Contents lists available at ScienceDirect

# Geoderma

journal homepage: www.elsevier.com/locate/geoderma

# Short and long-term impact of urban gardening on soil organic carbon fractions in Lixisols (Burkina Faso)

Rayangnéwendé Adèle Ouédraogo<sup>a,b,\*</sup>, Caroline Chartin<sup>a</sup>, Fabèkourè Cédric Kambiré<sup>b</sup>, Bas van Wesemael<sup>a</sup>, Bruno Delvaux<sup>a</sup>, Hélène Milogo<sup>b</sup>, Charles L. Bielders<sup>a</sup>

<sup>a</sup> Earth and Life Institute, Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium <sup>b</sup> Institut de Recherche en Sciences Appliquées et Technologies/Direction régional de l'Ouest, Centre National de Recherche Scientifique et Technologique, Bobo-Dioulasso BP 2393, Burkina Faso

#### ARTICLE INFO

Keywords: Market gardening Soil organic carbon Carbon fractionation West Africa

#### ABSTRACT

In sub-Saharan Africa, market gardening relies on the intensive use of organic amendments, but little is known about the impact of these practices on soil organic carbon (SOC) dynamics. Recent studies have demonstrated that a better understanding of carbon dynamics can be achieved by considering different carbon pools. Here we used a simple method of physical SOC fractionation to assess the impact of market gardening practices on the evolution of total SOC and its stable and labile sub-fractions over a period of several decades. The study was conducted at the Kuinima market gardening zone in Bobo-Dioulasso (Burkina Faso). Composite soil samples (0-15 cm depth) were collected from a chronosequence of 69 fields including control plots and plots farmed for more than 50 years. Samples were wet sieved at 20 µm after agitation or sonication to assess carbon content in the fine (i.e. stable) and coarse fractions. Our results show an asymptotic increase in total carbon content, from 9 g C kg<sup>-1</sup> for uncultivated control plots to 28 g C kg<sup>-1</sup> for plots cultivated for more than 50 years. This increase tends to stabilize after 30 years. A similar trend is observed for C content in the coarse fraction  $> 20 \mu m$ . In contrast, carbon content in the fraction  $< 20 \,\mu m$  increased linearly over time, and this increase was greater in sonicated than in agitated samples. Based on the comparison of the two fractionation methods, a strong contribution of micro-aggregation to the physical stabilization of SOC was hypothesized. This stabilization appears favored by short-range-order (SRO) iron and aluminum oxides and/or metal-humus complexes, as suggested by the strong correlation between stable C content and oxalate-extractable Fe and Al. Large and repeated additions of organic amendments in market gardening thus appear to lead to increased SOC content and promote SOC storage in the stable fraction, thereby contributing to soil quality improvement and the mitigation of climate change.

#### 1. Introduction

Soil health is essential to ecosystem functioning and human wellbeing, and soil organic matter (SOM) plays a key role in the soil's ability to maintain its functioning and to provide environmental services. Indeed, SOM promotes nutrient retention, releases nutrients when decomposed, and helps maintain soil structure by forming large, stable aggregates, thereby improving water retention, soil resistance to erosion and providing habitat for soil micro-organisms (e.g. Milne et al., 2015). Soil organic carbon (SOC) storage has also been identified as an effective way to offset the increase in atmospheric  $CO_2$  concentrations worldwide (Smith, 2016; Minasny et al., 2017). Therefore, protecting, restoring, and even increasing the SOC content and stock has become a global priority (Chenu et al., 2019). Loveland and Webb (2003) also stressed the need for further research on the relationship between carbon and soil properties to better understand soil behavior and to improve our understanding of soil quality and related issues.

In tropical smallholder farming systems, SOC content is generally low because of limited inputs of organic amendments and rapid mineralization of SOC (Ouattara et al., 1997; Pallo et al., 2008, 2009). However, urban market gardens may be an exception because of large and frequent inputs of organic amendments, which are made possible by the commercial nature of the activity and easy access to a variety of organic amendments (Robineau and Dugué, 2018; Ouédraogo et al., 2019). While carbon contents are often below 5 g C kg<sup>-1</sup> in soils used for rainfed cultivation in Burkina Faso (Pallo et al., 2008), Kiba et al.

\* Corresponding author. *E-mail address:* delaoued@hotmail.fr (R.A. Ouédraogo).

https://doi.org/10.1016/j.geoderma.2019.114110

Received 7 October 2019; Received in revised form 26 November 2019; Accepted 27 November 2019 Available online 19 December 2019

0016-7061/ $\odot$  2019 Published by Elsevier B.V.





GEODERM

(2012) reported SOC contents ranging between 7 and 22 g C kg<sup>-1</sup> in market gardens in the capital city Ouagadougou. However, the factors that drive changes in SOC content in a market gardening context have so far received little attention. Besides the type and rate of amendments used by farmers, the accumulation of SOC may be related to the duration of cultivation as well as various to soil properties including clay and fine silt content, iron (Fe) and aluminum (Al) oxide content and the level of micro-aggregation (Six et al., 2002; Feng et al., 2013; Trigalet et al., 2016). A better understanding of the temporal dynamics of SOC in urban garden soils and of the factors that govern SOC accumulation would help in characterizing the environmental impact of urban gardening and in identifying pathways for improving gardening practices.

Total SOC content is often used as an indicator of soil quality but it has several limitations. Indeed, SOC content may be subject to rapid temporal fluctuations that hinder a robust estimate of SOC turnover, particularly for the more stable forms of SOC (Van Wesemael et al., 2019). It may also be insufficiently sensitive to the effects of soil and crop management practices. For instance, Trigalet et al. (2014) reported that crop residue additions increased the storage of carbon in the stable C fraction, even though no change was detected in the total SOC content. As a result, numerous studies have resorted to fractionation methods in order to characterize more relevant SOC fractions depending on the aim of the study (Zimmermann et al., 2007; Poeplau and Don, 2013; Trigalet et al., 2016). One commonly used approach is to distinguish between a labile fraction that is unprotected and consists of partially decomposed plant residues, and a stable fraction following physical or biochemical stabilization or chemical protection (Trigalet et al., 2017; van Wesemael et al., 2019).

The stable and labile SOC fractions do not have the same sensitivity to changes in management or environmental conditions and do not contribute equally to soil biological activity. The labile fraction is the main energy resource for microflora (Feller, 1995). It is rather sensitive to soil management and thus more variable over time. The stable carbon fraction corresponds to SOC protected against microbial mineralization through its close association with clay and fine silt particles (Baldock and Skjemstad, 2000; Six et al., 2002). It is therefore less sensitive to short-term management impacts.

Various protocols have been developed to separate SOC fractions stabilized by organo-mineral complexes from partially decomposed organic residues (von Lützow et al., 2007; Stewart et al., 2008; Poeplau et al., 2018). Recently, van Wesemael et al. (2019) proposed a simple physical fractionation method, which was applied to soils from temperate climates dominated by high activity clays. This method first involves shaking of the bulk soil and then its wet sieving at 20 µm, thereby separating the total carbon into a fine and more stable fraction and a coarse labile fraction. The simplicity of the approach makes it suitable for applications in developing countries where equipment limitations often restrict access to more complex approaches. van Wesemael et al. (2019) showed that the labile and stable C concentrations in temperate soils evolve differently over time in response to changes in management practices. They stated that the ratio of these two C fractions could help predict the short-term evolution of SOC concentrations induced by current management practices. Thus, the implementation of this simple method in routine analyses of arable land could be beneficial to farmers. However, low activity clay (LAC) soils have specific chemical and mineralogical properties that may have different effects on SOC fractions (Feller and Beare, 1997; Barthès et al., 2008), and the relevance of this fractionation method has not yet been tested on these soils. In particular, LAC soils dominated by kaolinitic clay and Fe and Al oxides are known to form strong micro-aggregates (Schofield and Samson, 1954; Uehara and Gillman, 1981), which may contribute to SOC stabilization through physical protection (Six et al., 2002) and SOC adsorption on mineral surfaces (Uehara and Gillman, 1981; Lehmann and Kleber, 2015).



**Fig. 1.** Location and duration of cultivation of the market garden plots sampled within the Kuinima site of Bobo Dioulasso.

effects of cultivation duration, soil properties and site characteristics on total as well as labile and stable SOC fractions in LAC soils of a market gardening site of Burkina Faso.

# 2. Materials and methods

#### 2.1. Study area

The study was carried out at the 60-ha, Kuinima market gardening site (N 11°09′21.46″; W 4°14′46.72″) in Bobo-Dioulasso, Burkina Faso (Fig. 1). Bobo-Dioulasso is the second largest city in Burkina Faso and is located 360 km southwest of the capital, Ouagadougou. The climate is south-Sudanian, characterized by a dry season from November to April and a rainy season from May to October. Annual rainfall ranges between 900 and 1200 mm, and average monthly temperatures between 25 °C and 30 °C (Robineau and Dugué, 2018). The site has a gently sloping topography with altitudes ranging from 441 to 478 m.

The Kuinima site was chosen because it is the largest market gardening site in Bobo-Dioulasso, and because the oldest fields have been cultivated for > 50 years. Fields are small, with a median area of 808 m<sup>2</sup>. On its northeastern edge, the site is bounded by the Houet river: the oldest fields are often located near the river whereas the most recent ones are further away (Fig. 1). The distance of the fields to the river varies between 12 and 540 m. Fields are located between 10 and 47 m above the river. Based on soil pits and an augering survey, soil characteristics appeared rather homogeneous all over the site. The dominant soils are Lixisols (Jones et al., 2015).

#### 2.2. Fields selection and soil sampling

Through interviews with the producers working at the site, 100 farmers were identified who were willing to participate in the study and allow soil sampling in their fields. For each field, the following information was collected: the geolocation (latitude, longitude, elevation), the number of years since it started being used for market gardening, the production period (seasonal or year-round), and the type and application rates of organic amendments during the last year of cultivation. In the end, 69 fields were selected to cover a range of durations of cultivation (from 0 to > 50 years) while ensuring a wide distribution across the site (Fig. 1). In addition, control fields were identified which had never been used for market gardening, although some had been used for rainfed annual cropping. These control fields are located near the edge of the site away from the river or just outside the site. Fields cultivated for > 50 years were arbitrarily given the age of 60 years.

A subplot of each field with a homogeneous land use was targeted for soil sampling. Five soil samples were taken to a depth of 0-15 cm from the two diagonals of the subplot. These five samples were mixed to form a composite sample per field. The sampling occurred at least 2 weeks after the last fertilizer or organic amendment input.

# 2.3. Soil analyses

#### 2.3.1. Measurements on bulk soil samples

The soil samples were air-dried and sieved at 2 mm. Particle size distribution (clay: < 20  $\mu$ m; fine silt: 2–20  $\mu$ m; coarse silt: 20–50  $\mu$ m; fine sand: 50  $\mu$ m – 0.2 mm; coarse sand: 0.2–2 mm) was determined by wet sieving (> 50  $\mu$ m) and sedimentation (< 50  $\mu$ m) after destruction (H<sub>2</sub>O<sub>2</sub>) of organic matter and chemical dispersion (Na-hexametaphosphate) at the laboratory of the Centre provincial de l'agriculture et de la ruralité of the Brabant Wallon (Belgium). The total carbon (Ctot) and nitrogen (Ntot) contents were determined using a Variomax Dry Combustion CN Analyzer (Elementar Analysensystem GmbH, Germany). Oxalate-extractable Al and Fe (Fe<sub>o</sub> + Al<sub>o</sub>) contents were determined with a 0.2 M ammonium oxalate extraction solution at pH 3 (solid to liquid ratio of 0.5 g : 50 ml, end-over-end shaking for 4 h in darkness; Blakemore et al., 1981). Concentrations of Al<sub>o</sub> and Fe<sub>o</sub> were measured by ICP (ICAP 6500, Thermo-Scientific).

#### 3. Fractionation procedure

SOC was divided into two pools (  $< 20 \ \mu m$  and  $> 20 \ \mu m$ ) based on a physical fractionation scheme adapted from Trigalet et al. (2017) and van Wesemael et al. (2019). One hundred ml of distilled water was added to 20 g of air-dried fine earth and shaken horizontally for 20 min. at 250 rpm to disrupt macro-aggregates. The resulting suspension was first passed through a 50-µm sieve to remove aggregates, sand and coarse free particulate organic matter (POM) in order to avoid clogging during subsequent sieving at 20 µm. The suspension that passed through the 50-µm sieve was subsequently passed through a 20-µm sieve. The suspension containing particles < 20 µm was first centrifuged (3600 rpm for 25 min) and the clear supernatant discarded. The  $> 20 \,\mu\text{m}$  fraction (sum of fractions retained on the 20- $\mu$ m and 50- $\mu$ m sives) and the < 20  $\mu$ m fraction were then dried at 60 °C, weighed and stored at room temperature. Organic carbon content was measured in the fraction  $< 20 \,\mu\text{m}$  and reported in g C kg<sup>-1</sup> of bulk soil (referred as C  $< 20 \mu m$ ) by considering the mass proportion of the fraction within the bulk soil sample. Organic carbon content of the  $> 20 \ \mu m$ fraction (C  $> 20 \,\mu$ m) was then determined as the difference between Ctot and C < 20  $\mu$ m (Hassink, 1997).

In tropical soils dominated by kaolinite, Fe and Al oxides, microaggregation can be especially strong (Schofield and Samson, 1954; Uehara and Gillman, 1981). Mechanical agitation may not destroy these micro-aggregates, which tend to be more resistant than aggregates stabilized by soil organic matter alone (Balesdent et al., 1988). To further characterize the role of these resistant micro-aggregates in C stabilization, 24 samples were subjected to ultrasonic dispersion using a Branson Sonifier 250 at  $100 \text{ J ml}^{-1}$  as recommended by Hassink (1997) (20 g of soil in 417 ml at 50 W for 15 min). Subsequent sieving, drying and organic carbon content measurements were done as described above. These 24 samples were selected based on their clay and total organic carbon content (Ctot) by means of conditional latin hypercube sampling using the clhs package in R (Minasny and McBratney, 2006).

Henceforth, the subscripts 'sh' or 'so' complete the references  $C<20~\mu m$  and  $C>20~\mu m$  in order to specify the fractionation method (shaking or sonication, respectively) that was used to obtain the considered fraction.

# 3.1. Data analysis

A correlation matrix was computed using the Pearson correlation factor. The matrix included all the organic carbon data (i.e., Ctot and its sub-fractions C < 20  $\mu$ m and C > 20  $\mu$ m) and selected soil and site characteristics. The significance level was set at  $\alpha = 0.05$ .

Because the content in C  $< 20 \ \mu m$  after sonication (C < 20-so) was only determined experimentally for 24 out of 69 samples, a multiple linear regression was fitted to the 24 observed values in order to estimate the C < 20-so content on the basis of soil and site characteristics. The independent variables used in the regression procedure were: number of years of market gardening cultivation, Ctot, C < 20sh,  $Fe_0 + Al_0$ , clay and fine silt content as measured by textural analysis (Clay + FS), pH, mass of organic amendment (Qom) added during the previous year (dry matter) and altitude difference with respect to the river (Alt.diff). We did not take into account C > 20-sh and Ntot because of the very high correlation between these variables and Ctot  $(r \ge 0.9)$ . A backward stepwise regression procedure was applied. Akaike's Information Criterion (AIC; Akaike, 1974) being used to select the final model. R<sup>2</sup>, root mean square error (RMSE) and ratio of prediction to deviation (RPD) were computed to evaluate the predictive power of the model. The fitted regression was then used to estimate the C < 20-so content of all 69 samples.

Linear and non-linear regression models were used to describe the evolution of Ctot, C < 20 µm and C > 20 µm contents as a function of the duration of cultivation. Conditional inference tree ensembles (CTree) were grown, each over 500 trees (with mtry = 2 using *cforest in party* package in R), in order to assess the contribution of various explanatory variables to Ctot, C < 20 µm and C > 20 µm contents. The significance level of all statistical tests was set at  $\alpha$  = 0.05. The performance of the CTree was estimated by computing the RMSE and the explained variance as the coefficient of determination R<sup>2</sup> (R<sup>2</sup> = 1 – MSE/variance) on the predicted Out-Off-Bag dataset, i.e. the validation dataset.

All the data analyses were performed in R (Strobl et al., 2007).

# 4. Results

#### 4.1. General characteristics of soil and organic amendments

The soil texture is sandy loam (IUSS Working Group WRB, 2015) with 64–82% sand and 8–23% clay (Table 1). The total carbon content (Ctot) ranges between 5.5 and 34.2 g C kg<sup>-1</sup>. The pH is slightly acidic to neutral. The soils are non-saline and rich in oxalate-extractable Fe (average = 811 mg kg<sup>-1</sup>) and Al (average = 652 mg kg<sup>-1</sup>).

Annual application rates of organic amendments are in the range of 0.87-184 t DM ha<sup>-1</sup> with a median of 42 t DM ha<sup>-1</sup>. The types of organic matter supplied by producers are diversified, both within and between fields. They consist mostly of urban waste, cattle, sheep or pig manure, poultry droppings, and compost. These organic amendments have average carbon contents ranging from 9 to 29%, average N

#### Table 1

Descriptive statistics of some soil parameters of the market garden fields.

	Clay %	Silt %	Sand %	Ctot g C kg <sup>-1</sup>	$Fe_o + Al_o$ mmol kg <sup>-1</sup>	C/N	pH <sub>eau</sub>	Electrical Conductivity $\mu S \ cm^{-1}$
Minimum	8	8	64	5.5	18	9.6	5	17
Maximum	23	16	82	34.2	60	15.9	7.6	255
Mean	12	13	75	19	38	12.7	6.6	101
St. Dev.	3.1	1.8	3.6	7.5	11	1.3	0.6	43.6

St. Dev: Standard deviation; Ctot = total organic carbon;  $Fe_{0} + Al_{0}$  is the sum of oxalate-extractable Fe and Al contents.

contents ranging from 0.41 to 1.75% and average C/N ratios ranging from 15.5 to 21.3 depending on the type of manure.

#### 4.2. Factor explaining the total organic carbon variability

Ctot was significantly correlated to  $Fe_o + Al_o$  content (r = 0.8) and the cultivation duration (r = 0.69) and, to a lesser extent, to the clay and fine silt content (r = 0.28; Table 2). The CTree model explained 62% percent of the variance in Ctot (Fig. 2). Fe<sub>o</sub> + Al<sub>o</sub> content is the factor that most influenced the variance of Ctot, followed by the cultivation duration. Additional factors, including texture, only contributed marginally to the conditional inference tree model. The relationship between Fe<sub>o</sub> + Al<sub>o</sub> content and the Ctot was confirmed as linear (R<sup>2</sup> = 0.64; Fig. 3).

Ctot tends to increase asymptotically with the number of years of cultivation, starting from a mean value of 8 g C kg<sup>-1</sup> on control plots and stabilizing after approximately 30 years at a mean value of 24 g C kg<sup>-1</sup> (Fig. 4). However, a large variability is observed around the mean trend. The C/N ratio increased linearly from a mean values of 11.7 on control field to 14.0 after 60 years of cultivation (not shown).

#### 4.3. Effect of shaking and sonication on fractions mass proportion

After shaking, the weight of the fraction  $< 20 \ \mu m$  represented between 3 and 10% (mean = 7%) of the bulk soil mass (Fig. 5). In comparison, the fraction  $< 20 \ \mu m$  obtained by texture analysis, i.e. after destruction of soil organic matter and chemical dispersion, ranged between 13 and 21% (mean = 18%) of the bulk soil mass. Hence, after fractionation by shaking, a large proportion (61% on average) of the  $< 20 \ \mu m$  particle size class did not pass through the 20  $\mu m$  sieve, indicating that these particles were part of shaking-resistant micro-aggregates  $> 20 \ \mu m$  in size. These micro-aggregates may contain significant amounts of occluded carbon. After sonication, the mass proportion of particles  $< 20 \ \mu m$  was about twice (mean = 15%) that obtained after shaking (Fig. 5), which is close but still slightly less than the percentage of clay and fine silt obtained through textural analysis.

#### 4.4. Factors explaining the organic carbon fractions variability

The stepwise multiple linear regression approach showed that measured C < 20-so could be very well predicted using the number of years of cultivation, Ctot and C < 20-sh. The prediction performance of the model was excellent with an R<sup>2</sup> of 0.92, an RMSE of 0.66 g kg<sup>-1</sup> and an RPD of 3.5 (Fig. 6). Using this model, the C < 20-so content was predicted for all 69 samples.

Both after shaking and sonication, the C > 20 µm content was very strongly correlated to Ctot (Table 2). Based on the outcome of the conditional inference tree models, Fe<sub>o</sub> + Al<sub>o</sub> content was the factor that influenced most the C > 20 µm content after shaking and sonication, followed by the number of years of cultivation (Fig. 7a, b). Regarding the C < 20 µm content, the number of years of cultivation and the Fe<sub>o</sub> + Al<sub>o</sub> content were both strongly explanatory, with a significant additional contribution of the soils' clay and fine silt content (determined by textural analysis; Fig. 7c, d).

Whether extracted by shaking or sonication, the C  $< 20 \ \mu m$ 

4

content increased linearly as a function of the number of years of cultivation (Fig. 8). However, this relationship was much stronger after sonication ( $R^2 = 0.83$ ) than after shaking ( $R^2 = 0.40$ ). After shaking, the C content in the  $< 20 \mu m$  fraction increased from 2.4 g C kg<sup>-1</sup> initially to 4.5 g C kg<sup>-1</sup> on average after 60 years. After sonication, the C content in the  $< 20 \mu m$  fraction increased from 3.3 g C kg<sup>-1</sup> initially to 10.3 g C kg<sup>-1</sup> on average after 60 years. On average, the C content in the  $< 20 \mu m$  fraction represents about 15% of the Ctot after shaking and 31% of Ctot after sonication.

Because the C > 20  $\mu m$  content is the difference between Ctot and C < 20  $\mu m$ , there was a tendency for C > 20  $\mu m$  to first increase and then decrease with the duration of cultivation. C > 20-sh represented 85% on average of Ctot, with an average of 16.1 g C kg^{-1}, whereas C > 20-so represented 69% on average of Ctot, with an average of 13.0 g C kg^{-1}.

There was a linear relationship between Fe<sub>o</sub> + Al<sub>o</sub> and C < 20  $\mu$ m after sonication (R<sup>2</sup> = 0.56; Fig. 9a). This relationship is weak for C < 20  $\mu$ m after shaking (Fig. 9a). A linear relationship between Fe<sub>o</sub> + Al<sub>o</sub> and C > 20  $\mu$ m is also observed, whether fractionated by shaking (R<sup>2</sup> = 0.59) or sonication (R<sup>2</sup> = 0.56) (Fig. 9b).

Finally, a significant but weak positive correlation exists between C < 20  $\mu$ m and the soils' clay and fine silt content (Table 2). This relationship is similar after sonication (R<sup>2</sup> = 0.25) and after shaking (R<sup>2</sup> = 0.20) (Fig. 10). The relationship between C > 20  $\mu$ m and the soils' clay and silt content was not significant.

# 5. Discussion

In Kuinima's market garden, the majority of old fields are located near the river, and the most recent fields are furthest away (Fig. 1). Milogo, 2019 showed that the site expanded over time, starting from the river where access to water for irrigation was easiest. Consequently, a possible bias may have been introduced because fields could not be randomly selected across the site, i.e. recently cultivated fields cannot be found very close to the river and vice-versa. However, the correlation between Ctot and duration of cultivation was stronger than between Ctot and elevation above the river, which would support the fact that the observed trend in Ctot content resulted from cultivation rather than from a pre-existing spatial trend. The analysis by conditional inference tree ensemble (Ctree) confirmed that the difference in altitude between fields and river did not significantly explain Ctot content. Besides, there was no indication of the existence of a textural gradient across the site, as indicated for instance by the lack of correlation between clay and fine silt content (textural analysis) and elevation above the river (Table 2). Finally, gardens are small and often delimited by earthen bunds planted with Moringa oleifera plants, thereby effectively preventing fine sediment transfer between fields by overland flow.

# 5.1. Effect of the duration of cultivation

The results show that the duration of cultivation was a major factor explaining the evolution of SOC content. This relationship is asymptotic for Ctot, albeit with a great variability between fields which is discussed below. The evolution of Ctot depends on the balance between humification of organic inputs (mostly organic amendments and plant root

	Unit	Years	Clay + FS	Ctot	C < 20-sh	C > 20-sh	$C < 20-s0^{*}$	$C > 20-so^{*}$	$(C < 20-so)-(C < 20-sh)^*$	C/N	$Fe_o + Al_o$	Ηd	Qom	Alt.diff
Years	years	1	0.24	0.69	0.63	0.64	0.9	0.55	0.81	0.63	0.61	0.17	0.04	-0.17
Clay + FS	%	0.24	1	0.28	0.45	0.24	0.52	0.18	0.37	0.08	0.34	-0.1	-0.01	-0.01
Ctot	g C kg <sup>-1</sup>	0.69	0.28	1	0.39	0.99	0.74	0.98	0.85	0.55	0.8	0.05	0.06	-0.16
C < 20-sh	g C kg <sup>-1</sup>	0.63	0.45	0.39	1	0.28	0.76	0.21	0.44	0.5	0.48	0.17	-0.18	-0.23
C > 20-sh	g C kg <sup>-1</sup>	0.64	0.24	0.99	0.28	1	0.66	0.99	0.81	0.51	0.77	0.03	0.09	-0.14
C < 20-so	g C kg <sup>-1</sup>	0.9	0.52	0.74	0.76	0.66	1	0.58	0.92	0.6	0.72	0.46	0.3	-0.14
C > 20-so	g C kg <sup>-1</sup>	0.55	0.18	0.98	0.21	0.99	0.58	1	0.76	0.48	0.75	0.02	0.08	-0.13
(C < 20-so)-(C < 20-sl	y) g C kg <sup>-1</sup>	0.81	0.37	0.85	0.44	0.81	0.92	0.76	1	0.51	0.68	0.38	0.35	0.04
C/N	1	0.63	0.08	0.55	0.5	0.51	0.6	0.48	0.51	1	0.43	0.35	0.08	-0.09
$Fe_{o} + Al_{o}$	mmol kg <sup>-1</sup>	0.61	0.34	0.8	0.48	0.77	0.72	0.75	0.68	0.43	1	0.03	- 0.09	-0.11
Hd	I	0.17	-0.14	0.05	0.17	0.03	0.46	0.02	0.38	0.35	0.03	1	0.18	0.07
Qom	kg DM ha⁻¹	0.04	-0.01	0.06	-0.18	0.09	0.3	0.08	0.35	0.08	-0.09	0.18	1	0.03
Alt.diff	н	-0.17	-0.01	-0.16	-0.23	-0.14	-0.14	-0.13	0.04	-0.09	-0.11	0.07	0.03	1

**Table 2** 

H Ξ IN DIE U DXAIATE-EXTRACTABLE Ш 4° +  $\mu m$  fraction, after sonication, respectively ; Fe $_{
m o}$ 24. II  $\mathbf{Z}_{*}$ the river. 20 to = altitude difference with respect 20 µm and V = C content in the 20-so (dry matter); Alt.diff ٨ 20-so and C v U year ( biomass) and losses during SOM mineralization or because of soil erosion (Chenu et al., 2019). The asymptotic increase in Ctot indicates that, during the first years of cultivation, inputs were larger on average than losses through mineralization, leading to a rapid increase in Ctot, which reached a new equilibrium after several decades (approx. 30 years).

Although the overall trend in Ctot appears positive, a large variability across fields is observed (Fig. 3). Part of this variability may stem from the variability in initial SOC content, as observed for the control fields for which Ctot varied from 5 to 15 g C kg<sup>-1</sup>. This large variability in Ctot in control fields can be explained by the fact that some of these fields had been used during the rainy season for annual cropping (e.g., maize) while others had not been cultivated at all. Actually, control fields with the highest carbon contents were those that had not been cultivated previously and were occupied by herbaceous species and shrubs. Additional variability across fields may result from other sources, including variations in oxalate-extractable Fe and Al content  $(Fe_0 + Al_0)$  across the site, as highlighted by the Ctree model (Fig. 2), but also differences in the type and application rates of organic amendments. Indeed, farmers resort to a variety of amendments, from urban waste and compost to various types of manure (cattle, sheep, pig, poultry), which vary widely in terms of composition (mean carbon contents ranging from 9 to 29%, mean N ranging from 0.41 to 1.75% and mean C/N ratio ranging from 15.5 to 21.3 depending on the type of manure). Survey results also indicated a wide range of application rates during the year preceding soil sampling, from < 1 to 184 t DM ha<sup>-1</sup> yr<sup>-1</sup> depending on the farmer and type of amendment used. The conditional inference tree model did not highlight the quantity of amendments as a significant variable influencing Ctot variance, but this can be easily understood since the reported quantities relate to the year that preceded the sampling and may not be representative of the mean rates applied since the onset of the gardening activities, especially for the older fields. Finally, additional variability may have resulted from differences in total root biomass that are left to decompose in the soil after harvest, since farmers grow a wide variety of crops (Ouédraogo et al., 2019).

Numerous authors have reported a relationship between total organic carbon and clay + fine silt content (Feller, 1995; Trigalet et al., 2017). In the present study, this relationship was weak, which may in part have resulted from the limited range in clay and fine silt contents across fields. In addition, the clay and fine silt mostly affects the stable organic carbon fraction rather than the total organic carbon, whereas in the present study Ctot is dominated by labile carbon (C > 20  $\mu$ m) rather than stable carbon (C < 20  $\mu$ m). Finally, the effect of texture on Ctot may have been occluded by the dominant effects of cultivation duration and other management effects.

# 5.2. Role of oxalate-extractable Fe and Al components

Feo + Alo content was strongly related to Ctot. Feo + Alo encompasses two types of soil constituents: short-range-order (SRO) Fe and Al oxides and (Fe, Al)-humus complexes. (Fe, Al) oxides readily interact with 1:1 clay minerals due to electrostatic forces through the positive and negative surface charges of (Fe, Al) oxides and 1:1 clays, respectively (Schofield and Samson, 1954; Uehara and Gillman, 1981). These interactions are even stronger with SRO oxides (Pochet et al., 2007). Oxalate-extractable Fe and Al thus play a key role in the soil micro-aggregation process (Chauvel et al., 1976). In addition, SRO Fe and Al oxides have a greater affinity for organic matter than clay minerals. Indeed, sorption of organic molecules on these oxides is a major mechanism by which Fe and Al can stabilize SOC (Six et al., 2002; Wagai and Mayer, 2007; Schneider et al., 2010; Eusterhues et al., 2014). SRO Fe and Al oxides may therefore be more important as a storage factor for SOC than other mineral components of the soil (Jones and Edwards, 1998; Kaiser and Zech, 1998; Kaiser et al., 2002). More generally, the interactions between organic compounds and nanoscale



Relative variable importance %

Fig. 2. Relative variable importance of co-variates in total organic carbon (Ctot) variance explanation by conditional inference tree model (Ctree). The vertical dashed line indicates the mean relative variable importance. Fe<sub>o</sub> + Al<sub>o</sub> = sum of oxalate extractable contents of iron and aluminum; Alt.diff = altitude difference with respect to the river; Clay + FS = clay and fine silt content determined by textural analysis; Prod\_per = production period; Qom = Mass of organic amendment added during the previous year (dry matter).



Fig. 3. Relationship between total organic carbon content (Ctot) and the oxalate-extractable iron and aluminum content (Fe $_{o}$  + Al $_{o}$ ).

SRO consisting mainly of Al, Fe, Si polymers are key drivers of carbon storage in soils (Basile-Doelsch et al., 2015). Apart from SRO Fe and Al oxides, (Fe<sub>o</sub> + Al<sub>o</sub>) also includes (Fe, Al)-humus complexes, which consist of organo-mineral associations (OMA) that play a key role in carbon storage (Deng and Dixon, 2002).

The strong correlation between  $Fe_o + Al_o$  and the duration of cultivation questions the mechanisms that may have caused the progressive accumulation of oxalate-extractable Fe and Al components in soils. Caner et al. (2000) in India, Do Nascimento et al. (2004) and Fritsch et al. (2011) in Brazil, and Van Ranst et al. (2019a,b) in Cameroon, observed the transformation of highly weathered, oxide-rich ferrallitic soils into OMA-rich soils that currently undergo podzolization (Do Nascimento et al., 2004; Fritsch et al., 2011) or andosolization (Caner et al., 2000; Van Ranst et al., 2019a,b). In fact, these studies converge to show that the transformation of ferrallitic soils was driven by the accumulation of soil organic matter (SOM), promoted by



**Fig. 4.** Evolution of the total organic carbon content (Ctot) in market garden plots as a function of the number of years of cultivation.



Fig. 5. Proportion of particles  $< 20 \mu m$  (individual particles and micro-aggregates  $< 20 \mu m$  in size) as affected by the extraction method. N = 24.



Fig. 6. Correlation between observed and predicted C content in the  $<20~\mu m$  fraction after sonication.

changes in climate or microclimate conditions, and iron reduction by bacteria (Caner et al., 2011). A first step is the decrease in the particle size of (Fe, Al) oxides and the increase in Al content of Fe oxides (Fritsch et al., 2005). In a second step, organic acids dissolve nanoscale Fe and Al oxides, promote the synthesis of OMA involving dissolved organic matter and SRO oxides such as ferrihydrite (Van Ranst et al.,



**Fig. 7.** Relative variable importance of co-variates in variance explanation of the C content in the  $> 20 \mu$ m fraction after shaking (a) and sonication (b) and of the C content in the  $< 20 \mu$ m fraction after shaking (c) and sonication (d) by means of conditional inference tree models (Ctree). The vertical dashed lines indicates the mean relative variable importance. Alt.diff = altitude difference with respect to the river; Clay + FS = clay and fine silt content determined by textural analysis; Prod\_per = production period; Qom = Mass of organic amendment added during the previous year (dry matter).



o C<20-sh ● C<20-so ◆ Ctot

Fig. 8. Evolution of total organic carbon content (Ctot) and the C content in the  $<20~\mu m$  fraction after shaking (C <20-sh) and sonication (C <20-so) in market garden plots according to the number of years of cultivation.

2019b), and eventually form complexes with Al and Fe (Fritsch et al., 2011; Van Ranst et al., 2019b). This process is promoted by the small particle size of (Fe, Al) oxides and by environmental factors that enhance SOM accumulation (Van Ranst et al., 2019b). In our case study, SOM accumulation is directly linked to the intensive and long supply of

organic residues in urban gardens.

In line with the above-mentioned studies, we propose that the repeated supply of organic matter in the studied urban gardens has induced SOM accumulation. This process led to the transformation of secondary oxides into small-scale SRO (Fe, Al) oxides that acted as a source of Fe and Al to form (Fe, Al)-humus complexes. In this line, we may explain SOM accumulation through (i) the management practices, (ii) the formation of SRO (Fe, Al) oxides and (Fe, Al)-humus complexes, which both strongly contribute to SOM preservation. Nevertheless, our experimental data lead us to raise the question of timescales. The precise lengths of time involved in the andosolic transformation of ferrallitic soils of Mount Bambouto in Cameroon (Van Ranst et al., 2019a; Van Ranst et al., 2019b) are unknown. In contrast, the studies carried out in the Amazon Basin clearly show that the Ferralsol-Podzol transformation is a current process exhibiting a seasonal character as revealed by soil solution studies (Balan et al. 2005; do Nacimento et al., 2008; Fritsch et al. 2011). In particular, present-day physicochemical conditions promote rapid dissolution-recrystallization cycles, but only in the upper horizons of ferrallitic soils and generating nano-sized minerals (Balan et al., 2005; Fritsch et al., 2009). Besides, soil solution analyses clearly revealed that current processes occur on a seasonal basis (do Nacimento et al., 2008). Within this time scale, podzolic environments in the upper Amazon Basin correspond to a sink of carbon and chelated metals for soils, and to a major source of organic colloids and metal cations either soluble or involved in OMA (Fritsch et al., 2009; Fritsch et al. 2011). In these waterlogged soils, reducing and acidic environments promote both the dissolution of clay minerals and organic complexation of metal cations (Fe and Al) (Fritsch et al., 2009; Fritsch et al. 2011). Previous studies have highlighted that OM



Fig. 9. Relationship between the C content in the < 20  $\mu m$  fraction (C < 20  $\mu m$ ) (a) or the C content in the > 20  $\mu m$  fraction (C > 20  $\mu m$ ) (b) after shaking and sonication and the oxalate-extractable iron and aluminum (Fe\_o + Al\_o) contents in market garden plots.



Fig. 10. Relationship between the C content in the  $<20~\mu m$  fraction (C  $<20~\mu m$ ) after shaking or sonication and the clay and fine silt content determined by textural analysis (Clay + FS).

accumulation promotes the current dissolution of Al oxides and 1:1 clay minerals (Wilke and Schwertmann, 1977), as well as seasonal mineral instability (Zabowski and Ugolini, 1992). Besides, earlier studies have

pointed to the role of soil colloids in reacting with organic metabolites resulting in turnover times of months, years or decades (Anderson and Paul, 1984) as well as to rapid (actually daily) accumulation of organic substances on oxide surfaces (Huang et al., 2002). Furthermore, secondary nano-sized hydrous Fe and Al phases are recognized as crucial for OM accumulation (Kleber et al. 2007; Basile-Doelsch et al., 2015; Lehmann and Kleber, 2015). Our experimental data indicate that anthropogenic OM additions increase the capacity of the soil to store carbon if Al and Fe sources are present in soil. On this basis, we advocate for experiments aimed at assessing the lengths of time required to accumulate OM and testing the challenging hypothesis proposing that large and frequent OM additions improve the conditions to store more SOM in low-activity clay soils.

# 5.3. Stable and labile pools of SOC

Following fractionation by shaking, two pools of SOC were obtained. The C  $\,<\,$  20  $\mu m$  fraction consists of SOC associated with free fine silt and fine clay particles and SOC present in micro-aggregates smaller than 20 µm (Trigalet et al., 2017). It may also contain fragments of free POM < 20 µm in size (Poeplau and Don, 2013), but because of the limited energy exerted during shaking, the latter component should be minimal (Schmidt et al., 1999). Consequently, C < 20 µm is dominated by organic compounds that are not easily mineralized by soil micro-organisms because they are adsorbed onto mineral surfaces or involved in OMA or trapped within micro-aggregates. The C  $> 20 \ \mu m$ fraction on the other hand consists of SOC associated with free coarse silt and sand particles, free POM  $> 20 \mu m$  but also SOC trapped inside aggregates that withstood shaking. Hence, this fraction contains labile carbon but it may also contain substantial amounts of SOC inside aggregates that are not easily accessible to soil micro-organisms through physical of chemical protection.

# 5.4. Methodological considerations.

Compared to textural analysis, only 40% of the total clay and fine silt particles were recovered by shaking, indicating that micro-aggregates were still a significant part of the fraction  $> 20 \ \mu m$  after shaking. This was confirmed by sonication, which resulted in a doubling (82%) of the  $< 20 \ \mu m$  fraction (Fig. 5). Compared to shaking, sonication caused an increase in the C  $< 20 \ \mu m$  content from 6.9 to 14.0 g C kg<sup>-1</sup> on average. This increase in C  $< 20 \ \mu m$  is much higher than the 30% increase reported for temperate soils by van Wesemael et al. (2019). Sonication therefore appears to be a necessity in these tropical soils. It will avoid underestimating the amount of C contained in shaking-resistant micro-aggregates  $> 20 \ \mu m$  in size. Even so, a small proportion (18% on average) of clay and fine silt particles remained entrapped in aggregates  $> 20 \ \mu m$  that resisted sonication (Fig. 5).

Following the fractionation by shaking and sonication, it becomes possible to identify three carbon fractions (Fig. 7c). First, a C > 20-so fraction obtained after sonication, which is associated with coarse silt and sand particles, free particulate organic matter (POM) and a small contribution of micro-aggregates > 20  $\mu$ m that resisted sonication. Then, a C < 20  $\mu$ m fraction which corresponds to intra-aggregate POM as well as C bound to fine silt and clay inside aggregates that resisted shaking but were destroyed by sonication ((C < 20-so) – (C < 20-sh)). And finally a C < 20-sh fraction obtained after shaking and containing C associated with free fine silt and clay particles or present inside micro-aggregates smaller than 20  $\mu$ m which were destroyed by shaking, as explained above.

The C < 20-sh fraction is only weakly affected by the duration of cultivation (Fig. 7c). This may result from the low content in clay- and fine silt-sized particles, whose surfaces would be easily covered by organic compounds. Indeed, the level of stable carbon saturation in soil depends on its clay and fine silt content (Hassink, 1997; Six et al., 2002; Feng et al., 2013). In addition, kaolinite, which is expected to dominate

the clay fraction of the studied soils, has a low specific surface area. The small rate of increase in the C < 20-sh fraction over time may result from increased trapping of SOC inside micro-aggregates < 20  $\mu$ m in size. Nevertheless, given such a low rate of increase, the opportunity for C storage in this fraction appears very limited.

In contrast, the C < 20-so fraction strongly increases with the duration of cultivation. Assuming that most of this fraction was linked to shaking-resistant micro-aggregates > 20  $\mu$ m in size, this indicates that there is a strong potential for C storage in micro-aggregates > 20  $\mu$ m in these soils. The stronger correlation observed between Fe<sub>o</sub> + Al<sub>o</sub> and C < 20-so compared to Fe<sub>o</sub> + Al<sub>o</sub> and C < 20-sh would corroborate that sonication disrupts micro-aggregates > 20  $\mu$ m in size that were largely stabilized by SRO Al and Fe oxides. Van De Vreken et al. (2016) also reported a linear relationship between Fe and Al oxides and the C < 20  $\mu$ m fraction.

Because of the linear increase in the C < 20-so content and the asymptotic increase in Ctot, the C > 20-so fraction first increases with the duration of cultivation, then decreases. The initial increase likely resulted from the fact that the application rates of organic amendments initially exceeded the SOM mineralization rate, leading to the accumulation of SOC mostly in the C > 20-so pool. However, it appears that some of this SOC was progressively entrapped inside shaking-resistant micro-aggregates. When the total C accumulation rate becomes lower than the rate of increase of C < 20-so, i.e. when more C is transferred to the C < 20-so pool than there is C accumulation in the soil, the C > 20-so begins to decrease.

The fractionation by shaking and sonication thus revealed that a significant amount of carbon got stabilized over time in a  $> 20 \ \mu m$  pool which resisted shaking yet was destroyed by sonication. This pool is most likely dominated by micro-aggregates as well as by OMA associations. Preferential carbon storage in aggregates is an ideal indicator for long-term preservation (Denef et al., 2004; Kong et al., 2005). Aggregation creates a physical barrier between decomposers and soil organic matter. This favored carbon storage by up to 5.85 g kg<sup>-1</sup> after 60 years (Fig. 8), comparable to that obtained by van Wesemael et al. (2019) in temperate zones albeit for soils richer in clays of 2:1 type. The preferential stabilization of SOC by micro-aggregates linked to the presence of Fe and Al oxide is a major asset in the fight against climate change, especially since SOC storage has become a global priority to offset the increase in atmospheric CO<sub>2</sub> concentration.

#### 5.5. Effect of organic amendments

Given the positive evolution of the SOC content, we can conclude that the intensive use of organic amendments in market gardening improves soil quality by maintaining the SOC content above the sustainable production threshold, which varies between 2.5 and 13.7 g C kg<sup>-1</sup> for a clay and fine silt content ranging between 5 and 40% (Feller, 1995). It is also likely to have a positive effect on soil biological quality as several authors established a close relationship between organic carbon content and soil biological activity (Feller, 1995; van Wesemael et al., 2019). However, given the observed increase in C/N ratio with the number of years of cultivation, the impact of the large additions of organic amendments of mixed origins on soil biological activity needs to be verified.

# 6. Conclusion

Through the intensive use of organic amendments, market gardening practices have a positive effect on the dynamics of SOC. Total organic carbon content seems to increase asymptotically with the duration of cultivation, albeit with great variability between fields. One observes a rapid increase in the labile fraction  $> 20 \ \mu m$  in size, which has a potentially positive effect on soil biological fertility. Concurrently, part of this carbon is stabilized by association with clay and fine silt particles. There is also a significant physical stabilization in the microaggregates favored by iron and aluminum components that are both SRO oxides and OMA. In our case study, market gardening transforms soil components, improves SOC preservation, and thus helps mitigate the impact of climate change through organic carbon stabilization.

In our case study, the best predictors of SOC content are the duration of cultivation and (Fe<sub>o</sub> + Al<sub>o</sub>), i.e. the sum of oxalate-extractable (Fe, Al) contents. These two parameters should be considered in SOC stabilization estimation models with similar physicochemical properties. When considering the fractionation of low activity clay soils, sonication should be considered rather than shaking since the latter would result in an underestimation of the C < 20  $\mu$ m fraction, given the importance of microaggregation on SOC stabilization in these soils.

Although carbon stocks were not quantified in the present study, the large carbon storage in the C  $< 20 \,\mu$ m fraction may indicate a strong C sequestration potential in the tropical soils that were investigated.

# **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

# Acknowledgements

This research was funded by the Académie de Recherche et d'Enseignement supérieur (ARES-CCD). The authors would like to thank Idrissa Savadogo (IRSAT), Mamourou Ouattara (INERA), Marco Bravin (UCLouvain), Anne Iserentant (UCLouvain) for technical support. We would like to thank the Féderation des Producteurs et Productrices Agricoles du Burkina Faso (FEPAB) and all the vegetable producers in Kuinima for their availability.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2019.114110.

#### References

- Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control 19, 716–723.
- Anderson, D.W., Paul, E.A., 1984. Organo-mineral complexes and their study by radiocarbon dating. Soil Sci. Soc. Am. J. 48, 298–301.
- Balan, E., Allard, T., Fritsch, E., Sélo, M., Falguères, M., Chabaux, F., Pierret, M.-C., Calas, G., 2005. Formation and evolution of lateritic profiles in the middle Amazon basin: insights from radiation-induced defects in kaolinite. Geochimica and Cosmochimica Acta 69, 2193–2204.
- Baldock, J.A., Skjemstad, J.O., 2000. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Organic Geochemistry, 31, 697–710. Org Geochem. 31, 697–710.
- Balesdent, J., Wagner, G.H., Mariotti, A., 1988. Soi1 organic matter tumover in long term field experiments as revealed by carbon 13C natural abundance. Soil Sci. Soc. Am. J. 52, 118–124.
- Basile-Doelsch, I., Balesdent, J., Rose, J., 2015. Are interactions between organic compounds and nanoscale weathering minerals the key drivers of carbon storage in soils? Environ. Sci. Technol. 49, 3997–3998.
- Blakemore, L.C., Searle, P.L., Daly, B.K., 1981. Methods for Chemical Analysis of Soils. New Zealand Soil Bureau Scientific Report 10A. Department of Scientific and Industrial Research, New Zealand.
- Barthès, B.G., Kouakoua, E., Larré-Larrouy, M.-C., Razafimbelo, T.M., de Luca, E.F., Azontonde, A., Neves, C.S.V.J., de Freitas, P.L., Feller, C.L., 2008. Texture and sesquioxide effects on water-stable aggregates and organic matter in some tropical soils. Geoderma 143, 14–25. https://doi.org/10.1016/j.geoderma.2007.10.003.
- Caner, L., Bourgeon, G., Toutain, F., Herbillon, A.J., 2000. Characteristics of non-allophanic Andisols derived from low-activity clay regoliths in the Nilgiri Hills (Southern India). Eur. J. Soil Sci. 51, 553–563.
- Caner, L., Petit, S., Joussein, E., Fritsch, E., Herbillon, A.J., 2011. Accumulation of organo-metallic complexes in laterites and the formation of Aluandic Andosols in the Nilgiri Hills (southern India): similarities and differences with Umbric Podzols. Eur. J. Soil Sci. 62, 754–764. https://doi.org/10.1111/j.1365-2389.2011.01389.x.
- Chauvel, A., Pedro, G., Tessier, D., 1976. Rôle du fer dans l'organisation des matériaux kaoliniques. Sci. Sol 2, 101–115.
- Chenu, C., Angers, D.A., Barré, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: knowledge gaps and potential

innovations. Soil Tillage Res. 188, 41–52. https://doi.org/10.1016/j.still.2018.04. 011.

- Denef, K., Six, J., Merckx, R., Paustian, K., 2004. Carbon sequestration in micro-aggregates of no-tillage soils with different clay mineralogy. Soil Sci. Soc. Am. J. 68, 1935. https://doi.org/10.2136/sssaj2004.1935.
- Deng, Y., Dixon, J.B., 2002. Soil organic matter and organic-mineral interactions. In: Dixon, J.B., Schulze, D.G. (Eds.), Soil Mineralogy with Environmental Applications. Soil Science Society of America Inc, Madison, Wisconsin, USA, pp. 69–197.
- do Nacimento, N.R., Fritsch, E., Bueno, G.T., Bardy, M., Grimaldi, C., Melfi, A.J., 2008. Podzolization as a deferralitization process: dynamics and chemistry of ground and surface waters in a Acrisol-Podzol sequence of the upper Amazon Basin. Eur. J. Soil Sci. 59, 911–924.
- do Nascimento, N.R., Bueno, G.T., Fritsch, E., Herbillon, A.J., Allard, T., Melfi, A.J., Astolfo, R., Boucher, H., Li, Y., 2004. Podzolization as a deferralitization process: a study of an Acrisol-Podzol sequence derived from Palaeozoic sandstones in the northern upper Amazon Basin. Eur. J. Soil Sci. 55, 523–538. https://doi.org/10. 1111/j.1365-2389.2004.00616.x.
- Eusterhues, K., Neidhardt, J., H\u00e4drich, A., K\u00fcsel, K., Totsche, K.U., 2014. Biodegradation of ferrihydrite-associated organic matter. Biogeochemistry 119, 45–50. https://doi. org/10.1007/s10533-013-9943-0.
- Feller, C., Beare, M., 1997. Science Direct Geoderma physical control of soil organic matter dynamics in the tropics. Geoderma 79, 69–116.
- Feller, C., Orstom, 1995. La matière organique du sol : un indicateur de la fertilité. Application aux zones sahélienne et soudanienne. Agric. développement = ISSN 1249-9951. (1995-12) n°8, p. 35–41.
- Feng, W., Plante, A.F., Six, J., 2013. Improving estimates of maximal organic carbon stabilization by fine soil particles. Biogeochemistry 112, 81–93. https://doi.org/10. 1007/s10533-011-9679-7.
- Fritsch, E., Balan, E., do Nascimento, N.R., Allard, T., Bardy, M., Bueno, G., Derenne, S., Melfi, A.J., Calas, G., et al., 2011. Deciphering the weathering processes using environmental mineralogy and geochemistry: towards a general model of laterite and podzol genesis in the Upper Amazon Basin. Compt. Rendus Geosci. 343, 188–198.
- Fritsch, E., Allard, Th., Benedetti, M.F., Bardy, M., do Nascimento, N.R., Li, Y., Calas, G., 2009. Organic complexation and translocation of ferric iron in podzols of the Negro River watershed. Separation of secondary Fe species from Al species. Geochim. Cosmochim. Acta 73 7, 1813–1825.
- Fritsch, E., Morin, G., Bedidi, A., Bonnin, D., Balan, E., Caquineau, S., Calas, G., 2005. Transformation of haematite and Al-poor goethite to Al-rich goethite and associated yellowing in a ferralitic clay soil profile of the middleAmazon Basin (Manaus, Brazil). Eur. J. Soil Sci. 56, 575–588.
- Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with silt and clay particles. Plant Soil 191, 77–87.
- Huang, P.M., Wang, M.K., Kämpf, N., Schulze, D.G., 2002. Aluminum hydroxides. Soil Mineral. Environ. Appl. 261–289. https://doi.org/10.2136/sssabookser7.c8. SSSA book series.
- IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.
- Jones, A., Breuning-Madsen, H., Brossard, M., Chapelle, J., Dampha, A., Deckers, J., Dewitte, O., Dondeyne, S., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., Zougmore, R., 2015. Atlas des sols d'Afrique. Bureau des publications de l'Union Europeenne, Luxembourg, Commission europeenne, pp. 176.
- Jones, D.L., Edwards, A.C., 1998. Influence of sorption on the biological utilization of two simple carbon substrates. Soil Biol. Biochem. 30, 1895–1902. https://doi.org/10. 1016/S0038-0717(98)00060-1.
- Kaiser, K., Eusterhues, K., Rumpel, C., Guggenberger, G., Kögel-Knabner, I., 2002. Stabilization of organic matter by soil minerals — investigations of density and particle-size fractions from two acid forest soils. J. Plant Nutr. Soil Sci. 165, 451. https://doi.org/10.1002/1522-2624(200208)165:4 < 451::AID-JPLN451 > 3.0. CO;2-B.
- Kaiser, K., Zech, W., 1998. Soil dissolved organic matter sorption as influenced by organic and sesquioxide coatings and sorbed sulfate. Soil Sci. Soc. Am. J. 62 (1), 129–136.
- Kiba, D.I., Zongo, N.A., Lompo, F., Jansa, J., Compaore, E., Sedogo, P.M., Frossard, E., 2012. The diversity of fertilization practices affects soil and crop quality in urban vegetable sites of Burkina Faso. Eur. J. Agron. 38, 12–21. https://doi.org/10.1016/j. eja.2011.11.012.
- Kleber, M., Sollins, P., Sutton, R., 2007. A conceptual model of organomineral interactions in soils: self assembly of organic molecular fragments into zonal structures on mineral surfaces. 2007. Biogeochemistry 85, 9–24.
- Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., van Kessel, C., 2005. The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Sci. Soc. Am. J. 69, 1078. https://doi.org/10.2136/ sssai2004.0215.
- Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. Nature 528, 60–68. https://doi.org/10.1038/nature16069.
- Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil Tillage Res. 70, 1–18.
- Milne, E., Banwart, S.A., Noellemeyer, E., Abson, D.J., Ballabio, C., Bampa, F., Bationo, A., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Black, H., Buschiazzo, D.E., Cai, Z., Cerri, C.E., Cheng, K., Compagnone, C., Conant, R., Coutinho, H.L.C., de Brogniez, D., Balieiro, F. de C., Duffy, C., Feller, C., Fidalgo, E.C.C., da Silva, C.F., Funk, R., Gaudig, G., Gicheru, P.T., Goldhaber, M., Gottschalk, P., Goulet, F., Goverse, T., Grathwohl, P., Joosten, H., Kamoni, P.T., Kihara, J., Krawczynski, R., La Scala, N., Lemanceau, P., Li, L., Li, Z., Lugato, E., Maron, P.-A., Martius, C., Melillo, J., Montanarella, L., Nikolaidis, N., Nziguheba, G., Pan, G., Pascual, U., Paustian, K., Piñeiro, G., Powlson,

D., Quiroga, A., Richter, D., Sigwalt, A., Six, J., Smith, J., Smith, P., Stocking, M., Tanneberger, F., Termansen, M., van Noordwijk, M., van Wesemael, B., Vargas, R., Victoria, R.L., Waswa, B., Werner, D., Wichmann, S., Wichtmann, W., Zhang, X., Zhao, Y., Zheng, Jinwei, Zheng, Jufeng, 2015. Soil carbon, multiple benefits. Environ. Dev. 13, 33–38. https://doi.org/10.1016/j.envdev.2014.11.005.

- 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., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.
- Minasny, B., McBratney, A.B., 2006. A conditioned Latin hypercube method for sampling in the presence of ancillary information. Comput. Geosci. 32, 1378–1388. https:// doi.org/10.1016/j.cageo.2005.12.009.
- Ouattara, B., Serpantié, G., Ouattara, K., Hien, V., Lompo, T., Bilgo, A., 1997. Etats physico-chimiques des sols cultivables en zone cotonnière du Burkina. Effets de l'histoire culturale et du type de milieu. Jachère Maint. la Fertil.
- Ouédraogo, R.A., Kambiré, F.C., Kestemont, M.-P., Bielders, C.L., 2019. Caractériser la diversité des exploitations maraîchères de la région de Bobo-Dioulasso au Burkina Faso pour faciliter leur transition agroécologique. Cah. Agric. 28, 20.
- Pallo, F.J.P., Sawadogo, N., Zombré, N.P., Sedogo, M.P., 2009. Statut de la matière organique des sols de la zone nord- soudanienne au Burkina Faso. Biotechnol. Agron. Soc. Environ. 13, 139–142.
- Pallo, F.J.P., Sawadogo, N., Sawadogo, L., Sedogo, M.P., Assa, A., 2008. Statut de la matière organique des sols dans la zone sud-soudanienne au Burkina Faso. Biotechnol. Agron. Soc. Environ. 12, 29–38.
- Pochet, G., Van der Velde, M., Vanclooster, M., Delvaux, B., 2007. Hydric properties of high charge, halloysitic clay soils from the tropical South Pacific region. Geoderma 138 (1–2), 96–109.
- Poeplau, C., Don, A., 2013. Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. Geoderma 192, 189–201. https://doi.org/ 10.1016/j.geoderma.2012.08.003.
- Poeplau, C., Don, A., Six, J., Kaiser, M., Benbi, D., Chenu, C., Cotrufo, M.F., Derrien, D., Gioacchini, P., Grand, S., Gregorich, E., Griepentrog, M., Gunina, A., Haddix, M., Kuzyakov, Y., Kühnel, A., Macdonald, L.M., Soong, J., Trigalet, S., Vermeire, M.-L., Rovira, P., van Wesemael, B., Wiesmeier, M., Yeasmin, S., Yevdokimov, I., Nieder, R., 2018. Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils – a comprehensive method comparison. Soil Biol. Biochem. 125, 10–26. https://doi.org/10.1016/j.soilbio.2018.06.025.
- Robineau, O., Dugué, P., 2018. A socio-geographical approach to the diversity of urban agriculture in a West African city. Landscape Urban Plann. 170, 48–58. https://doi. org/10.1016/j.landurbplan.2017.09.010.
- Schmidt, M.W.I., Rumpel, C., Kögel-Knabner, I., 1999. Evaluation of an ultrasonic dispersion procedure to isolate primary organomineral complexes from soils. Eur. J. Soil Sci. 50, 87–94. https://doi.org/10.1046/j.1365-2389.1999.00211.x.
- Schneider, M.P.W., Scheel, T., Mikutta, R., van Hees, P., Kaiser, K., Kalbitz, K., 2010. Sorptive stabilization of organic matter by amorphous Al hydroxide. Geochim. Cosmochim. Acta 74, 1606–1619. https://doi.org/10.1016/j.gca.2009.12.017.
- Schofield, R.K., Samson, H.R., 1954. Flocculation of kaolinite due to the attraction of oppositely charged crystal faces. Faraday Discuss. 18, 135–145.
- Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176.
- Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. Glob. Chang. Biol. 22, 1315–1324. https://doi.org/10.1111/gcb.13178.
- Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2008. Soil carbon saturation: evaluation and corroboration by long-term incubations. Soil Biol. Biochem. 40, 1741–1750. https://doi.org/10.1016/j.soilbio.2008.02.014.
- Strobl, C., Boulesteix, A.-L., Zeileis, A., Hothorn, T., 2007. Bias in random forest variable importance measures: illustrations, sources and a solution. BMC Bioinf. 8, 25. https:// doi.org/10.1186/1471-2105-8-25.
- Trigalet, S., Chartin, C., Kruger, I., Carnol, M., Van Oost, K., Wesemael, B., 2017. Soil organic carbon fractionation for improving agricultural soil quality assessment – a case study in Southern Belgium (Wallonia). Biotechnol. Agron. Soc. Environ. 21.
- Trigalet, S., Gabarrón-Galeote, M.A., Van Oost, K., van Wesemael, B., 2016. Changes in soil organic carbon pools along a chronosequence of land abandonment in southern Spain. Geoderma 268, 14–21. https://doi.org/10.1016/j.geoderma.2016.01.014.
- Trigalet, S., Van Oost, K., Roisin, C., van Wesemael, B., 2014. Carbon associated with clay and fine silt as an indicator for SOC decadal evolution under different residue management practices. Agric. Ecosyst. Environ. 196, 1–9. https://doi.org/10.1016/j. agee.2014.06.011.
- Milogo, H., 2019. Contribution de la géomatique a la gestion des sols du périmètre maraîcher de Kuinima. Mémoire de master professionnel en système d'information géographique. Universite ouaga I Professeur Joseph Ki-Zerbo (Burkina Faso). 90p.
- Uehara, G., Gillman, G., 1981. The mineralogy, chemistry, and physics of tropical soils with variable charge clays. West view tropical agriculture series, 170p. Boulder, Colorado.
- Van De Vreken, P., Gobin, A., Baken, S., Van Holm, L., Verhasselt, A., Smolders, E., Merckx, R., 2016. Crop residue management and oxalate-extractable iron and aluminium explain long-term soil organic carbon sequestration and dynamics. Eur. J. Soil Sci. 67, 332–340. https://doi.org/10.1111/ejss.12343.
- Van Ranst, E., Doube, M., Mees, F., Dumon, M., Ye, L., Delvaux, B., 2019a. Andosolization of ferrallitic soils – the properties and classification of soils of the Bambouto Mountains in Western Cameroon revisited. Geoderma 340, 81–93.
- Van Ranst, E., Mees, F., de Graeve, E., Ye, L., Cornelis, J.-T., Delvaux, B., 2019b. Impact of andosolization on pedogenic Fe oxides in ferrallitic soils. Geoderma 347, 244–251.

van Wesemael, B., Chartin, C., Wiesmeier, M., von Lützow, M., Hobley, E., Carnol, M., Krüger, I., Campion, M., Roisin, C., Hennart, S., Kögel-Knabner, I., 2019. An indicator for organic matter dynamics in temperate agricultural soils. Agric. Ecosyst. Environ. 274, 62–75. https://doi.org/10.1016/j.agee.2019.01.005.

von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B., 2007. SOM fractionation methods: relevance to functional pools and to stabilization mechanisms. Soil Biol. Biochem. 39, 2183–2207. https://doi.org/ 10.1016/j.soilbio.2007.03.007.

Wagai, R., Mayer, L.M., 2007. Sorptive stabilization of organic matter in soils by hydrous iron oxides. Geochim. Cosmochim. Acta 71, 25–35. https://doi.org/10.1016/j.gca. 2006.08.047.

- Wilke, B.M., Schwertmann, U., 1977. Gibbsite and halloysite decomposition in strongly acid podzolic soils developed from granitic saprolite of the bayerischer wald. Geoderma 19, 51–61.
- Zabowski, D., Ugolini, F.C., 1992. Seasonality in the mineral stability of a subalpine Spodosol. Soil Sci. 154, 497–504.
- Zimmermann, M., Leifeld, J., Schmidt, M.W.I., Smith, P., Fuhrer, J., 2007. Measured soil organic matter fractions can be related to pools in the RothC model. Eur. J. Soil Sci. 58, 658–667. https://doi.org/10.1111/j.1365-2389.2006.00855.