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Abstract

Predicting soil organic carbon (SOC) mineralisation in the field is crucial to assessing the impact of changes in land use and tillage practices. Although soil data from long-term field experiments are essential to calibrate model parameters for SOC mineralisation, these are frequently lacking regarding some parts of the tropics. The aim of this study was to develop and test an indicator for the in situ SOC mineralisation rate constant using data obtained during soil incubation in the laboratory. Sixty-nine plots corresponding to four soil types (andosol, nitisol, ferralsol and vertisol) under six crops (banana, sugarcane, vegetables, yam, melon and pineapple) involved in 12 tropical cropping systems were analysed. Soil sampling and laboratory incubation procedure were designed to reflect the long-term impact of cropping systems on SOC dynamics. Data from long-term experiments were obtained from a previous study performed on the same cropping systems in Guadeloupe (Caribbean). While SOC contents and stocks were only controlled by soil type, mineralised SOC in the laboratory (C_{min}) was con- trolled to the same degree by both soil type and crop. Moreover, the C_{min}/SOC ratio, which is an indicator of the more active SOC fraction, was only controlled by the crop. Although C_{min} and C_{min}/SOC were not affected by recent C inputs from crop residues, they were negatively correlated with the rate constant of SOC mineralisation observed in the field (k_{field}). These results indicate that differences between the cropping systems (i.e. perennial vs. annual crops) concerning the management of soil tillage markedly affected depletion of the mineralisable SOC fraction. Overall, the results showed that C_{min} measured under regulated laboratory

conditions could be helpful to estimate k_{field}. This is important in tropical regions in order to anticipate the effects of changes in land use and tillage management before changes in SOC stocks become noticeable in the field.

Keywords: Caribbean, Cropping system, Indicator, Long-term effect, Soil incubation, Soil type

1. Introduction

The accurate prediction of soil organic carbon (SOC) mineralisation under field conditions is of crucial importance from both the agronomic and environmental points of view (Oelbermann et al., 2017). In the long-term (e.g. decade or century), predicting SOC mineralisation is necessary to assess the impact of changes in land use, farming practices and tillage management on soil quality and C emissions (Lal, 2004). Although some authors used soil incubations to estimate the rate constants to be included in models devoted to conceptualising and de- scribing SOC mineralisation in the field (Brisson et al., 2003), an alternative procedure involves the statistical fitting of data obtained from diachronic measurements of SOC content in the field (e.g. Andriulo et al., 1999; Sierra et al., 2015). The advantage of this method over laboratory incubations is that it integrates all aspects of managing the plant-soil system over many years, including the impacts on SOC turnover of crop residue management and soil tillage (Cerri et al., 2007). However, this method requires a relatively important soil database including information on the farming practices that affect SOC turnover (e.g. rotations, amount and quality of crop residues, management of organic amendments, intensity of soil tillage), which may be unavailable, particularly in tropical regions (Sierra et al., 2017).

Although changes in agricultural management may influence the mineralisation rate constant, the ability of the models of SOC dynamics to assess the impact of such changes depends on including of farming practices in the model framework. For example, only a few models of SOC dynamics have explicitly considered the increase in SOC decomposition following soil tillage (Bortolon et al., 2009), which is a major process that affects the SOC balance (Martínez et al., 2017). In the case of the Century model adapted to the conditions of Southern Brazil, soil tillage is represented by a cultivation parameter which operates as a multiplier to enhance the mineralisation rate constant of SOC fractions during the two months that follow tillage operations

(Bortolon et al., 2011). However, it may be difficult to extrapolate this empirical approach based on local information about farming practices to other tropical regions such as the Caribbean, where these practices may vary considerably as a function of farmer's resources and the orientation of agricultural production; e.g. perennial crops such as sugarcane and banana vs. annual food and vegetable crops (IFAD, 2014). For example, Sierra et al. (2017) found that vegetable crop systems in Guadeloupe, an archipelago in the Caribbean, could be represented by five farm types that applied contrasting tillage systems on very different soil types, ranging from manual cultivation to more labour-intensive strategies which include up to six tillage operations per year. By contrast, soil tillage under perennial crops is only applied once every five or six years, at the time of planting (Raphael et al., 2012).

Compared with complex models of SOC dynamics, simple models of the annual SOC balance require minimal data inputs and few parameters (Saffih-Hdadi and Mary, 2008) and are therefore well suited to situations with scarce agricultural data, such as in the Caribbean. This also concerns the lack of suitable model parameters regarding most tropical food and vegetable crops (Nin-Pratt et al., 2011). Undoubtedly, such models may be less robust than process-based models, so that their accuracy in assessing the impact on SOC dynamics of new cropping systems or changes of farming practices needs to be tested (Coucheney et al., 2015). In this context, the use of soil indicators of the SOC mineralisation rate constant calibrated from long-term field experiments may be helpful to predict SOC changes under new agricultural scenarios. This is important in tropical regions in order to anticipate the effects of changes in land use (e.g. conversion of food to energy crops) and practices (e.g. manual vs. mechanical soil tillage) (FAO Subregional Office for the Caribbean, 2013), before changes in SOC stocks may be noticed in the field.

In a previous study, Sierra et al. (2015) designed the MorGwanik model of SOC dynamics adapted to the pedoclimatic conditions of the Caribbean in order to assess SOC changes under export and diversified agriculture at the level of the Agro-Ecological Region (AER). The aim of the present study was to evaluate the ability of an indicator based on SOC mineralisation under laboratory conditions to predict the mineralisation rate constants obtained by these authors from long-term field studies, which involved twelve cropping systems under contrasting tillage management. To achieve this, four conditions were imposed to the laboratory experiment: i- only soils under monoculture were selected for the trial in order to best reflect the impact of the management of each crop, ii- soil sampling from each

selected plot was carried out on sub plots that did not receive crop residues following the harvest of the previous crop, in order to reduce their effect on the mineralisable C fraction, iii- soil samples were neither dried nor disrupted to reduce the presence of artefacts linked to sample handling during soil incubation (e.g. the Birch effect; Jarvis et al., 2007) and, iv- relatively long-term soil incubation periods (i.e. 15 wk) were applied to obtain a substantial amount of mineralised C so as to ensure the reliability of the analysis. Under these conditions, we hypothesise that SOC mineralisation during the laboratory experiment reflects the impact of the cropping systems on SOC dynamics in the field. The goal was therefore to develop and to test an indicator that could be used during future research concerning the impact of new agricultural practices on SOC stocks in the soils of the Caribbean region. The study was carried out in the Guadeloupe archipelago (Lesser Antilles) which within a small area displays nearly every physical landscape and cropping system found in the Caribbean.

2. Materials and methods

2.1. Study location

The study was carried out in the Guadeloupe archipelago in the eastern Caribbean. Guadeloupe is composed of two main islands (Basse- Terre: 848 km^2 and Grande-Terre: 586 km^2) and several smaller islands. Only the soils of the two main islands were analysed during this study. Although Grande-Terre is characterised by a gently undulating surface, Basse-Terre Island is dominated by a volcanic mountain chain oriented northwest to southeast with elongated hills with convex slopes in the lowlands. We analysed four soil types (FAO, 2006):

i- Andosols located in the uplands of southern Basse-Terre, which had developed on young ash deposits. These soils are acidic (Table 1) and characterised by high allophanic clay contents (75%). The mean temperature in this region is 23.9 °C and the mean annual rainfall is 3800 mm.

ii- Nitisols located in the lowlands of southern Basse-Terre, which had developed on old ash deposits. These soils are acidic and rich in halloysite clay (70%). The mean temperature is 25.0 °C and the mean annual rainfall is 2200 mm.

iii- Ferralsols located in the northern and eastern parts of Basse-Terre, which had developed on old ash deposits. These soils are acidic and rich in kaolinite clay (70%)

and active aluminium and iron hydrous oxides. The mean temperature is 25.4 °C and the mean annual rainfall is 2300 mm.

iv- Vertisols located in Grande-Terre, which had developed on coral reef limestone. These soils are relatively alkaline and characterized by a high clay content (80%) dominated by smectite. The mean temperature is 26.5 °C and the mean annual rainfall is 1100 mm.

In all of these regions there is a dry season from December to May; it is less pronounced in the uplands of southern Basse-Terre (i.e. 45% of annual rainfall during the dry season) and more marked in Grande- Terre (i.e. only 30% of annual rainfall during the dry season).

2.2. Management o the cropping systems

In this section we present the principal characteristics of the management of the cropping systems analysed in this study, mainly those that directly affect SOC dynamics.

Sugarcane is the dominant crop in Guadeloupe and it is cultivated on ferralsols and vertisols as a monoculture or in rotation with tuber and vegetable crops. When sugarcane is cultivated in rotation this is under a 5–6-yr cycle. The growth season is 12 months and harvesting is mechanical, where residues (tops and leaves) are shredded before being returned to the soil surface. After harvesting, the remaining stubble grows new shoots (ratoon crop). For this reason, soil tillage is only applied before planting in the first year of the cycle. Most sugar production is exported to European markets.

Banana is mainly cultivated on andosols, ferralsols and nitisols, as a monoculture or in rotation with vegetable crops with a 5–6-yr cycle. Harvesting is manual and each plant is harvested separately. Residues (leaves and stems) are cut and placed on the soil surface. After harvesting, a sucker from a lateral shoot of the mother plant grows a new stem. Soil tillage is therefore only applied before planting in the first year of the cycle. Most banana production is exported to European markets.

Most diversification crops (i.e. vegetables, yam, pineapple, melon) are cultivated in rotation with export crops (i.e. sugarcane and banana), but vegetable crops and pineapple are also cultivated as monocultures. Vegetables are cultivated on andosols, nitisols and vertisols, yam on ferralsols and vertisols, melon is only cultivated on vertisols, and pineapple is only grown on ferralsols. All these crops are managed as annual crops and their cycle within the rotation varies from 3 yr for yam to 6 yr for pineapple. Soil tillage is quite intensive in these cropping systems, with 4–6 tillage

operations per year. Yam is cultivated on mechanically-prepared ridges. Except for yam, harvesting is manual and the residues (leaves and stems) are placed on the soil surface or buried at a depth of 0.1–0.2 m. Pineapple residues are shredded before being returned to the soil. Yam is harvested mechanically and the residues (leaves and stems) are partially buried during ridge removal. Most production from diversification crops supply local markets, except for melon which is mainly exported to Europe.

2.3. Laboratory experiment

Sixty-nine plots representing 12 soil x crop situations were selected using the database developed for the TropEmis Project carried out in Guadeloupe (Sierra et al., 2015). The soil x crop situations and mean values of soil properties are presented in Table 1. This database contains information on soils, crop management and farm characteristics that cover all AERs of the archipelago. Only plots under monoculture were selected for the sugarcane, banana and vegetable crops. For other crops, the length of the cycle at the time of soil sampling was 3 yr for yam, 6 yr for pineapple and 5 yr for melon. To reduce the effect of recent crop residues, soil samples for each selected plot were collected from five sub-plots of 10 m^2 that had not received crop residues following the last harvest. Soil samples were collected after harvest in the last year of the cycle of each crop, from January 2015 to March 2015. For all the selected plots, soil sampling was performed after a rainfall, thus raising soil moisture to a level slightly higher than field capacity. This was designed to prevent the effect of drying and rewetting the soil sample on the burst of C respiration following the start of the laboratory experiment (i.e. the Birch effect; Wade et al., 2016). Soil samples were taken from the upper 0.25 m soil layer on a systematic grid using a 0.06-m diameter auger and collecting three sub- samples per sub-plot. Although it is well known that the contribution of deeper layers to SOC mineralization can be important (e.g. Zhu et al., 2017), in this study we focused on the topsoil because SOC in that layer is very sensitive to changes in land use and tillage management in the tropical soils analysed here (Sierra et al., 2015).

Soil organic C (determined with a C analyser) and organic N (Kjeldahl method) analyses were performed on a composite sample at the SADEF Soil Testing Laboratory in France. The stock of SOC (SOC_{stock}, Mg C ha^{-1}) was calculated as:

$$SOC_{stock} = SOC_{cont} \times (BD \times L \times 10{,}000) \quad (1)$$

where SOC_{cont} (Mg C Mg^{-1} soil) is the SOC content, BD (Mg soil m^{-3} soil) is the bulk density of the soil, L (m) is the depth of the soil layer analysed for SOC_{cont} (i.e. 0.25 m in this study) and 10,000 (m^2 ha^{-1}) is used to express SOC_{stock} by hectare. Bulk density was determined using the soil core method (NRCS, 2014) with 5 replicates per plot.

A part of the composite sample was used for laboratory incubations but the sample was not sieved (aggregate size 5 mm) to reduce the effect of soil disturbance (Balesdent et al., 2000). Soil moisture was set at −30 kPa using a regulated vacuum pump. At this water potential the gravimetric water contents were on average 0.66 kg kg^{-1} for andosols, 0.40 kg kg^{-1} for nitisols, 0.43 kg kg^{-1} for ferralsols and 0.46 kg kg^{-1} for vertisols. Laboratory incubations were carried out as described by Raphael et al. (2012). Briefly, a glass vial containing 20 g (dry matter) of soil was placed in a glass jar and incubated at 30 °C in the dark for 15 wk using four replicates per plot. The CO_2 released from SOC mineralisation (i.e. microbial respiration) was trapped in a 0.3 M NaOH solution and determined by titrimetry. The traps containing the NaOH solution were changed after each measurement which was performed seven times during the experiment.

Differences in SOC stocks and SOC mineralisation between soil-crop situations were assessed using ANOVA under an incomplete two-way design with the version 19.5 of the XLSTAT program.

2.4. Field rate constant of SOC mineralisation

The SOC mineralisation rate constants in the field (k_{field}, in yr^{-1}) for each soil-crop situation analysed during the present study had been reported by Sierra et al. (2015), who determined changes of SOC stocks using the following equation:

$$dSOC_{stock}/dt = [C_{res} \times h_{res}] - [SOC_{stock} \times (k_{AER} \times k_{crop})] \quad (2)$$

where $dSOC_{stock}/dt$ is the annual change in SOC stock (Mg C ha^{-1} yr^{-1}), C_{res} (Mg C ha^{-1} yr^{-1}) is the annual C input from crop residues, h_{res} (unitless) is the humification coefficient of crop residues, k_{AER} (yr^{-1}) is the mineralisation rate constant for each AER (i.e. for each soil type in the present study), and k_{crop} (unitless) is the coefficient accounting for the effect of the cropping system on k_{AER}. Although k_{AER} reflects the effect of pedoclimatic conditions on SOC mineralisation, k_{crop} links with the impact of soil tillage on SOC mineralisation (Sierra et al., 2015). Therefore, k_{crop} is

lower for perennial crops where soil tillage is applied every 5–6 yr (e.g. banana and sugarcane), and higher for annual crops that involve several tillage operations per year (e.g. vegetables and yam).

Using this approach, the rate constant of SOC mineralisation in the field (k_{field}, yr^{-1}) can be calculated as:

$$k_{field} = k_{AER} \times k_{crop} \quad (3)$$

Sierra et al. (2015) estimated k_{AER} and k_{crop} using 253 plots with diachronic measurements of SOC stocks between 1998 and 2014, and information concerning the rotations and management of C inputs included in the database. The k_{AER}, k_{crop} and k_{field} values for each soil-crop situation included in the present study are presented in Table S1 of the Supplementary Data file. The characteristics of crop residues are presented in Table S2 (e.g. residue biomass, N and lignin content, C/N ratio, coefficient of humification and C input from crop residues).

3. Results and discussion

3.1. SOC stocks and C mineralisation under laboratory conditions

The organic C and organic N contents were highest in andosols, and there were no significant differences between the other soil types ($P < 0.05$) (Table 1). SOC stocks were mainly affected by soil type (Table 2), which was due to differences in SOC content (Table 1). SOC stocks in the 0–0.25 m soil layer decreased significantly in the following order: andosols (74 Mg C ha^{-1}) > vertisols (60 Mg C ha^{-1}) = ferralsols (58 Mg C ha^{-1}) > nitisols (46 Mg C ha^{-1}) ($P < 0.05$) (Table 1). It is well known that andosols store a great amount of SOC because allophanic minerals incorporate organic compounds that develop amorphous gels, which in turn provide physical protection for SOC against microbial decomposition (Kramer and Chadwick, 2016). By contrast, in lowlands dominated by nitisols under a less humid climate, some gel minerals gradually reorganise into crystalline 1:1 clay minerals (e.g. halloysite), which adsorb organic matter on their surfaces thus decreasing the degree of physical protection (Colmet-Daage and Lagache, 1965). Aluminium and iron hydrous oxides in ferralsols and smectite clay in vertisols offer a degree of physical SOC protection that is intermediate between the allophanic minerals of andosols and the halloysite clay of nitisols, which

289 explain their intermediate SOC stocks compared to these soil types (Powers and
290 Schlesinger, 2002). ANOVA indicated that SOC contents and SOC stocks were not
291 affected by the crop (Table 2), which confirms that although crop management may
292 affect the annual SOC balance (Sierra et al., 2015), it does not affect the differences in
293 SOC between soils, which are dependent on the inherent pedoclimatic characteristics
294 of each AER (Cabidoche et al., 2004).
295 The procedure applied to evaluate SOC mineralisation under laboratory
296 conditions was suited to preventing artefacts due to sample handling. Indeed, SOC
297 mineralisation displayed a linear time course without evidence of an initial stimulation of
298 CO_2 release due to rewetting and soil disruption during the preparation of soil samples
299 (Jarvis et al., 2007) (Fig. 1). Such a linear time course differed from the results of SOC
300 mineralisation under laboratory experiments reported by other authors who observed an
301 exponential pattern of C release indicating first-order kinetics and a dependence of C
302 mineralisation upon the size of the mineralisable SOC pool (e.g. Benbi and Khosa,
303 2014). However, other authors found that in some cases, SOC mineralisation could be
304 described by applying different kinetics models (i.e. zero-order, first-order, mixed zero-
305 and first-order) (Saviozzi et al., 2014). In our laboratory experiment the rate of SOC
306 mineralisation was constant in time, which suggests that the decrease in the size of the
307 mineralisable SOC fraction during soil incubation did not affect that rate. This apparent
308 zero-order kinetics was probably linked to the relatively small size of the mineralised
309 SOC fraction when compared with the total amount of SOC (e.g. the C_{min}/SOC ratio
310 averaged 3.7% for the 69 soils; Table 1).
311 Unlike the findings with respect to SOC contents and SOC stocks, soil type
312 and crop affected in a similar extent the amount of mineralised SOC after 15 wk of
313 laboratory incubation (C_{min}) ($P < 0.01$; Table 2). On average, C_{min} ranged from 1.4
314 g C kg^{-1} in andosols (4.0% of the SOC content) to 0.8 g C kg^{-1} in vertisols (3.5%),
315 and from 1.3 g C kg^{-1} in soils under banana (4.8%) to 0.6 g C kg^{-1} under sugarcane
316 (3.0%) (Table 1). It appears that the effect of soil type on C_{min} was driven by the
317 SOC content, as suggested by the highest values being observed in andosols
318 (Table 1) and the significant correlations found between the two variables in
319 andosols and vertisols (Fig. 2). However, this correlation was induced by small
320 number of extreme high SOC values in both soil types (i.e. two extreme high values
321 in andosols and one extreme high value in vertisols; Fig. 2a and d). In fact, when
322 these extreme values were excluded from the analysis, the correlation between C_{min}
323 and SOC content was not significant in either andosols or vertisols ($P < 0.05$). The
324 weakness of the relationship between C_{min} and SOC was induced by the impact of

the crop on C_{min}, which was particularly noticeable in ferralsols and nitisols (Fig. 2b and c). Indeed, soils under banana in nitisols and ferralsols, and under pineapple in ferralsols, presented the highest C_{min} values regardless of their SOC content. Some authors have reported that crop residues recently returned to the soil may increase the more biodegradable SOC fraction and then boost soil respiration (e.g. Austin et al., 2017; Lian et al., 2017). Our results indicated than the relationship between C_{min} and C input from crop residues was not significant ($P < 0.05$; Fig. 3), and the same was found between C_{min} and other chemical and biological characteristics of the residues for the six crops analysed during this study (i.e. residue biomass, N and lignin contents, C/N ratio and coefficient of humification; Table S2) (these relationships are not shown in Fig. 3). Similarly, although soils under sugarcane presented simultaneously the highest C input from residues and the lowest C_{min}, soils under banana exhibited the highest C_{min} and a C input value that was 40% lower than that from sugarcane (Fig. 3). As discussed in Section 3.2, it appears that C_{min} was dependent on the global impact of the cropping system rather than on recent C inputs from crop residues. This supports the suitability of the procedure used for soil sampling, whose aim was to reduce the impact of residues from the previous crop.

3.2. Relationship between SOC mineralisation under field and laboratory conditions

Negative and significant correlations were observed between C_{min} and k_{field} and between C_{min} and k_{crop} ($P < 0.05$) (Fig. 4). The relationship between C_{min} and k_{AER} ($R^2 = 0.22$) was not significant ($P < 0.05$; data not shown in Fig. 4). These negative relationships support our hypothesis concerning a direct link between k_{field} and SOC mineralisation under the conditions imposed to the laboratory experiment. These results suggest that the organic C pool involved in SOC mineralisation under laboratory conditions was depleted in soil-crop systems with high SOC mineralisation in the field (i.e. high k_{field} and k_{crop}), which induced a lower C_{min}. It is interesting to note that this C pool could not be expressed in terms of SOC content because its relationship with C_{min} was quite inconsistent for most of the soil-crop systems analysed in this study (Fig. 2). Further, although the negative relationship between C_{min} and k_{crop} indicated that the cropping system affected C_{min} (Fig. 4b), ANOVA revealed that the crop did not affect the SOC content (Table 2). It thus follows that the organic C pool involved in SOC mineralisation during the laboratory experiment was probably associated with the more labile fractions of organic matter, which were more

or less depleted as a function of the level of C mineralisation in the field. These results disagree with those of some studies which reported a significant correlation between total C and N contents and the mineralised N observed under laboratory conditions (e.g. Ros et al., 2011; Wade et al., 2016). However, our results are in line with those obtained from long-term field experiments concerning the impact of tillage systems on SOC dynamics (Martínez et al., 2017; Muñoz-Romero et al., 2017). These authors found that the labile SOC fraction was larger under a no-tillage system than with conventional tillage, and that this fraction controlled SOC mineralisation under laboratory conditions. These results were attributed to the effect of tillage on the degree of exhaustion of the less stable forms of SOC in the field. This proposal could be utilised to interpret some of the differences between cropping systems observed during the present study. For example, in banana systems, soil tillage is applied every 5 yr and its impact on the labile C fraction would be smaller than that in yam and vegetable crop systems including several operations of tillage per year. Therefore, the marked differences in C_{min} observed between these cropping systems reflected the effects of farming practices on SOC turnover. Under our approach, the effect of soil tillage was represented by the k_{crop} coefficient (Eq. (2)).

A more interesting finding was that the C_{min}/SOC ratio was markedly affected by the crop but not by the soil type (Table 2). This ratio is frequently referred as being an indicator of the more active SOC fraction involved in SOC mineralisation under laboratory conditions (e.g. Campbell and Souster, 1982). During our study, the C_{min}/SOC content ratio decreased significantly in the following order (Table 1): banana (5.0%) > pineapple (4.2%) > melon (3.4%) > vegetables (3.2%) = yam (3.2%) > sugarcane (3.0%) ($P < 0.05$). The lack of an effect of the soil on this ratio was associated with the strong impact of banana and sugarcane, which respectively presented the highest and lowest C_{min}/SOC values regardless of soil type. Martínez et al. (2017) reported significant correlations between the active SOC fraction determined under laboratory conditions and C input from previous crops. As cited above, this relationship was not significant in the present study (Fig. 3). We therefore concluded that SOC mineralisation as determined in the laboratory reflected the overall impact of the soil-crop system on SOC over several years of crop monoculture. This conclusion was supported by the significant relationship between C_{min} and k_{field}; the latter was determined from a long-term field study (i.e. 17 yr; Sierra et al., 2015).

Whilst the soil and crop could explain almost 80% of total C_{min} variation (Table 2), some results still need to be explained. Firstly, because the soil × crop

interaction was not significant some apparent interactions concerning vertisols (i.e. similar C_{min} values for four contrasting crops characterised by a broad range of soil tillage intensities; Fig. 4) could not be accurately assessed. This was probably due to the small number of degrees of freedom attributed to the interactions in our incomplete two-way design. In other words, because the crops are not cultivated in all the AERs concerned, only a small number of interactions were included in the ANOVA. Secondly, soils under sugarcane presented the lowest values for C_{min} and C_{min}/SOC despite its high rate of annual C input from residues and low intensity soil tillage. We feel these two issues might be linked to the biochemical characteristics of crop residues that could affect the level of the labile pool of SOC and then C_{min}. Several authors found that when lignocellulosic material decomposes in soil, the lignin fraction is not incorporated into microbial biomass but is directly transferred into SOC (e.g. Corbeels et al., 2005). Taking account of the fact that the turnover of microbial metabolites contributes to the labile SOC fraction (Paul, 2016), it could be hypothesised that part of the residues from sugarcane, with the highest lignin content observed during the present study (Table S2), was not recycled into the more labile C fraction, thus causing a relatively low C_{min}. By contrast, banana residues have low lignin content (Table S2), which together with a relatively large quantity of residues induced the highest values for C_{min} and the C_{min}/SOC content ratio observed in this study. It is possible that the similar C_{min} values observed in vertisols under the four contrasting cropping systems (i.e. sugarcane, vegetables, yam and melon) were linked to the combined effects of the quantity and quality of residues on the size of the labile C pool throughout the cycle of monocultures. Despite some discrepancies between the field and laboratory experiments, our results suggest that C_{min} could be used as an indicator of the impact of new cropping systems and practices on SOC, and to assess k_{field} before SOC changes become noticeable in the field. However, the impact of residue quality on the size of the mineralisable C fraction is not currently included explicitly in the k_{field} and k_{crop} coefficients. Further work is therefore necessary to determine the relationship between the biochemical properties of crop residues and the distribution of SOC fractions in tropical soils under contrasting tillage management.

4. Conclusions

The major finding of this study was that SOC mineralisation under the

conditions imposed to the laboratory experiment (C_{min}) was a suitable indicator of the impact of cropping systems on the mineralisation rate constant (k_{field} and k_{crop}) estimated from long-term field experiments. The negative relationship between C_{min} and k_{field} was mainly controlled by the degree of depletion of the labile SOC fraction induced by the management of the soil-crop system. Differences in the intensity of soil tillage between cropping systems (i.e. represented by k_{crop}) were probably the key factor affecting the degree of this depletion. It is important to point out that a low C_{min} does not imply that k_{field} and k_{crop} values will fall in the near future due to exhaustion of the labile SOC fraction. In fact, C_{min} indicates an earlier impact of the cropping system but it does not predict a change to k_{field}, which is dependent on the management of the cropping system and the pedoclimatic conditions that prevail in each AER. Although laboratory soil incubation is a time-consuming method, our results indicate that C_{min} could be useful to quantify the impact of new agricultural practices (e.g. manual vs. mechanical tillage) before SOC changes become noticeable in the field. To achieve this, further work is necessary to assess the effect of residue quality on k_{crop} under contrasting tillage management in tropics.

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Appendix A. Supplementary data

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

References

Andriulo, A., Mary, B., Guerif, M., 1999. Modelling soil carbon dynamics with various cropping sequences on the rolling pampas. Agronomie 19, 365–377.

Austin, E., Wickings, K., McDaniel, M.D., Philip Robertson, G., Grandy, A.S., 2017. Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. GCB Bioenergy 9, 1252–1263.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53, 215–230.

Benbi, D.K., Khosa, M.K., 2014. Effects of temperature, moisture, and chemical composition of organic substrates on C mineralization in soils. Commun. Soil Sci. Plant Anal. 45, 2734–2753.

Bortolon, E.S.O., Mielniczuk, J., Tornquist, C.G., Lopes, F., Fernandes, F.F., 2009. Simulação da dinâmica do carbono e nitrogênio em um Argissolo do Rio Grande do Sul usando o modelo Century. R. Bras. Ci. Solo 33, 1635–1646 (in Portuguese).

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., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J.,Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model STICS. Eur. J. Agron. 18, 309–332.

Cabidoche, Y.M., Blanchart, E., Arrouays, D., Grolleau, E., Lehmann, S., Colmet-Daage, F., 2004. Les Petites Antilles : des climats variés, des sols de natures contrastées et de fertilités inégales sur des espaces restreints. Cahiers du PRAM 4, 21–25 (in French).

Campbell, C.A., Souster, W., 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. Can. J. Soil Sci. 62, 651–656.

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.

Colmet-Daage, F., Lagache, P., 1965. Caractéristiques de quelques groupes de sols dérivés de roches volcaniques aux Antilles françaises. Cahiers ORSTOM Série Pédologie 3, 91–121 (in French).

Corbeels, M., McMurtrie, R.E., Pepper, D.A., O'Connell, A.M., 2005. A process based

505 model of nitrogen cycling in forest plantations. Part I. Structure, calibration and
506 analysis of the decomposition model. Ecol. Modell. 187, 426–448.
507 Coucheney, E., Buis, S., Launay, M., Constantin, J., Mary, B., García de Cortázar-
508 Atauri, I., Ripoche, D., Beaudoin, N., Ruget, F., Andrianarisoa, K.S., Le Bas, C.,
509 Justes, E., Léonard, J., 2015. Accuracy, robustness and behavior of the STICS
510 soil-crop model for plant, water and nitrogen outputs: evaluation over a wide
511 range of agro-environmental conditions in France. Environ. Modell. Softw. 64,
512 177–190.
513 FAO, 2006. World Reference Base for Soil Resources: a Framework for International
514 Classification, Correlation and Communication. Food and Agriculture
515 Organization of the United Nations, Rome.
516 FAO Subregional Office for the Caribbean, 2013. CARICOM Food import bill, food
517 security and nutrition. Available at:
518 http://www.fao.org/fsnforum/caribbean/sites/caribbean/files/files/Briefs/Food%20I
519 mport%20brief%20.pdf (Accessed 11 July 2017).
520 IFAD, 2014. The adoption of organic agriculture among small farmers in Latin America
521 and the Caribbean. Available at: http://www.ifad.org/evaluation/public_html/
522 eksyst/doc/thematic/pl/organic.htm (Accessed 13 July 2017).
523 Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., Banza, J., David,
524 J., Miglietta, F., Borghetti, M., Manca, G., Valentini, R., 2007. Drying and wetting
525 of Mediterranean soils stimulates decomposition and carbon dioxide emission:
526 the “Birch effect”. Tree Physiol. 27, 929–940.
527 Kramer, M.G., Chadwick, O.A., 2016. Controls on carbon storage and weathering in
528 volcanic soils across a high-elevation climate gradient on Mauna Kea, Hawaii.
529 Ecology 97, 2384–2395.
530 Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food
531 security. Science 304, 1623–1627.
532 Lian, T., Jin, J., Wang, G., Tang, C., Yu, Z., Li, Y., Liu, J., Zhang, S., Liu, X., 2017. The
533 fate of soybean residue-carbon links to changes of bacterial community
534 composition in Mollisols differing in soil organic carbon. Soil Biol. Biochem. 109,
535 50–58.
536 Martínez, J.M., Galantini, J.A., Duval, M.E., López, F.M., 2017. Tillage effects on labile
537 pools of soil organic nitrogen in a semi-humid climate of Argentina: A long-term
538 field study. Soil Tillage Res. 169, 71–80.
539 Muñoz-Romero, V., López-Bellido, R.J., Fernández-García, P., Redondo, R., Murillo, S.,
540 López-Bellido, L., 2017. Effects of tillage, crop rotation and N application rate on

541 labile and recalcitrant soil carbon in a Mediterranean vertisol. Soil Till. Res. 169,
542 118–123.
543 Nin-Pratt, A., Johnson, M., Magalhaes, E., You, L., Diao, X., Chamberlin, J., 2011. Yield
544 gaps and potential agricultural growth in west and central Africa. IFPRI Research
545 Monograph, Washington, DC. Available at: https://doi.org/10.2499/
546 9780896291829 (Accessed 12 July 2017).
547 NRCS, 2014. Kellogg soil survey laboratory methods manual. Soil Survey Investigations
548 Report No. 42 Version 5.0. Available at: http://www.nrcs.usda.gov/Internet/FSE_
549 DOCUMENTS/stelprdb1253872.pdf (Accessed 3 October 2015).
550 Oelbermann, M., Echarte, L., Marroquin, L., Morgan, S., Regehr, A., Vachon, K.E.,
551 Wilton, M., 2017. Estimating soil carbon dynamics in intercrop and sole crop
552 agroecosystems using the century model. J. Plant Nutr. Soil Sci. 180, 241–251.
553 Paul, E.A., 2016. The nature and dynamics of soil organic matter: plant inputs, microbial
554 transformations, and organic matter stabilization. Soil Biol. Biochem. 98, 109–
555 126.
556 Powers, J.S., Schlesinger, W.H., 2002. Relationships among soil carbon distributions
557 and biophysical factors at nested spatial scales in rain forests of northeastern
558 Costa Rica. Geoderma 109, 165–190.
559 Raphael, L., Sierra, J., Recous, S., Ozier-Lafontaine, H., Desfontaines, L., 2012. Soil
560 turnover of crop residues from the banana (Musa AAA cv. Petite-Naine) mother
561 plant and simultaneous uptake by the daughter plant of released nitrogen. Eur. J.
562 Agron. 38, 117–123.
563 Ros, G.H., Temminghoff, E.J.M., Hoffland, E., 2011. Nitrogen mineralization: a review
564 and meta-analysis of the predictive value of soil tests. Eur. J. Soil Sci. 62, 162–
565 173.
566 Saffih-Hdadi, K., Mary, B., 2008. Modeling consequences of straw residues export on
567 soil organic carbon. Soil Biol. Biochem. 40, 594–607.
568 Saviozzi, A., Vanni, G., Cardelli, R., 2014. Carbon mineralization kinetics in soils under
569 urban environment. Appl. Soil Ecol. 73, 64–69.
570 Sierra, J., Causeret, F., Chopin, P., 2017. A framework coupling farm typology and bio-
571 physical modelling to assess the impact of vegetable crop-based systems on soil
572 carbon stocks. Application in the Caribbean. Agric. Syst. 153, 172–180.
573 Sierra, J., Causeret, F., Diman, J.L., Publicol, M., Desfontaines, L., Cavalier, A., Chopin,
574 P., 2015. Observed and predicted changes in soil carbon stocks under export
575 and di- versified agriculture in the Caribbean. The Case Study Guadeloupe.
576 Agric. Ecosyst. Environ. 213, 252–264.

Wade, J., Horwath, W.R., Burger, M.B., 2016. Integrating soil biological and chemical indices to predict net nitrogen mineralization across California agricultural systems. Soil Sci. Soc. Am. J. 80, 1675–1687.

Zhu, R., Zheng, Z., Li, T., Zhang, X., He, S., Wang, Y., Liu, T., Li, W., 2017. Dynamics of soil organic carbon mineralization in tea plantations converted from farmland at Western Sichuan, China. PLoS ONE 12, e0185271. http://dx.doi.org/10.1371/journal.pone.0185271

Table 1

Some soil properties of the 0–0.25m soil layer corresponding to the 12 cropping systems analysed during this study. For each property, mean values followed by different letters are significantly different at $P < 0.05$. SOC: soil organic C; SON: soil organic N; Cmin: mineralised C accumulated during the 15-wk laboratory experiment.

Soil	Crop	Number of plots	Bulk density $Mg\ m^{-3}$	pH	SOC $g\ kg^{-1}$	SON	SOC/SON ratio	SOC stock $Mg\ ha^{-1}$	C_{min} $g\ C\ kg^{-1}$	C_{min}/SOC ratio %
Andosol	Banana	6	0.81d	5.9 b	40.8 a	4.0 a	10.0 a	82 a	1.63a	4.2bc
Andosol	Vegetables	5	0.82d	5.9 b	32.8 a	3.2 a	10.0 a	66 a	1.12b	3.4c
Nitisol	Banana	5	0.92c	5.1 c	19.9 b	2.0 b	9.9 a	45 c	1.20b	6.2a
Nitisol	Vegetables	5	0.92c	5.0 c	21.2 b	2.1 b	9.8 a	48 c	0.51e	2.4d
Ferralsol	Banana	5	1.05b	5.2 c	24.1 b	2.4 b	9.9 a	63 ab	1.05bc	4.6b
Ferralsol	Sugarcane	6	1.05b	5.2 c	21.4 b	2.1 b	10.0 a	56 b	0.55e	2.5d
Ferralsol	Yam	5	1.07b	5.2 c	21.3 b	2.1 b	9.9 a	56 b	0.59e	2.8d
Ferralsol	Pineapple	6	1.03b	5.1 c	21.1 b	2.1 b	10.0 a	55 b	0.89cd	4.2bc
Vertisol	Sugarcane	8	1.14a	7.1 a	21.8 b	2.1 b	9.9 a	60 b	0.74de	3.4c
Vertisol	Vegetables	6	1.12a	7.2 a	21.4 b	2.2 b	10.0 a	59 b	0.78de	3.6bc
Vertisol	Yam	5	1.14a	7.0 a	21.6 b	2.1 b	10.0 a	59 b	0.80de	3.7bc
Vertisol	Melon	7	1.15a	7.2 a	21.6 b	2.2 b	10.0 a	59 b	0.73de	3.4c

Table 2

Results of the analysis of variance. SOC: soil organic carbon; Cmin: mineralised C accumulated during the 15-wk laboratory experiment. The % variance refers to the contribution of each source of variation to the total variance observed for each soil parameter.

Source of variation	Degrees of freedom	SOC content			SOC stock			C_{min}			C_{min}/SOC content		
		% variance	F-value	P-value	% variance	F-value	P-value	% variance	F-value	P-value	% variance	F-value	P-value
Soil	3	67	46.3	< 0.01	45	18.9	< 0.01	44	39.3	< 0.01	5	2.3	0.09
Crop	5	3	1.1	0.35	5	1.2	0.32	34	18.1	< 0.01	45	10.3	< 0.01
Soil × Crop	3	3	2.3	0.09	5	2.1	0.11	1	0.7	0.56	6	2.4	0.09
Error	57	27			45			21			44		

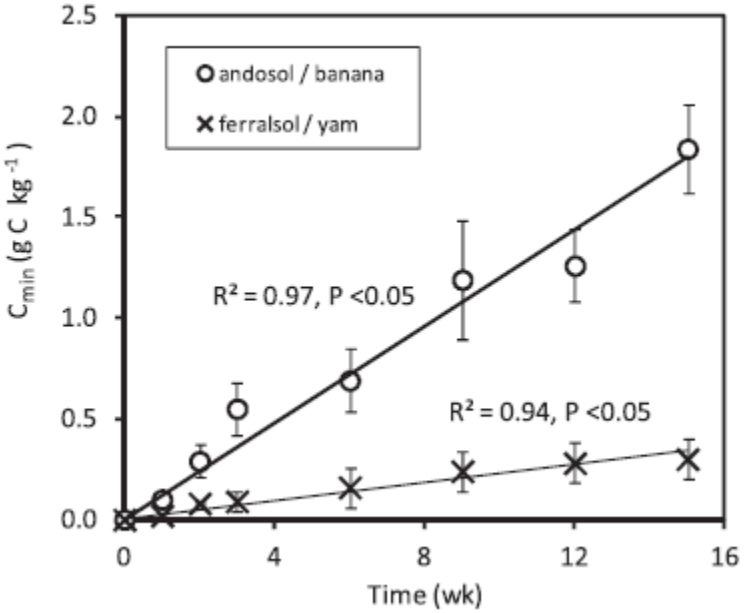

Fig. 1. Time course of SOC mineralisation during the laboratory experiment (C_{min}). The two soil-crop situations presented correspond to the extreme mineralised C values observed during this study. Vertical bars indicate the standard deviation.

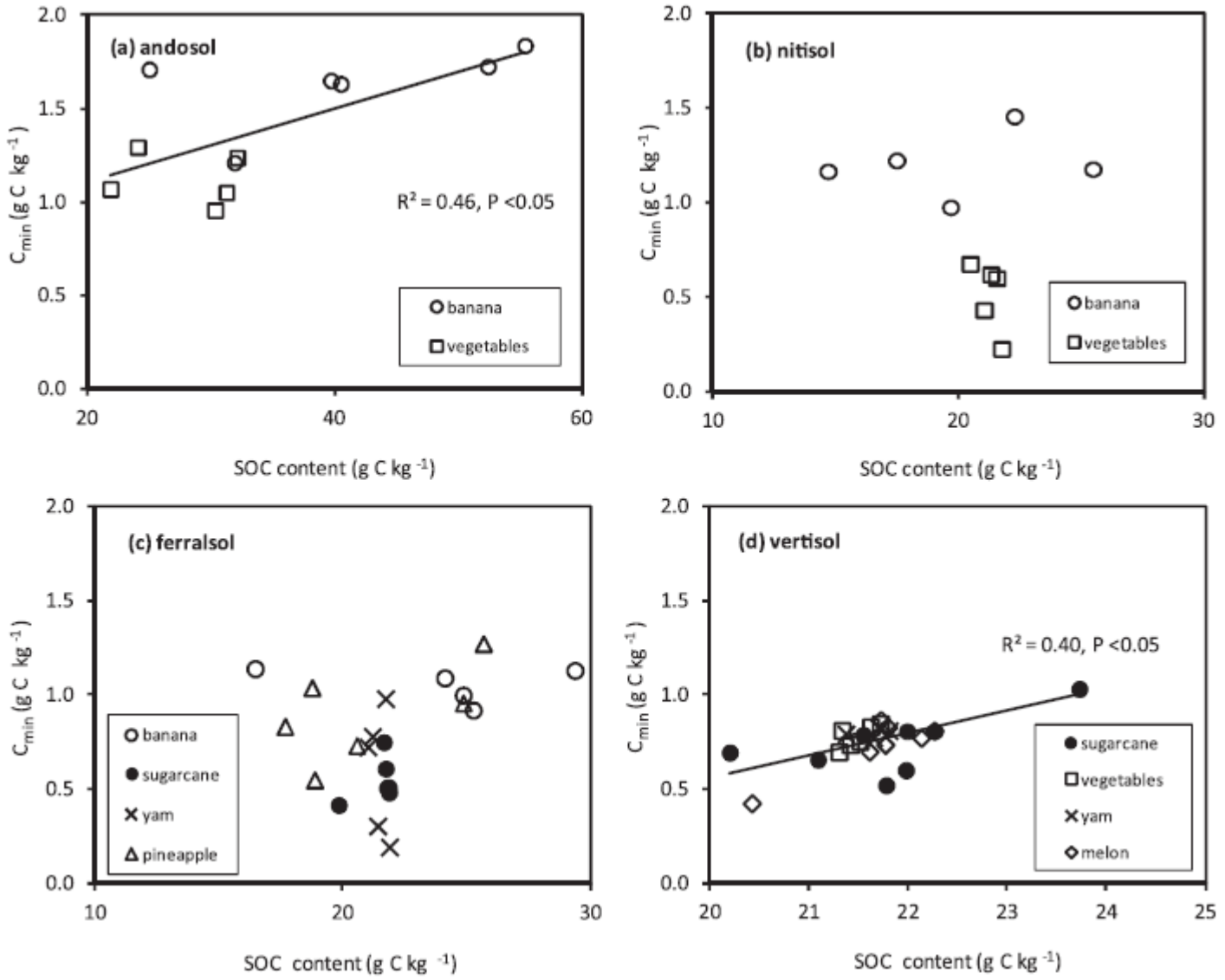

Fig. 2. Relationship between accumulated mineralised C after 15 wk of soil incubation in the laboratory (C_{min}) and the SOC content for each soil type and crop.

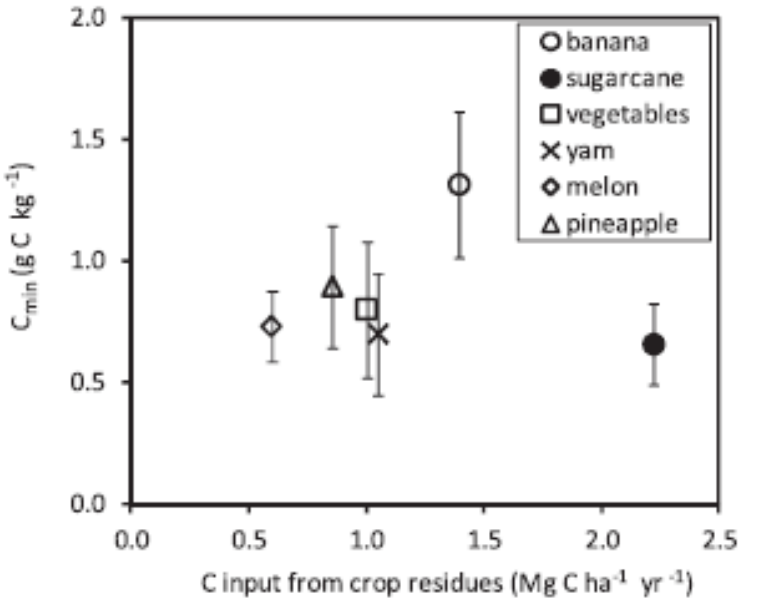

Fig. 3. Relationship between accumulated mineralised C after 15 wk of soil incubation in the laboratory (C_{min}) and C input from crop residues. Vertical bars indicate the standard deviation.

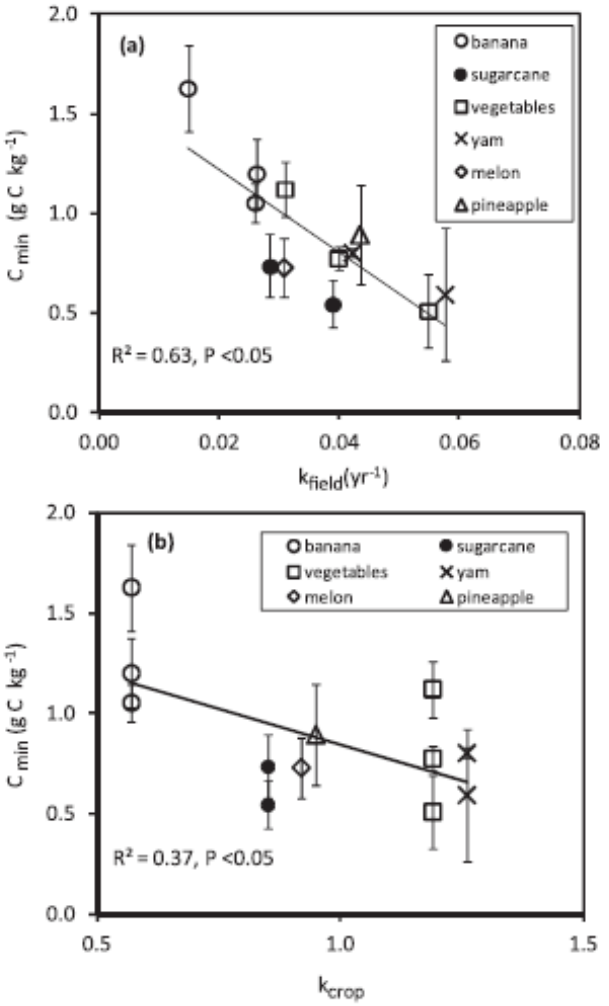

Fig. 4. Relationship between accumulated mineralised C after 15 wks of soil incubation in the laboratory (C_{min}) and (a) the SOC mineralisation rate constant (k_{field}), and (b) the coefficient reflecting the impact of tillage management on SOC mineralisation (k_{crop}). k_{field} and k_{crop} were obtained by Sierra et al. (2015) from long-term field experiments. Vertical bars indicate the standard deviation.