The Rock-Eval® signature of soil organic carbon in arenosols of the Senegalese groundnut basin. How do agricultural practices matter?

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Oscar Pascal Malou[1,2 *], David Sebag[3,4,5], Patricia Moulin[1,6], Tiphaine Chevallier[7], Yacine Badiane-Ndour[1,8,9] , Abou Thiam[2], Lydie Chapuis-Lardy[1,7]

1 LMI IESOL, ISRA-IRD Bel-Air Center, Dakar, Senegal

2 Institute of Environmental Sciences, Cheikh Anta Diop University, Dakar, Senegal

3 University of Normandy, UNIROUEN, UNICAEN, CNRS, M2C, Rouen, France

4 Institute of Earth Surface Dynamics, Géopolis, University of Lausanne, Lausanne, Switzerland

5 current address, IFPEN, Geosciences Dept, Rueil-Malmaison, France

6 LAMA, Imago, IRD, IRD-ISRA Bel-Air Center, Dakar, Senegal

7 Eco&Sols, University of Montpellier, CIRAD, INRAE, IRD, Institut Agro, Montpellier, France

8 LNRPV, ISRA, ISRA-IRD Bel-Air Center, Dakar, Senegal

9 current address, FAO, regional office, Dakar, Senegal

Corresponding author: Oscar Pascal Malou (oscar-pascal.malou@ird.fr and opmalou@gmail.com), LMI IESOL, Ecological Intensification of Cultivated Soils in West Africa, IRD-ISRA-UCAD Bel-Air Center, B.P. 1386, CP 18524, Dakar – Senegal.

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Abstract

Soil organic carbon (SOC) ensures soil quality and productivity of cultivated systems in the Sahelian region. This study uses Rock-Eval pyrolysis to examine how cultural practices impact the quantity of SOC and quality of SOM in cultivated sandy soils in the Senegal groundnut basin. This cost-effective method provides information on SOC thermal stability, which has been shown to be related qualitatively to biogeochemical stability of SOC. We sampled soils within two villages in agricultural plots representative of local agricultural systems, and in two local preserved areas (tree plantation and shrubby savanna). SOC concentrations ranged from 1.8 to 18.5 $g.kg^{-1}$ soil in the surface layer (0-10 cm) and from 1.5 to 11.3 g.kg^{-1} soil in the 10-30 cm layer. SOC contents of cultivated soils decreased significantly (p-value < 0.0001) according to field amendment, in the following order: addition of organic wastes > addition of manure > millet residues left after harvest > no organic input. We found that the quantity and the quality of SOC are linked, and that both depend on land-use and agricultural practices, especially upon the type of organic inputs. Quantity of SOC and quality of SOM are correlated strongly in the tree plantation (R^2 = 0.98) and in the protected shrubby savanna (R^2 = 0.97). They are also correlated significantly in cultivated soils receiving organic wastes (R^2 = 0.82), manure (R^2 from 0.74 and 0.91), or millet residues (R^2 = 0.91) but not in soils that receive no organic inputs. Indexes based upon Rock-Eval pyrolysis were represented in an I/R diagram that illustrates the level of SOC stabilization. The indexes of the studied soils were plotted against comparable results from literature. Thermal signatures of the Senegalese Arenosols show an inversion of I and the R indexes compared to data from the literature. This result highlights SOC stabilization as a function of soil depth. Indeed, the refractory pool in the studied soils (where refractory pool ranged from 7.7 to 21.3 % in the 0-10 cm layer, and from 12.5 to 24.3 % in the 10-30 cm) was more abundant than in Ferralsols in natural conditions, where refractory pool ranged from 2 to 9%. The soil organic matter in these Arenosols while positively affected by organic inputs, is dominated by more or less labile forms that mineralize quickly: a quality that is excellent for productivity of these agrosystems, but not for mitigation of climate change in the long term.

1. Introduction

Carbon (C) is the key element for the overall flow of both matter and energy in terrestrial ecosystems. It is thus involved directly or indirectly in all ecological functions of soils. Soil organic matter (SOM) constitutes a C stock three times larger than that of the vegetation from which it comes (Schmidt et al., 2011; Scharlemann et al., 2014). This organic reservoir obviously plays an essential role in the proper functioning of ecosystems. Certain agricultural practices that improve soil organic carbon (SOC) contents could contribute to improving the quality of soils, and therefore to the sustainable productivity of agroecosystems (Lal, 2018, 2004), while reducing or even offsetting anthropogenic greenhouse gas emissions (Minasny et al., 2017; Soussana et al., 2017). Thus, although cropping practices are aimed primarily at improving the productivity of agrosystems, they increasingly occupy a place in national plans to combat climate change (Schlesinger and Amundson, 2018). In general, the linkage between agricultural productivity and carbon storage seems well established (Ogle et al., 2005; Howden et al., 2007; Wood et al., 2018; Oldfield et al., 2019). For example, Lal (2006) estimates that in the developing countries, an increase in the stock of SOC (by 1 $MgC.ha^{-1}.yr^{-1}$) may increase the yield of food crops by 24-39 million Mg yr^{-1} while offsetting fossil-fuel emissions by 0.5 Pg C per year. Theoretically, it therefore seems possible to couple food security (Chabbi et al., 2017; Nath et al., 2018) and mitigation of anthropogenic carbon fluxes (Paustian et al., 2016) by identifying and promoting agricultural practices that contribute to SOC storage. Several agriculture practices, especially those based upon the organic inputs (Eden el al., 2017; Maillard et Angers, 2014; Fujisaki et al., 2018a) have been shown to increase SOC (Powlson et al., 2016). In sub Saharan areas, agroforestry parks are also reported to increase SOC (Corbeels et al., 2018).

While the effects of agricultural practices on SOC stocks are quite well documented (Arrouays, 2008; Chenu et al., 2014; Paustian et al., 2016), the same is not true for the effects of those practices upon the forms in which SOC is stored (Fujisaki et al., 2018ab;

Singh et al., 2018). By analysing the distribution of C among the particle-size fractions of different soils, Fujisaki et al. (2018b) found that the SOC content in the coarse fraction (> 50 μm) of sandy soils was higher than in other soil types (specifically, Cambisols, Acrisols, Luvisols, Lixisols, Ferralsols, Nitisols, and Andosols). This fraction, which includes particulate organic matter, contained on average 41.3 ± 15.4% of SOC regardless of soil texture. Wood et al. (2016) showed that crop yields were positively related to fast-cycling, particulate organic matter but negatively linked to slower-cycling, mineral-associated organic matter, thus questioning the view that stabilization of organic matter improves food security. A key issue regarding the linkage between food security and carbon storage concerns the biogeochemical stability of SOM: C sequestration involves increasing the stocks of SOC preferentially in pools with slow turnover, while improvement of agricultural productivity requires that SOC be in quickly mineralizable organic forms that can release nutrients that are essential for plant growth (Janzen, 2006). The labile forms are particularly important in sandy soils, which by nature have a limited capacity for SOC storage (Yost and Hartemink, 2019).

Meeting these two challenges (productivity and mitigation) simultaneously requires documentation of both the quantity and the quality of SOC so that the practices leading to the best possible trade-off may be identified. It is from this perspective that we focus on the agro-sylvo-pastoral systems of West Africa. In this region, the integration of agriculture and livestock plays an important role in agricultural productivity and soil fertility. Indeed, the sustainability of agriculture in this area is based upon a strong complementarity between agriculture and livestock—specifically millet and cattle (Lericollais, 1999). Livestock practices (overnight parking, cattle fattening, range pasturing, etc.) impact agricultural practices, particularly organic manuring, that are essential to supporting the fertility of these low-OM-content soils (Ganry and Badiane, 1998; Guérin and Roose, 2017; Harris, 2002; Tschakert, 2004). Manlay et al. (2004) estimate that in these agro-sylvo pastoral systems, animal-husbandry practices contribute up to 80% of the carbon, nitrogen, and phosphorus inputs. Night parking of ruminant livestock is one of the main sources of OM, in the form of animal faeces and urine (De Rouw, 1999; Grillot, 2018). Cattle fattening is another local practice that generates OM for improving soil fertility (Grillot, 2018). The OM from animal husbandry and other practices is not applied homogeneously in these agro-sylvo-pastoral systems; instead, the landscape is organized in halos around villages (Manlay et al., 2004; Ramisch, 2005). A compound ring of fields adjoining the houses receives regular inputs derived from organic resources (manure or household wastes), while a bush ring of distant fields generally receives smaller amounts of exogenous organic inputs. Usually, the only organic inputs to that ring are crop residues left on the soil surface.

The Rock-Eval pyrolysis, developed by IFPEN for petroleum industry (Espitalie et al., 1986; Lafargue et al., 1998), is a simple, fast, cost-effective method for obtaining information on the carbon content, composition, and thermal stability of OM. In the context of soil science, it is recommended for quantitative and qualitative characterization of SOM (Derenne and Quenea, 2015; Disnar et al., 2003; Feller et al., 2010). The literature has shown that the thermal status of SOM during Rock-Eval pyrolysis provides an overall approximation of its biogeochemical stability (Barré et al., 2016; Fernández et al., 2011; Gregorich et al., 2015; Plante et al., 2011).

This study aims at identifying how agricultural practices influence SOC quantitatively and qualitatively in Sahelian agroecosystems. Management practices that increase C inputs in soil may be relevant for meeting food security and climate change challenges. However, the balance for OM decomposition that would provide soil nutrients and OM stabilization that would increase long-term carbon storage depends on the stability of the carbon fraction where the C is stored. We anticipated that SOC would be increased after organic inputs on farmers' field. More interestingly, we also expected that organic inputs would be an important control on SOM thermal status in these systems. We hypothesized that SOC is dominated by thermally labile forms in link with the sandy nature of the soils. Then we expected that the carbon stored in the sandy soils of these agro-ecosystems responds more to productivity needs than to the challenge of climate-change mitigation.

2. Material

2.1. Study area

The study area is in the Senegal groundnut basin, which is the country's main growing region. In this agricultural landscape, woody vegetation is dominated by *Faidherbia albida* distributed in parkland. The geological substratum consists of tertiary sandstones. The soils that developed upon this substratum have incorporated materials from aeolian deposits. They are classified as Arenosols (IUSS Working Group WRB, 2015), and are mostly low in clay (less than 5%, mainly kaolinite). Fertility is low due to low buffering and ion-exchange capacity. The climate is Sudano-Sahelian (average annual temperature: 30 ° C; average annual rainfall: 530 mm), marked by a very strong seasonal contrast. The short rainy season (from July to October) is suitable for crops. Soils are not exploited during the long dry season.

As our study area, we selected two villages (Diohine Sassem: 14°29'51''N and 16°30'36''W; Sob: 14°29'16''N and 16°26'3''W) in the Niakhar Population-Environment-Health Observatory. Lands around the villages are organized in halos. Plots in the house-fields (i.e., those closest to the concession) receive larger amounts of inputs than the distant plots, which are referred to as the out-fields (Ramisch, 2005). Specifically, house-fields in our study area received between 5 and 8 Mg ha^{-1} yr^{-1} (dry weight) of organic inputs, vs. ≤ 1 Mg ha^{-1} yr^{-1} for the out-fields (Tounkara et al., 2020). However, the quantity and quality of organic inputs vary even among the plots within a given ring.

2.2 Selection of the cultivated situations

Agricultural plots were mapped in the area by previous research projects. Together, the sets of soil samples from each field constitute a pedological library of *ca.* 1800 fields, from which we selected those of interest according to several criteria (Table 1). The first criterion is the type of organic inputs received by the agricultural plots in the previous year: (1) millet residues left at soil surface after harvest (denoted "+Millet residues"; n = 10 out-fields; Table 1), (2) manure, consisting of uneaten plant residues plus ruminant faeces and urine (denoted "+Manure"; n = 20 house-fields + 20 out-fields; Table 1), and (3) organic residual products consisting of crop residues, organic wastes from the households, and ashes ("+Organic wastes"; n = 10 house-fields). In this study, the term "exogenous inputs" refers to situations in which organic products were applied by farmers as manure or organic wastes. We also included "No-input" situations (n = 20 house-fields + 40 out-fields), which were cultivated plots that received either no organic amendments during the previous year, or only the annual fallow. The latter case was included because farmers practice a biennial crop rotation—especially in the territory of Diohine Sassem.

The soil samples analysed in this study were collected during either the cropping cycle (corresponding to the rainy season) or the non-cropping period (dry season). Samples of topsoil were taken from a 1-m square at the centroid of each plot. Two layers were sampled: 0-10 cm and 10-30 cm. Both layers have, potentially, been impacted by agricultural activities (FAO, 2003). In addition, the 30-cm depth is the minimum recommended for studying carbon storage in soils (IPCC, 2006). For each layer in each plot, a composite sample was prepared by mixing five separate samples: one from the square's centre, plus one from each of the corners.

2.3 Local unexploited situations

As reference samples of local soils in the study area, we sampled unexploited soils from two "preserved" situations that had gone decades without anthropogenic impacts: (i) a savanna area protected against human activities and cattle for more than 30 years in Mbadane (the neighbouring village of Diohine Sassem, 14°29'23''N and 16°35'36''W), with the shrub *Guiera senegalensis as* the main species; and (ii) a tree plantation established in 1976, and not exploited since (Bandia, 14°34′19′′N and 17°00′54′′W). Because the profiles of the unexploited soils are a valuable local reference for characteristics of preserved soils, we sampled them at five depth intervals (0-10, 10-20, 20-30, 30-40, and 40–50 cm) rather than (as in the case of cultivated soils) only two.

For each depth interval in each plot, we took samples from the corners and centre of a 1-m square at the plot's centroid, then blended them to make a composite sample. Therefore, the resulting dataset included a total of 10 composite samples.

2.3. External reference dataset

As a basis for comparing the studied Arenosols to other situations, we used data published by Sebag et al. (2016) on Ferralsols (≤0-15 cm deep) from profiles of soils in Gabonese forests and savannahs that had not been disturbed by human activities. The Rock-Eval signatures of the selected 87 samples, corresponding to organic layers (OL, OF, OH and Op, n= 25) and organo-mineral layers (A, Ah; n = 62), are representative of the diverse undisturbed situations reported in Sebag et al.'s (2016) worldwide dataset. The signatures of these 87 samples were referred to as the "Humic trend" by Sebag et al. (2016), as described in more details in the following section.

3. Methods

3.1. Rock-Eval pyrolysis

Samples of soil (< 200 µm, mass = 55 to 73 mg) were analysed at the University of Lausanne using a Rock-Eval 6 pyrolyser manufactured by Vinci Technologies. The analytical protocol consisted of two phases: (i) pyrolysis by heating from 200°C to 650°C at 25°C/min in an inert atmosphere (N_2); and (ii) oxidation of residual carbon in an artificial atmosphere (N_2/O_2: 80/20, starting at 400°C and ending at 850°C with a heating rate at 20°C/min (Behar et al., 2001; Lafargue et al., 1998). Gases released were monitored by a flame ionisation detector (FID) for hydrocarbon compounds (HC), and by infrared detectors (IR) for CO and CO_2. Total Organic Carbon (TOC in wt%) and Mineral Carbon (MINC in wt%) were calculated by integrating the amounts of HC, CO, and CO_2 produced during thermal cracking of OM between defined temperature limits (Behar et al., 2001; Lafargue et al., 1998). Because carbonates are not present in our Arenosols, the SOC values found via Rock-Eval measurements are equal to the sum TOC

+ MINC. Those values were strongly and positively correlated (R^2 = 0.99) to the TOC contents that were measured with a CHN analyser (Supplementary material S1).

In this study, thermal status of SOM was characterized by combining two indexes (denoted R and I) calculated from five subdivided areas of the S2 thermograms related to HC (Disnar et al., 2003; Sebag et al., 2006; 2016). Areas were calculated between the following bounds (or nodes): 200-340°C for A1, 340-400°C for A2, 400-460°C for A3, 460-520°C for A4, and 520-650°C for A5. The forms of S2 thermograms depend upon the OM cracking temperature, as expressed through five pools corresponding to the sections of the thermograms: highly labile (A1), labile (A2), resistant (A3), refractory (A4) and highly refractory (A5) (Disnar et al., 2003; Sebag et al., 2016, 2006).

By construction, the R-index (R = [A3+A4+A5]/100) relates to the most thermally resistant and refractory pools of organic matter, while the I-index ($I=\log_{10}[(A1+A2)/A3]$) is related to the most thermally labile pools (details in Sebag et al., 2016). As derived from a mathematical construct, these two indexes may be heavily inversely correlated to each other when OM stabilization results from progressive decomposition of organic components according to their biogeochemical stability (Lehmann and Kleber, 2015). Then, a decrease in labile (A1 and A2) pools result in a concomitant increase in more thermally stable pools (A3 to A5), as observed in compost samples by Albrecht et al. (2015). In other words, the stable pools increase at the expense of the labile pools during the decomposition of OM. Thus, SOM thermal stabilization can be followed on a I-index vs R-index diagram (called thereafter I/R diagram) along a strong linear relationship, described as "Humic trend" in Sebag et al. (2016), as a continuum of decomposing organic materials in soil profile from biological tissues to a mixture of organic constituents derived from SOM humification (Lehmann and Kleber, 2015). Therefore, the "Humic trend" reflects the linear relationship between decaying processes of labile organic pools and OM stabilization in undisturbed (non-agricultural or non-human impacted) soils. However, situations with OM mixture from different sources or where decomposition is so intense that it even affects the more thermally stable pools

(A3 to A5) may generate a distribution in the I/R diagram aside the “Humic trend”, i.e. a poorly related I-R indexes. Such situations were observed for instance in Fluviosol (Sebag et al, 2016), in Arenosol (Romanens et al., 2019; Sebag et al., 2016), in the B horizons of alpine soils derived from calcareous lithologies containing inherited (or « petrogenic ») OM (Matteodo et al., 2018), and in artificial substrates mixing minerals and fresh plant tissues (Schomburg et al., 2019, 2018). In this work, we use the "Humic trend" as a reference model and we focused on Delta-R (ΔR) calculated as the distance (or residual) from the “Humic trend” line (ΔR = Rmeasured - Rmodel).

The synthesis conducted by Sebag et al. (2016) on a worldwide panel of soils representative of contrasting situations shows a continuous evolution of these thermal parameters in the main horizons of soil: decrease of labile pools (A1 and A2) and I-index, and increase of stable pools (A3, A4 and A5) and R-index. Nevertheless, as pointed out by Sebag et al. (2016), *“in order to avoid any misinterpretation, it is necessary to emphasize that […] this approach based on the new Rock-Eval I- and R-indices does neither identify nor quantify the elementary chemical compounds because four basic components (A1 to A4) cannot accurately describe the diversity of biological compounds and their soil derivatives”*. However, a few studies make it possible to relate the thermal status to the chemical composition (Barré et al., 2016; Carrie et al., 2012; Soucémarianadin et al., 2018). Albrecht et al. (2015) show, for example, that Alkyl C is significantly and positively correlated with the most labile pool (A1), O-alky C and alkyl C are together significantly and positively correlated with labile pools (A1 and A2), phenolic C is significantly and positively correlated with thermally stable pools (A3, A4 and A5), and aromatic C significantly and positively correlates with the most refractory pools (A4 and A5). Similar results are also obtained using the same methodology (^{13}C MNR spectroscopy) in a new recent publication (Le Mer et al., 2020). With another approach, Sanderman and Grandy (2020) recently indicated that the thermal fractions are, except for the most stable fraction, heterogeneous mixtures of fast- and slow- cycling SOM. Moreover detailed composition of different thermal fractions analyzed using stepped pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS) show a reproducible shift in the chemistry of pyrolysis products across the temperature gradient (between 330 to 735°C) trending from mainly polysaccharides and lipids at low temperature to lignin- and biological-derived compounds at middle temperatures and dominant phenol, aromatic and unknown compounds at the highest temperatures (Sanderman and Grandy, 2020).

3.2. Statistical analyses

We used R software (R Development Core Team, 2013) for all statistical analyses. Analyses of variance (ANOVA) employed the Tukey test (HSD) at probability level p = 0.05. Linear, logarithmic, and power-law regressions used the ggplot2 package's *lm* function. Student's t-tests were carried out to determine the significance of the regressions. To display the distributions of data, we constructed box plots that show the minimums, the first quartiles, the median values, the third quartiles, and the maximum values, as well as the outliers when appropriate.

4. Results

4.1. Soil organic carbon content

SOC contents of Arenosols in preserved situations decreased gradually with depth (Figure 1a). The average SOC in those soils was 4.5 $g.kg^{-1}$ soil in the 0-10 cm layer, versus 2.1 $g.kg^{-1}$ in the 40-50 cm layer.

SOC contents in cultivated plots differed significantly, at both sampled depths, from those in "preserved" soils (p-value < 0.0001 for the 0-10 cm depth; p-value = 0.03 for the 10-30 cm depth). The magnitude of the difference depended upon the soil amendments. SOC contents were highest in situations where organic wastes were applied (Figure 1b). SOC contents in situations without exogenous organic inputs (No input; n = 60; Figure 1b) were significantly higher at the surface than at depth (p = 0.01). In situations with millet residues left on field (+Millet residues; n = 10; Figure 1b), the SOC content measured at the surface was not significantly different (p = 0.05) from the content at depth. In cultivated situations with manure inputs (+Manure; n = 40; Figure 1b), SOC was significantly higher in the upper soil layer than below (p = 0.002). In cultivated situations with organic-waste inputs (+Organic wastes; n = 10; Figure 1b), SOC was also significantly higher at the surface than at depth (p-value = 0.01).

The location of the fields also seemed to impact SOC contents. House-fields had significantly higher SOC contents than out-fields (p-value < 0.0001). The SOC in fields that received manure was significantly higher in house-fields than in out-fields (p-value = 0.02; Supplementary material 2a). In the plots that did not receive exogenous organic inputs, SOC was significantly higher in house-fields than in out-fields (p-value < 0.03; Supplementary material 2b). In contrast, the season (i.e. rainy or dry) does not seem to affect SOC contents significantly at any depth (p-value = 0.64; Supplementary material 2c).

4.2. Measurement of thermal stability by the Rock-Eval pyrolysis method

4.2.1. R-index

For the studied Senegalese Arenosols, average R-index values were between 0.4 and 0.6 at all depths and in all situations. The average R value was 0.5 ± 0.003 (Figure 2). In Arenosols of preserved situations, the R-index decreased with depth (Figure 2a). In 0-10 cm layer, the average R-index was 0.54, versus 0.5 in the 40-50 cm layer. In the surface layers (0-10 cm) of cultivated situations, the R-index did not differ significantly upon the soil amendments (p-value = 0.09). However, the R-index differed significantly according to soil amendments in the 10-30 cm layer (p-value < 0.01).

In situations without any exogenous organic input, the R-index was significantly higher at the surface than at depth (p-value < 0.02). This trend (surface R-index > R-index at depth) was also observed in situations with millet residue left in the field (p-value < 0.03) and in situations where organic wastes were applied (p-value < 0.002). In contrast, in situations with manure the R-index was not significantly different in the 0-10 cm layer than in the 10-30 cm layer (p-value < 0.09). It should also be noted that in the 0-10 cm depth, the R-index in preserved situations was not significantly different from that in the cultivated situations (p-value = 0.6).

4.2.2. I-index

For the studied Senegalese Arenosols, average values of the I-index varied between 0.14 and 0.6 in all depths, with an average value of 0.34 ± 0.01 (Figure 3). In preserved situations, the I-index increased with depth (Figure 3a). The average I-index was 0.3 in the 0-10 cm layer and 0.5 in the 10-30 cm layer.

In cultivated situations, the I-index did not differ significantly upon the soil amendments at any depth (p-value > 0.4). In situations with no exogenous organic inputs, the I-index was significantly lower in the surface layer than in the 10-30 cm layer (p-value < 0.0001). This trend (I-index in surface layer < I-index at depth) was also observed in situations with millet residue left in the field (p-value < 0.01) and in situations with manure (p-value < 0.004). On the other hand, in situations with organic wastes the I-index did not vary significantly with depth (p-value = 0.1). Moreover, the measured I-index in the 0-10 cm depth was not significantly different in preserved situations than in cultivated situations (p-value = 0.9).

4.2.3. R versus I

For all situations, the correlation between R and I indexes of the studied Senegalese Arenosols is strong and linear (Figure 4). However, the slope of the regression line derived from the Senegalese Arenosols was larger (more negative) than that of the "Humic trend" derived from the Ferralsols studied by Sebag et al. (2016). This “Humic trend” is a satisfactory external reference set for our samples because according to the literature, organic compounds (such as composts) and the main soil classes studied thus far by the Rock-Eval pyrolysis fall along or close to the “Humic trend” line (Albrecht et al., 2015; Sebag et al., 2016; Matteodo et al., 2018; Schomburg et al., 2018, 2019).

Signatures of soils from preserved situations and plots that received the "+Millet residues" situation are fairly similar (Figure 4). R-index values for those soils are lower than for other cultivated soils, and their regression-line slopes are larger. Signatures are fairly comparable for cultivated soils amended with manure or with no exogenous organic inputs, although some samples of soil amended with manure fall along the "Humic trend". Signatures of soils that received organic wastes vary with depth: data points for the 0-10 cm layer fall along the "Humic trend", while signatures for samples from the 10-30 cm layer are comparable to those of the surface horizon of Senegalese Arenosols that either received no inputs, or were amended with manure.

4.2.4. S2 thermograms

The average S2 thermograms and associated standard deviations in cultivated situations are shown in Figures 5a (for the 0–10 cm layer) and 5b (for the 10–30 cm layer). The area below each curve corresponds to the total HC amount (with respect to an equivalent sample weight) released during the pyrolysis phase. Those amounts are directly correlated to the amounts of organic carbon ($R^2 = 0.81$; p-value <0.0001).

For each situation, HC contents were significantly larger in surface samples than in deeper layers, in agreement with results obtained for SOC contents (Figure 1). Moreover, S2 thermograms of surface-layer soils are qualitatively different from those from deeper layers (Figure 5ab): S2 thermograms of surface soils tend to be bimodal, but S2 thermograms for deeper soils tend to be unimodal.

S2 thermograms for the 0-10 cm layer of preserved soils (savanna and tree plantation) are fairly comparable to those of cultivated soils that received either millet residues or no exogenous organic inputs. These S2 thermograms are different from those obtained for cultivated situations that received manure or organic-waste amendments. Indeed, the S2 thermograms for situations with exogenous organic inputs (+Manure and +Organic wastes) have a bimodal distribution. The first mode corresponds to a relative enrichment of labile pools, mainly A2. The second mode corresponds mainly to an enrichment of more resistant or refractory pools, primarily A3 and A4.

Shapes of S2 thermograms for soils at lower depths in preserved situations are quite similar to those of cultivated soils that received either no exogenous organic inputs, or only the millet residues left on the field after harvest. The S2 thermograms for these situations are dominated significantly by A2, A3, and A4. In addition, their pool sizes show very little variance. The S2 thermograms obtained from soils at depth in situations with no inputs are unimodal. The peak corresponds to a relative enrichment of the resistant or refractory pools, mainly A3 and A4. In addition, the variability of pool sizes was quite large in S2 thermograms of soils collected at depth in the preserved situations, and in cultivated soils without any exogenous organic inputs. Specifically, the pools for no-input fields were distinct from those where millet residues were left on the soil surface after harvesting the crop.

5. Discussion

5.1. SOC contents

The SOC contents measured in preserved unexploited situations, in situations without any exogenous organic inputs, and in situations with millet residues left on field after harvest are comparable to those reported in the literature for sandy soils. Indeed, the meta-analysis by Yost and Hartemink (2019) has shown that in sandy soils in arid zones, the average levels of SOC are less than 5 $g.kg^{-1}$ soil. Feller (1979) reported SOC values ranging between 3 and 5 $g.kg^{-1}$ soil for sandy soils in Senegal. Bationo and Buerkert (2001) have reported SOC contents ranging between 1 and 8 $g.kg^{-1}$ soil in the Sudano-Sahelian zone of West Africa. Those results confirms that sandy soils are naturally poor in OM (Osman, 2018; McClintock and Diop, 2005). The SOC contents in our situations with millet residues left on fields are comparable to values found in Niger by Bationo and Buerkert (2001) during a long-term experiment (between 1984 and 1996) that applied 4 T of crop residue ha^{-1} along with mineral fertilisers (SOC between 1.7 and 3.3 $g.kg^{-1}$ soil). However, Yost and Hartemink (2019) and Bationo and Buerkert (2001) have both shown that organic inputs increase SOC in sandy soils. The SOC contents in our situations with exogenous organic inputs (+Manure or +Organic wastes) were higher than those measured in other situations; i.e. in preserved sites, or in agricultural systems with either no inputs, or the "+Millet residues" application. These SOC contents were of the same order of magnitude as those measured by Šimanský et al. (2019) during 25 years of experiments on sandy soils with inputs of manure (6.07 $g.kg^{-1}$ soil), or of manure + NPK (8.38 $g.kg^{-1}$ soil).

In preserved soils, the SOC was low despite regular additions of OM through litterfall from trees or shrubs. Arenosols are poor in SOC due to a fairly low primary production (Bationo et al., 2007; Blanchart et al., 2007), and to the sandy texture, which favours decomposition of OM and mineralization of SOC (Feller et al., 1991; Don et al., 2009).

In cultivated soils that received no exogenous organic inputs, or only the millet residues left in the field, SOC contents were fairly comparable on the whole to those for preserved soils. This result corroborates findings of Blanchart et al. (2007). Those authors have shown that in sandy soils, the content of SOC under perennial vegetation is comparable to that of soils in annual cultivation because sandy soils have a very low potential for carbon storage, given the quick decay of plant debris and soil OM. On the other hand, SOC content is significantly higher in situations with manure or organic wastes. This relative enrichment is particularly marked in samples taken from the 0–10 cm layer, because OM inputs constitute the most important lever for increasing SOC levels in tropical soils (Blanchart et al., 2007; Fujisaki et al., 2018a) as well as in temperate soils (Chenu et al., 2014). Numerous studies have shown that manure additions increase the organic carbon content of the soil (Haynes and Naidu, 1998; Li et al., 2018; Liu et al., 2013). Long-term treatment of soils with organic inputs can increase organic carbon contents in the topsoil by +24 to +92% depending on the type of organic amendment (Diacono and Montemurro, 2010). Daouk et al., (2015) showed that organic amendments contribute to increasing SOC significantly in sandy soils north-west of Dakar, particularly in the 0-10 cm layer. Liu et al. (2013) have also shown that improving soils with manure has positive effects on SOC stocks. Li et al. (2018) estimate that the composition of manures rich in recalcitrant organic compounds contributes to high levels of organic carbon in soils treated with manure.

It also appears that SOC contents are affected by differences in management practices and inputs, which are in turn related to the "halo" arrangement of the village landscape: SOC contents are generally higher in house-fields than in out-fields. Because plot productivity relies upon the organic inputs, farmers concentrate organic amendments upon the house-fields in order to maximize agricultural yields near the compounds. This result agrees with findings obtained by Manlay et al. (2004) in Southern Senegal; by Corbeels et al. (2018) in East Africa; by Tittonell et al. (2013) in Kenya and Uganda; and by Zingore et al. (2011) in Zimbabwe. All of these authors reported finding organic-carbon gradients in connection with an unequal allocation of organic resources between the fields closest to the compounds (house-fields) and the most distant (out-fields).

5.2. Thermal stability as an indicator of SOC quality

Calculated R-index values of the Senegalese Arenosol topsoils were significantly lower (p-value < 0.0001) than those of the Gabonese Ferralsols (Sebag et al., 2016) that we used as a reference for general undisturbed situations (Figure 6a). However, Figure 6a shows that the R-index values for Arenosol topsoils with SOC < 5 $g.kg^{-1}$ soil are comparable to those of the Ah horizons of soils in the reference set (with SOC between 15.5 and 57.2 $g.kg^{-1}$ soil). Those values for the two soils are comparable even though the R-index values of the Arenosol topsoils were lower than those of the A horizons in the reference set that had SOC contents between 3 and 73.2 $g.kg^{-1}$ soil.

Similarly, the I-indexes derived from Senegalese Arenosols were similar to those of the reference set's Ah horizons, and significantly higher than those of that set's A horizons (Figure 6b).

In summary, I/R signatures of the Arenosols' surface layers are close to the "Humic trend" (Figure 4) defined by Sebag et al. (2016), but the signatures of the 10-30 cm layer in the Arenosols deviate from this model.

5.3. OM quality as a function of depth

The surface layers of Senegalese Arenosols have higher R-index values and lower I-index values than the deeper layers. These signatures are contrary to those documented in other situations by Sebag et al. (2016) and Matteodo et al. (2018), who found that I-indexes decrease with depth, and that R-indexes increase. This inversion can be understood by examining the S2 thermograms from which we extracted the data (i.e., the contributions of A1 to A5) used to calculate the two indexes.

The bimodal pattern of topsoil S2 thermograms reflects a relative enrichment of the labile (A2) and refractory (A4) C pools, and a corresponding impoverishment of the resistant C pool (A3). S2 thermograms of deeper soils have a unimodal pattern in which the resistant C pool (A3) predominates.

These characteristics provide an explanation for the differences between I/R signatures of the Senegalese Arenosols and those of the A horizons of the reference Gabonese Ferralsols, which are from natural situations but have similar contents of SOC. The A1 contributions are slightly larger in the Arenosols (Supplementary material S3), than in the Ferralsols, but the A3 contributions are significantly smaller (Supplementary material S5). In both soils, the A2 contributions are broadly comparable (Supplementary material S4). Therefore, the I-index ($I=\log_{10}[(A1+A2)/A3]$) in Arenosols is lower at the surface and higher at depth than in the Gabonese Ferralsols.

The inversion of the R-index trend may be explained by differences between the A3, A4, and A5 contributions. The A3 and A4 contributions are slightly smaller in the Arenosols (Supplementary materials S5 and S6), but the A5 contributions is two to three times larger (Figure 7). Therefore, the R-index ($R=[A3+A4+A5]/100$), in the Senegalese Arenosols is higher at the surface than at depth, while the reverse is true in the

Gabonese Ferralsols that were used as references for plotting the I/R diagram (Figure 4). The higher values of A5 in our study, compared to those reported by Sebag et al., (2016), reveal an extreme decomposition of OM in the sandy Arenosols: residual carbon generated by mineralization of C in pools A1 to A4 accumulates in the most-refractory pool (A5).

5.4. Quality of the OM according to the situations

Analyses of the S2 thermograms highlight how the different situations affect the quality of OM.

The forms of the S2 thermograms of soils from preserved situations indicate small labile C pools, but larger pools of resistant and refractory C. The small size of labile C pools can be explained by high decomposition of OM in sandy soils (Feller et al., 1991). In the studied region, the combination of a long dry season and year-long high temperatures favours mineralization of labile C pools that are not physically protected (Badiane et al., 2000; Bationo et al., 2007). Therefore, both the resistant pool (A3) and the refractory (A4) pools increase, and become dominant over the more labile A1 and A2 pools. Albrecht et al. (2015), who considered composts an excellent material for studying the evolution of organic products, observed that Rock-Eval signatures change during the composting process: the A1 labile pool decreased from 32 to 23% between the 4th day and the 128th day of composting, while the A2 labile pool decreased from 33 to 26% during the same period. The more stable pool (A3 + A4 + A5) increased correspondingly. Our results are comparable: the resistant pool (A3) and the refractory pool (A4) decreased, leading to a relative increase in the most-refractory pool (A5).

S2 thermograms of soils in cultivated situations that received no exogenous organic inputs are similar to those that received only some millet residues: the labile pools in both are larger than those of soils in preserved situations. This labile C pool favours the growth of crops that produce more biomass (fine roots and future litter) capable of enriching soils with fast-cycling carbon (Balesdent et al., 2013). In contrast, vegetation in soils of preserved areas consists of woody species with larger roots. Balesdent et al. (2013) have shown, for example, that the carbon transferred by roots of wheat plants consists largely of sugars which decay very quickly, thereby contributing to increasing the labile C pools. The increase of that pool is also favoured by tillage and coarse soils, both of which increase soil aeration, and thereby provide aerobic conditions that speed the decay of organic compounds.

Compared to other cultivated situations, those that received organic wastes or manure had larger labile, resistant, and refractory pools. The literature reports that manure applications increase slow-cycling C pools while contributing, as well, to growth of labile C pools (Majumder et al., 2008; Liu et al, 2018; Liang et al., 2012). Indeed, the bimodal shape of the S2 thermograms for situations that received organic wastes or manure shows that the thermal C pools were not increased equally. Organic inputs increased the size of the most labile C pools (A1 and A2, grouped in the first peak of the thermograms), which mineralize very quickly because they are more sensitive to land management (Bongiorno et al., 2019; Awale et al., 2017) and to activity of soil microorganisms (Pansu, 1991; von Lützow et al., 2007). The greater variability of the labile pool size in soils receiving manure or organic wastes could be explained by differences in the quantity and the frequencies of inputs, the methods of application and the quality of the amendments (Bhogal et al., 2018), which all differ among households. In contrast, the size of more refractory C pool can be explained by Dragon and Icard (2010)’s finding that OM which has not decomposed became more complex and stabilized. The burning of some components collected from households generates ashes, the presence of which in household wastes (which are applied mainly to house-fields) could explain the size of the refractory C pool. Lutfalla et al. (2017) reported that combustion of organic products has such an effect on refractory-C pools in temperate soils. Sandermann and Grandy (2019) also reported that stable aromatics and phenols that may compose the most thermal refractory pool can be attributed to the fire events.

In summary, results from the Rock-Eval pyrolysis highlighted the presence of (i) a significant refractory C pool that is quite comparable in size for all situations in the studied agrosystem, and (ii) the dominance of a thermally labile C pool that does vary among situations. Specifically, the size of that pool increases as follows: preserved < No-input < +Millet residues < +Manure < +Organic wastes. Le Mer et al. (2020) recently showed that OM stabilization through the formation of aggregates and/or organo-mineral associations resulted in an increase of the most stable pools. However, as the Arenosols are poor in clay, it can be assumed that beside A1 and A2 pools the A3 and even A4 pools could also be mineralized because they were not protected from degradation by organo-mineral complexation, or by formation of aggregates (as a consequence of dominance of quartz particles in sandy soils; Lehmann and Kleber, 2015; Osman, 2018). The lack of OM protection, associated with a low SOC content, suggest an easy access to, and a rapid turnover of SOC in Arenosols. This extreme mineralization impedes renewal of the A3 and A4 pools, thereby leading to a relative accumulation of organic C in the most-refractory pool (A5), but this slow-cycling C pool is also limited in size by the sandy nature of soils nonetheless (Yost and Hartemink, 2019). This mineralization of relatively stable C pool (i.e. A3 and A4) would also explain the particular signature of the studied soils in the I/R diagram (i.e. above the "Humic trend"): the decrease in the relative contributions of A3 and A4 is counterbalanced by the corresponding increase of A5 in the calculation of the R-index (R= [A3+A4+A5]/100), but the decrease in A3 results in a relative increase in the I-index ($I=\log_{10}[(A1+A2)/A3]$) compared to soils with an equivalent R-index. This hypothesis appears to be consistent with the results recently published by Sanderman & Grandy (2020) which confirm that the most abundant compounds at middle pyrolysis temperatures (between 400 and 500°C) are still mineralizable, especially those corresponding to A3 which are still rich in polysaccharides. It would then be logical to generalize this hypothesis to all sandy soils, which is consistent with previous results showing that other Arenosols (in Niger, North Cameroon and Bolivia; in Fig. 3D from Sebag et al., 2016) or sandy soils (Botswana, in fig. 4 from Romanens et al, 2019) have a specific signature above the "Humic trend".

Some researchers have argued strongly that the long-term build-up of SOM will have co-benefits for both food security and climate change mitigation (Lal, 2004). Arenosols have low SOC that mainly relied on the thermal labile C pools which are affected by short-term organic inputs, confirming reports from literature on low biogeochemical stability of SOM in sandy soils (e.g., Fujisaki et al, 2018; Yost and Hartmink, 2019). Previous studies reported the relationship between the thermally labile SOC pool obtained from Rock-Eval pyrolysis and C derived from a SOM fractionation scheme isolating particulate organic matter (POM; Saenger et al., 2015; Soucémarianadin et al., 2018). POM represents a fast-cycling SOC pool with a residence time of ca. a couple decades that is meaningful regarding SOC stock changes. However, fast SOM decomposition in the studied Arenosols seems to also affect SOC pools that would be considered as more thermally stable in other environments. Then, organic annual inputs would therefore be necessary to keep SOM at an adequate level for soil fertility, to ensure stability of yields and contribute to food security. But, especially within the context of high competition for organic resources in sub-Saharan Africa, these organic inputs could be insufficient to replenish mineralized labile C at a level that would allow on the long term accumulation of SOC in soils serving SOC sequestration and climate change mitigation purpose.

5.5. SOC quantity versus SOM quality depending upon the situations

As described in Section 3.1, the value of Delta-R (ΔR) for each soil sample was calculated as the deviation of that sample's R-index from the reference model obtained for Gabonese Ferralsols, which we considered representative of general undisturbed situations (Sebag et al., 2016). By construction, positive Delta-R values reflect an excess of more thermally stable C pools (A3+A4+A5) compared to soils in the reference set. Interpretation of the ΔR values is aided by a study of the relative sizes of the resistant, refractory, and highly refractory pools (A3, A4, and A5 respectively) involved in the calculation of the R-index. Linear regressions between ΔR and each of these pools (Table 2) reveal that the A5 pool is strongly and positively correlated to ΔR (R^2 = 0.92; p-value

< 0.0001). On the other hand, ΔR is strongly and negatively correlated with A3 (R^2 = 0.88; p-value < 0.0001) and more weakly with A4 (R^2 = 0.46; p-value < 0.0001).

Moreover, ΔR is linearly and strongly correlated with SOC content in the two preserved situations (R^2 = 0.96 in both the tree plantation and the protected savanna area; Figure 8a). At these two sites, the ΔR value is low at the surface and higher at depth (Figure 8a). The surface layers in these unexploited soils are enriched in carbon by biological contributions from woody vegetation. The strong linear correlation between SOC and ΔR, together with an increase in the refractory C pool and the gradual decrease in SOC, suggest that the labile biological contribution in these soils is being diluted by stabilized refractory SOC from surface to depth.

In the No-input situations, the correlations between SOC and ΔR are generally weak with coefficients of determination ranging from 0.15 to 0.54 and not significant (Figure 8bcd). The absence of relationship between the two terms means that in the absence of significant biological contributions, SOC levels are generally low, and the processes of OM decomposition and SOC mineralization that can be variable in time and space lead to the quality of OM being independent of the quantity of SOC.

In situations with organic inputs (+Millet residues, +Manure and +Organic wastes) the deterministic (logarithmic-type) and significant relationships between SOC content and ΔR (R^2 ranging from 0.74 to 0.91; p < 0.001) would suggest that organic inputs and their stability constitute in cultivated Arenosols a key factor, linking quality of SOM and quantity of SOC (Figure 8efg). Indeed, as previously discussed the thermal A3 pool in these soils may be subjected to relatively fast decomposing processes so that a decrease in its relative contribution benefits to the A5 pool into the calculation of the R-index (R= [A3+A4+A5]/100), affecting in turn the deviation of that R-index from the "Humic trend". In the reference model obtained from Ferralsols, the A3 pool is considered as a thermally resistant C pool being relatively protected from degradation by association with minerals (Sebag et al., 2016). In addition, the logarithmic type of the relationship between SOC content and ΔR in cultivated situations compared to the linear one in preserved situations suggests that these anthropogenic inputs are more efficient in terms of C storage in soils than natural inputs since, for equivalent quality, the lower ΔR, the higher SOC contents. This result is in agreement with studies which have shown that in tropical sandy soils, the organic inputs, especially those exogenous, are essential for their fertility and influences the forms of SOC, especially the fast-cycling ones (Feller and Beare, 1997; Fujisaki et al., 2018a).

5.6. Limitations of the study

SOC contents are known to be affected by soil management, and may change quickly due to high decomposition of SOM and mineralization of SOC. The sample set used in the study was derived from an existing soil collection that didn't allow us to investigate the possibility that decomposition and mineralization processes vary seasonally. Although most of the management practices employed in the region's cultivated systems are consistent over the years, only the management used on each plot during the previous year was used as a criterion for sorting soil samples into categories. Moreover, amounts of organic inputs applied on soil were not recorded. Additionally, the dominance of the labile C pools in surface layers of cultivated soils that received manure or organic wastes may reflect a phenomenon known as 'priming', in which these inputs cause changes to the dynamics of SOC. Either a more-oriented sampling or an experiment design with controlled applications of organic products would address current limitations, and improve the understanding of the link between SOC quantity and SOM quality in these Arenosols.

6. Conclusion

Rock-Eval signatures of these sandy soils reveal an inversion of I and R indexes compared to those reported in the literature for other classes of soils and then a specific I/R signature for Arenosols. In cultivated soils of the Senegal groundnut basin, SOC storage is highly dependent upon the type of farming practices. Cultivation practices based upon the organic amendments like manure or organic wastes influence the quantity of SOC and quality of SOM, which are closely linked. Indeed, this study made it possible to show that the nature of organic inputs, which affects the forms in which SOC will be stored, is an important driver in conditioning SOM thermal stability. In these Arenosols of Sahelian agrosystems, the thermally highly-refractory pool that is probably generated by high SOM decomposition and SOC mineralization is relatively more important in these soils than in Ferralsols but not affected by agricultural practices. Thus SOC variations in Arenosols are governed by organic inputs that generates thermally labile OM forms which would decompose quickly, supplying nutrients to the crops. In other words, the SOM in these agrosystems contributes to soil fertility, and thus responds more to the needs of agricultural production than to climate change mitigation, which requires long-term C storage. Even if Arenosols cannot store large amounts of C and thus cannot contribute significantly to climate change mitigation, regular applications of exogenous organic matter in these cultivated systems is essential for improving productivity and for adaptation to climate change. Enhancing food production is still the major goal in many tropical countries, especially in sub-arid Western Africa but competition for organic resources is high in local agro-pastoral systems and organic inputs may not be available enough to farm smallholders.

The findings from this study add to the growing body of literature using Rock-Eval pyrolysis as a tool to understand the thermal status of SOM when managing agricultural systems but still need clarification on the mechanisms behind and real impact on crop yields. Future work should rely on *in-situ* experimental design testing amounts and type of organic inputs in cropping systems and push forward with studies connecting thermal approach to SOM cycling concept to avoid misinterpretations on the biogeochemical stability, especially in the particulate context of Arenosols.

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Tables

Table 1. Selection criteria for the 120 plots chosen among the *ca* 1,800 cultivated situations composing the agricultural mapping of the area.

Selected situations	**N**	**Place of collection**		**Land-use**		**Time of collection**	
		House-fields (n)	Out-fields (n)	Annual Fallow	Under cultivation	Cropping season	Off-crop cycle
No input	60	+ (20)	+ (40)	+	+	+	+
+Millet residues	10	-	+ (10)	n.a.	+	+	-
+Manure	40	+ (20)	+ (20)	n.a.	+	+	+
+Organic wastes	10	+ (10)	n.a.	n.a.	+	-	+

The plus (+) sign means that the situation was collected in the existing sample set and selected in the studied set as representative of the agriculture systems; The minus (-) sign means that the situation was considered uncommon, and wasn't collected in the existing sample set; n.a., non-applicable, refers to situations that do not exist in the agricultural systems of the studied area.

Table 2. Correlation matrix between Delta-R and the resistant pool (A3%), the refractory pool (A4%), and the highly refractory pool (A5%) in all situations studied.

	Delta-R vs.		
	Resistant pool (A3 %)	Refractory pool (A4 %)	Refractory pool (A5%)
Equation	y = - 0.009 * x + 0.28	y = - 0.012 * x + 0.26	y = 0.0093 * x + 0.08
R^2 value	0.88	0.49	0.92
p-value[a]	***	***	***

[a] ***** indicates that the difference was significant at *p* < 0.001**

Figure captions

Figure 1. Soil organic carbon (SOC) contents (a) along the soil profile in the unexploited situations (tree plantation and preserved shrubby savanna), (b) at 0-10 and 10-30 cm depths in the different agricultural situations. Lines corresponded to average values, by depth, of all situations being considered.

Figure 2. R-index in (a) preserved situations according to soil depth, and (b) agricultural systems according to amendment application and soil depth.

Figure 3. I-indexes in (a) preserved situations according to soil depth, and (b) agricultural systems according to amendment application and soil depth.

Figure 4. R vs I indexes derived from the Rock-Eval pyrolysis performed on the Senegalese Arenosols (the present study), and compared to the model derived from Gabonese Ferralsols used as an external reference (Sebag et al., 2016).

Figure 5. S2 thermograms obtained by Rock-Eval pyrolysis of (a) the surface layer, and (b) the deep layer for the different situations: preserved (grey), no input (black), +millet residues (brown), +manure (deep pink), and +organic wastes (dark green). Note that the vertical-axis scales are not the same for (a) and (b).

Figure 6. R-indexes (a) and I-indexes (b) in the surface layers (0-10 cm) of Senegalese Arenosols (this study) compared to the same indexes in the A or Ah horizons (depth ≤ 15 cm) of Gabonese Ferralsols used as the external reference set (Sebag et al., 2016).

Figure 7. A5 contribution (%) in the surface layers (0-10 cm) of Senegalese Arenosols (this study) compared to the contributions of A5 in the A or Ah horizons (depth ≤ 15 cm) of Gabonese Ferralsols (serving as the external reference set; Sebag et al., 2016).

Figure 8. Correlations between SOC (g.kg^{-1} soil) and Delta-R: (a) for all analysed soil depths in the two preserved situations; (b) for cultivated situations (collected during or outside of the crop cycle) in house-fields that received no organic inputs, at soil depths

0-10 and 10-30 cm; (c) same as (b), but in out-fields; (d) in annual fallows; (e), with manure application in house-fields; (f) with manure application in out-fields; and (g), in out-fields with millet residues or house-fields receiving organic wastes.

Supplementary materials - Figure captions

Supplementary Material S1. Correlation between SOC contents (g.kg^{-1} soil) measured by Rock-Eval pyrolysis and by dry combustion with a CHN analyser.

Supplementary material S2. SOC (g.kg^{-1} soil) in the different situations, according to (a) the field location, (b) the use of the plot, and (c) the season.

Supplementary Material S3. A1 contributions (%) in the S2 thermograms obtained by Rock-Eval pyrolysis of the surface layers (0-10 cm) of Senegalese Arenosols (this study) compared to values in the A or Ah horizons (depth ≤ 15 cm) of Gabonese Ferralsols (serving as the external reference set; Sebag et al., 2016).

Supplementary Material S4. A2 contributions (%) in the S2 thermograms obtained by Rock-Eval pyrolysis of the surface layers (0-10 cm) of Senegalese Arenosols (this study) compared to values in the A or Ah horizons (depth ≤ 15 cm) of Gabonese Ferralsols (serving as the external reference set; Sebag et al., 2016).

Supplementary Material S5. A3 contributions (%) in the S2 thermograms obtained by Rock-Eval pyrolysis of the surface layers (0-10 cm) of Senegalese Arenosols (this study) compared to values in the A or Ah horizons (depth ≤ 15 cm) of Gabonese Ferralsols (serving as the external reference set; Sebag et al., 2016).

Supplementary Material S6. A4 contributions (%) in the S2 thermograms obtained by Rock-Eval pyrolysis of the surface layers (0-10 cm) of Senegalese Arenosols (this study) compared to values in the A or Ah horizons (depth ≤ 15 cm) of Gabonese Ferralsols (serving as the external reference set; Sebag et al., 2016).