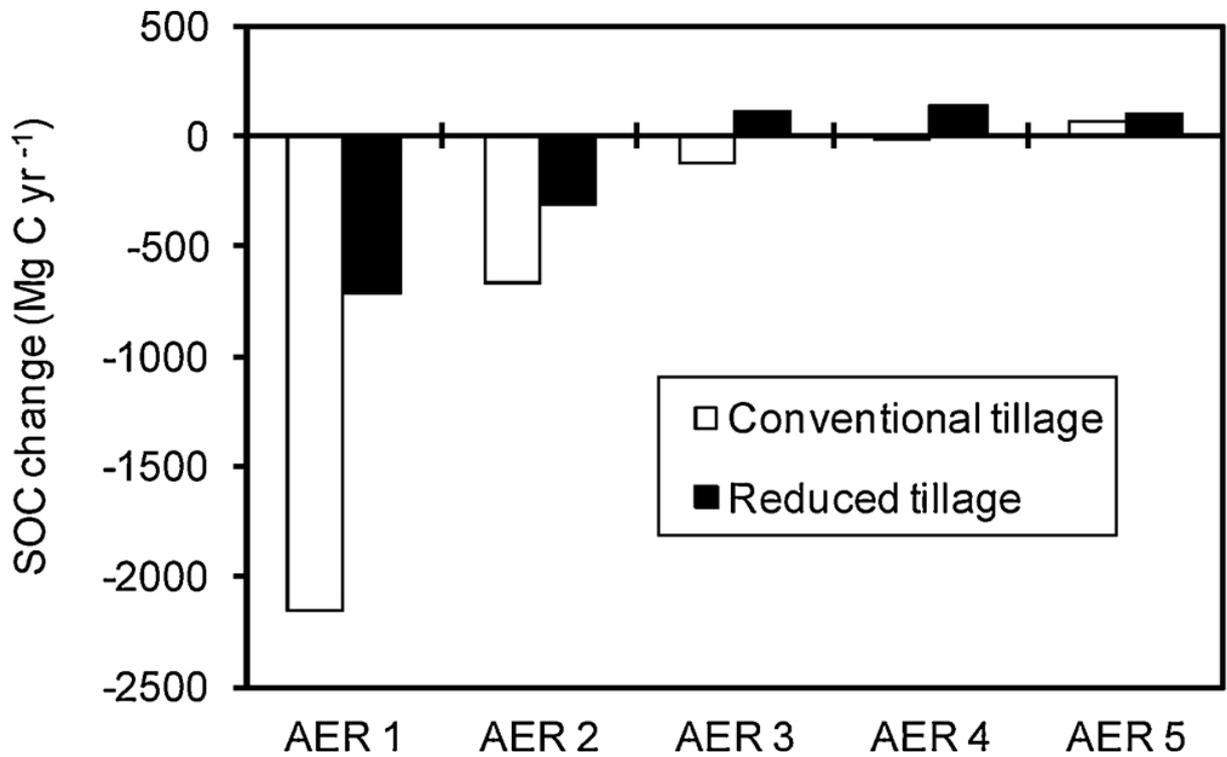


Fig. 5. Impact of conventional and reduced tillage on the annual rates of soil organic carbon (SOC) changes at the agro-ecological region (AER) scale. The rates correspond to the mean annual SOC changes in the scenarios involving conventional and reduced tillage, respectively (n=4).