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Soil organic carbon stocks in semi-arid West African drylands: implications for climate change adaptation and mitigation

Jérôme Ebagnerin Tondoh[1*], Issa Ouédraogo[2], Jules Bayala[3], Lulseged Tamene[4], Andrew Sila[5], Tor-Gunnar Vågen[5], Antoine Kalinganiré[3]

[1]WASCAL Competence Center, 06 P.O. Box 9507 Ouagadougou 06, Burkina Faso

[2]INERA Kamboinssé, 12 BP 33 Ouagadougou 12, Burkina Faso

[3]ICRAF West and Central Africa. Sahel Node BPE 5118 Bamako, Mali

[4]CIAT, Chitedze Research Station, Michinji Road, Lilongwe Box 158, Malawi

[5]ICRAF (World Agroforestry Centre), United Nation Avenue, Gigiri PO Box 30677, 00100, Nairobi, Kenya

*Corresponding author
Telephone: +226 67433619/63006876
Email: tondoh.e@wascal.org

Abstract

In the West African drylands, SOC sequestration is seen as one of the prominent strategies to both enhance the resilience of agro-ecosystems and mitigate global greenhouse effects. However, there is a dearth of baseline data that impede the design of site-appropriate recommended management practices (RMPs) to improve and sustain SOC accrual. In this study, the Land Degradation Surveillance Framework (LDSF), a nested hierarchical sampling design was used to assess SOC stock and its spatial variability across the semi-arid zones of Ghana (Lambussie), Burkina Faso (Bondigui) and Mali (Finkolo). Soil samples were collected from three sites of 100 km^2 stratified into 16 clusters and 160 plots and thereafter soil parameters were then analyzed using MIR spectroscopy. Regardless of soil strata, SOC storage with 95% confidence level in semi-arid landscapes potentially ranged between 112,200±14,000 and 253,000±34,000 Mg C corresponding to 411,400±51,333 Mg CO_2-eq and 927,666.7±124,666.7 Mg CO_2-eq in the entire study area. On the other hand, investigation on the potential of climate change mitigation through SOC revealed contrasted figures as accumulation rates in cultivated lands ranged from 0.04 to 0.18 Mg C ha^{-1} yr^{-1} and are balanced by higher depletion rates of -0.004 to - 0.73 Mg ha^{-1} yr^{-1}. This indicates the potential of semi-arid soils to store carbon through improved land management practices. Landscape study structured in cluster-level analysis revealed heterogeneity in the distribution of SOC stocks, a mandatory finer level analysis prior to effective decision-making about RMPs.

Keywords: Agro-ecosystems, land use, resilience, site appropriate management, soil organic carbon sequestration, West Africa.

1. Introduction

In drylands, biomass production is constrained by the recurrence of drought and poor soil quality (Lal, 2004a). As a result, the capacity of dryland soils to function and deliver key ecosystem services such as food production, climate and water regulation and nutrient cycling are severely undermined. This situation is even worsened by improper or unsustainable land use and poor management practices leading to further degradation. Once set-in motion, soil degradation brings about an ever increasing downward spiral that leads to decline in soil and environment quality magnified by overgrazing, residue removal and extractive farming (Lal, 2015). Indeed, traditional agricultural practices in West African drylands are mostly characterized by extractive farming characterized by the removal of almost all crop residues from the soil surface, which results in decreased soil organic matter (SOM), impaired soil biological activities, weakening of soil structure, and disrupted water dynamics- i.e., infiltration, retention and release for plant growth (Bationo et al., 2007; Karlen and Rice, 2015). Generally, soil degradation leads to the disruption of soil health, most importantly soil organic carbon (SOC), which is the key indicator for soil health due to its multiple effects in enhancing soil functions (Liu et al. 2006, Lal, 2015; Stockmann et al., 2015). SOC influences all aspects of soil fertility as it (i) provides available nutrients to plants, (ii) improves soil structure and water holding capacity, (iii) provides food for soil organisms and (iv) buffer toxic and harmful substances (Chan, 2010). Thus, depletion of SOC pool in agricultural lands leads to the reduction of soil carbon sink capacity and increases greenhouse gas (GHG) emission into the atmosphere (Powlson et al., 2011; Lal 2015; Milne et al., 2015). Therefore, enhancing SOC pools in agricultural lands through recommended management practices (RMPs) is now recognized as a global environmental challenge (Milne et al., 2015). It is also the most realistic and sustainable way to reduce soil degradation (Bationo et al., 2007, Rajan et al., 2010), improve soil health and long-term agricultural productivity (Syers, 1997; Lal, 2006; Forage et al., 2007; Cowie et al., 2011) and mitigate carbon dioxide (CO_2) concentration in the atmosphere through SOC sequestration (Lal, 2005; Powlson et al., 2011; Plaza-Bonilla, et al., 2015). More specifically, increasing SOC pool in cultivated lands beyond the recommended threshold of 15-20 g kg^{-1} is essential to set-in motion soil processes that lead to soil quality restoration and maintenance (Aune and Lal, 1997; Loveland and Webb, 2003; Lal, 2015). However, to date empirical data related to the response of SOC to land management at landscape and regional scales are rare. The objectives of the current study were to (i) provide baseline data of SOC stocks across sentinel sites in semi-arid landscapes of West Africa, where the Consultative Group on International Agricultural Research (CGIAR) Drylands program is being rolled out, (ii) discuss the potential of SOC storage to mitigate global warming effect, and (iii) make recommendations for site-specific interventions to improve soil health and enhance agricultural production.

2. Materials and methods

2.1 Study area

This study was conducted along the action site Wa/Bobo-Dioulasso/Sikasso (WBS) of the CGIAR Drylands Program spanning Ghana, Burkina Faso and Mali with special reference to the Strategic Research Theme 3 (SRT3) (CRP Drylands Systems, 2012). The objective of SRT3 was to sustainably intensify agricultural production systems in order to achieve food security and poverty reduction. The study area is a set of three sentinel sites each covering a 10 by 10 km (100 km^2) each located in the semi-arid zones of Lambussie (Upper-East region of Ghana), Bondigui (Southwestern Burkina Faso) and Finkolo (Southwestern Mali), respectively (Fig. 1). The three sites belong to the Sudanese savanna with an average total rainfall over 41 years (1970-2010) of 1014±181 mm, 841±132 mm, and 1109±181 mm in Lambussie, Bondigui and Finkolo, respectively (Fig. 2). They were derived from the network of the AfSIS program on soils across Sub-Saharan Africa (Vågen et al., 2010). Drought history across the study sites was analyzed using the Standard Precipitation Index (SPI) as recommended by Bordi et al. (2001). It revealed similar dry years across the sentinel sites ranging from 18 to 19 out of 41 years (Fig. 2). However, unlike Lambussie which is characterized by an aggregation of drought periods from 1970 to 1976 as well as 1981 to 1992 with the driest year being 1986, Bondigui and Finkolo showed a regular distribution of dry and wet years throughout the analyzed period. Rainfall ranges in the study sites were found to be 517-1326 mm, 611-1211 mm, 755-1535 mm in Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali), respectively. Broadly, soils of the three sites are sandy loam or finer and highly weathered soils which are classified as lixisols (FAO/EC/ISRIC, 2003; Towett et al., 2015). They are characterized by slight acidity with a clay-enriched subsoil and low nutrient-holding capacity.

Farming activities are the dominant human activities in the sites. Across the study areas, lands are prepared with fire along with oxen-driven plow at 8-10 cm depth. An overwhelming majority of farmers use organic fertilizers (manure and compost) as inputs to replenish soil fertility. Nevertheless, wealthier farmers use inorganic fertilizers (NPK most in cases) in their fields at the rate of 125 kg ha^{-1}, generally two weeks after emergence of seedlings (Becx et al., 2012; Sissoko et al., 2013). In Burkina Faso and Mali, cotton cultivation has contributed to the increase of maize yields (main staple food) that takes advantage of the presence of inorganic fertlizers in the soil, thereby contributing to enhancing agricultural production in some areas (Laris et al., 2015).

2.2 Field survey and soil sampling

Field surveys and soil sampling were carried out from 2009 to 2011 using the Land Degradation Surveillance Framework (LDSF) (Vågen et al., 2013; Vågen et al., 2016). Practically, the LDSF is a spatially stratified hierarchical sampling design targeting land degradation assessment. It consists of qualitative and quantitative field observations on land use, land geomorphology, soil description and sample collection, vegetation description and characterization within a site of 100 km^2 organized around 16 clusters each composed of 10 georeferenced sampling plots (Fig. 3). Both field survey and soil sample collection were undertaken at plot (1000 m^2) and subplot (100 m^2) levels. For each plot, a total of 160 topsoil (0 - 20 cm) and 160 subsoil (20-50 cm) samples were collected and kept in polythene ziplock bags for further laboratory processing and analyses.

In order to avoid high uncertainties in bulk density measurement using the sample corer, the cumulative mass approach was used in this study (Betemariam et al., 2011). For that, soil was collected with the help of an auger at the center point of each sampling plot at the same depths using a sampling plate to aid full recovery of the soil sample. Soil samples from each depth were labeled and taken to laboratory for processing and oven-dry moisture measurement.

2.3 Soil processing and analyses

2.3.1 Laboratory analyses

Air-dried standard soil samples were passed through 2 mm mesh of sieve of which 32 top and subsoil samples per site were selected for traditional wet chemistry methods to determine SOC, pH (1:1 solution in water) base cations (Melich-3 extraction) at the Crop Nutrition Laboratory (www.cropnuts.com) in Nairobi, Kenya. Texture was measured using a laser diffraction particle size analyzer after dispersion of soil samples as per the procedure detailed in Winowiecki et al. (2015). As for cumulative mass soil samples, they were sieved to fine and coarse fragments. Small quantities of each sample were weighed and oven-dried to derive the gravimetric water content that is to be used to determine oven-dried soil weight at 0-20 and 20-50 cm (Betemariam et al., 2011). The 32 samples were randomly selected from each site ensuring that both topsoil and subsoil were from the same sampling point to predict SOC concentration for the remaining soil samples grounded to < 100 µm with an agate mortar and pestle (Shepherd and Walsh, 2002; Vågen et al., 2006; Terhoeven-Urselmans et al., 2010).

2.3.2 Spectral calibration and soil organic carbon prediction

Mid-infrared Spectroscopy (MIRS), a non-destructive, cost-effective and rapid methodology, was used to analyze all soil samples. The acquired spectra were used to SOC prediction models SOC concentrations of the 32 samples obtained from a conventional analysis were calibrated to the first derivative of the reflectance spectra using partial least squares regression (PLSR) as recommended by Terhoeven-Urselmans et al. (2010). The regression models were thereafter used to predict SOC for the rest of the samples under investigation. The prediction performance was evaluated using the coefficient of determination (R^2) of the PLSR model along with the root mean square errors of calibration (RMSEC).

2.3.3 Calculation of soil organic carbon stocks and total CO_2 equivalent

For a given soil layer, SOC stock was calculated by multiplying the carbon concentration in soil fines with bulk density and soil depth (Betemariam et al., 2011):

$\mathrm{SOCstock} = \frac{C}{100}\ x\ Bd\ x\ D\ x\ (1 - frag) x\ 100$, where

- SOCstock= soil organic carbon stock (Mg C ha^{-1})
- C = soil organic carbon concentration of soil fines (fraction < 2 mm) determined in the laboratory (%, g kg^{-1})
- *Bd* = soil bulk density (i)
- D = depth of the sampled soil layer (cm)
- Frag = % volume of coarse fragments/100

100 is used to convert the unit to Mg C ha^{-1}

(i) $Bd = \frac{M}{V}$, where

M = oven-dry weight of soil (g)

V = volume of soil (cm^{-3}).

SOC total stock of a given sentinel site covering 100 km^2 was estimated by multiplying the value by 10 000. The obtained value was converted into carbon dioxide equivalents (CO_2-eq.)

by applying the conversion factor of (44/12) (Danielsen et al., 2009).

On the other hand, SOC storage rate was calculated by dividing SOC stocks by number of years that a land has been cultivated and semi-natural stands (Kongsager et al., 2013), which according to farmers, were estimated at 20, 20 and 21 years at Lambussie, Bondigui and Finkolo sites, respectively. In order to assess the potential rate of SOC storage in agricultural lands across sites, semi-natural lands were used as benchmark and compared to cultivated ones (Corsi et al. 2012).

2.4 Data analysis

The comparison of SOC across sentinel sites was performed using the non-parametric Kruskal-Wallis test along with the pairwise multiple comparison of mean ranks test of Nemenyi. The difference in SOC stocks between semi-natural and cultivated lands throughout the landscape was statistically assessed with the help of the non-parametric Mann-Whitney test. The relationship between SOC stocks and soil texture parameters were tested by computing a correlation matrix using Spearman correlation coefficient. All statistical analyses were done using R software version 3.2.2 (R Development Core Team, 2015) at a significance level of 0.05.

3. Results

3.1 Land use characterization

In general, the landscapes under investigation are flat with altitudes varying between 273 and 432 m (Bondigui: 273.2±12.6 m; Lambussie: 301.5±3.8 m; Finkolo: 431.8±12.6 m). The main land-use types include parklands associated with food crops (Table 1). Keystones tree species namely *Vitellaria paradoxa*, *Parkia biglobosa*, *Bombax costatum* and sometimes, exotic fruit trees such as *Mangifera indica*, *Citrus lemon* were regularly found across sites. Within parklands, crops were sown in the form of fallow/food crop rotations or recurrent cropping in Lambussie, Ghana. Mango orchards / maize (*Zea mays)* association, cotton (*Gossypium* *hirsutum*) /maize rotation, millet (*Pennisetum glaucum*) / cowpea (*Vigna unguiculata*) rotation were the most dominant in Bondigui, Burkina Faso. Finally, cotton/maize rotation, maize/sweet potato (*Ipomoea batatas*) association, *M. indica*/food crops alley cropping in mango and *Citrus lemon* orchards were found in Finkolo, Mali. Furthermore, the prevalence of surveyed areas under cultivation was on average 44±0.02% in Bondigui, 71±0.02% in Lambussie and 52±0.03% in Finkolo (Table 2).

3.2 Soil baseline data of sentinel sites

Soils of all sites were slightly acidic (pH 5.3 to 6.7) for both soil layers (Table 3). The values of pH and SOC were statistically lower at Finkolo in the topsoil as compared with the two other sites. Total N content followed almost the same trend and displayed low concentrations throughout the soil profiles with highest values in the topsoil. As for exchangeable cations, apart from Ca values, which in Bondigui and Lambussie reached about 5 fold the value of Ca in Finkolo; K, Mg concentrations were very low and similar irrespective of sites and sampling depths. Extractable P seemed to be linked to SOC variations in the topsoil as it showed moderate concentrations in Bondigui and Lambussie with very low value in Finkolo. Concerning soil texture, Bondigui was different from others with high percentage of clay and moderate proportions in silt and sand. Consequently, soils in Bondigui can be referred to as clay soil while Lambussie and Finkolo were identified as having clay loam soils.

3.3 Soil organic carbon (SOC) stocks

The correlation coefficient R^2 between SOC and the mid-infrared spectra was strong (0.97) along with 0.24 as RMSEC value indicating a good efficiency of MIRS to determine SOC. Figure 4 shows significant variations in SOC stocks across sentinel sites within the topsoil (0-20 cm), where the highest value (22.4±1.5 Mg C ha^{-1}) was obtained in Bondigui and the lowest in Finkolo (11.2± Mg C ha^{-1}). In the subsoil (20-50 cm), Lambussie displayed the highest value (25.3±1.7 Mg C ha^{-1}), Bondigui (20.5±1.4 Mg C ha^{-1}) and Finkolo (12.4±0.6 Mg C ha-

^{1}).

Intra-site variations of SOC at Lambussie site were markedly significant both in topsoil and subsoil (Fig. 8). In the 0-20 cm layer, the first zone with high values spanned clusters 2 to cluster 8, which values ranged from 12.4±2.6 Mg C ha^{-1} to 53.7±15.6 Mg C ha^{-1}. The second area stretching from cluster 12 to 16 had values ranging between 10.4±1.3 Mg C ha^{-1} and 23.0±5.6 Mg C ha^{-1}. In general, SOC stock values in the 20-50 cm layer were relatively high except the values in cluster 2 (9.7 ±3.0 Mg C ha^{-1}), cluster 5 (6.3 ±1.8 Mg C ha^{-1}) and cluster 8 (3.5 ±2.5 Mg C ha^{-1}), which were significantly low (Fig. 5).

Apart from cluster 4 (9.6 ±1.0 Mg C ha^{-1}) and cluster 10 (11.8±2.7 Mg C ha^{-1}), SOC stock values were high and varied markedly between 12.5±1.9 Mg C ha^{-1} and 37.4±7.8 Mg C ha^{-1} at Bondigui site. Values were even higher in subsoil (20-50 cm), where clusters 6 (10.7 ±3.6 Mg C ha^{-1}) and 8 (10.6 ±3.6 Mg C ha^{-1}) were among the lowest (Fig. 5).

Finkolo site had the lowest SOC stocks in both layers throughout all clusters. Only the topsoil showed significant variations across clusters as values ranged from 5.7 ±0.7 Mg C ha^{-1} (Cluster 2) to 17.2 ±3.3 Mg C ha^{-1} (Cluster 5). Though not significant, variations in the subsoil revealed the existence of discrepancies among clusters as evidenced by the wide range from 8.4±0.8 Mg C ha^{-1} to 21.0±3.1 Mg C ha^{-1}.

The potential values of SOC stored in soils of study sites with 95% confidence level based on total area covered (100 km^{2}) in each sentinel site were estimated in the topsoil at 191,500±37,000 Mg C; 224,000±30,000 Mg C and 112,200±14,000 Mg C in Lambussie, Bondigui and Finkolo, respectively (Table 4). In the same way, total SOC stock at ± 95% confidence level in the subsoil varied from 124,000±28,000 Mg C at Finkolo to 253,000±34,000 Mg C at Bondigui.

3.4 Variation in SOC across land use types

Cultivation resulted in significant drop in topsoil SOC stock in the Lambussie site as indicated by the reduction in SOC stock from 29.7±5.9 Mg C ha^{-1} (Semi-natural areas) to 15.7±1.4 Mg C ha^{-1} (Cultivated lands). However, no significant impacts were observed in Bondigui and Finkolo though values showed huge intra-site variations (Table 5). In the subsoil, there were no meaningful changes brought about by cultivation as values of SOC stocks were similar in semi-natural and cultivated lands in Lambussie (19.5±3.4 Mg C ha^{-1} versus 20.7±1.6 Mg C ha^{-1}), Bondigui (23.4±2.1 Mg C ha^{-1} vs 26.9±2.5 Mg C ha^{-1}) and Finkolo (12.4±1.1 Mg C ha^{-1} vs 12.3±0.8 Mg C ha^{-1}).

On the other hand, figure 6 showed a very reasonable rise (+4.2%) of SOC stocks in cultivated areas in Bondigui resulting in an accumulation rate of 0.04 Mg C ha^{-1} yr^{-1}, while Lambussie and Finkolo showed a drop on cultivated lands as compared to semi-natural ones. Hence, land use change brought about a moderate (-21.4%) and significant (-47.4%) loss in SOC stocks in Finkolo and Lambussie, respectively. As a result, depletion rates were estimated at -0.13 Mg C ha^{-1} and -0.71 Mg C ha^{-1} Finkolo and Lambussie respectively. However, in the subsoil, SOC storage rates were not significantly different between semi-natural and cropped areas, SOC positively accumulated in Bondigui (+0.18 Mg ha^{-1} yr^{-1}) and Lambussie (+0.07 Mg C ha^{-1} yr^{-1}) while almost no storage (-0.004 Mg C ha^{-1} yr^{-1}) was found in Finkolo.

4. Discussion

4.1 Site characterization

Among the sentinel sites, Lambussie in Ghana was most cultivated with little variation across clusters, indicating a fairly homogeneous distribution. The moderate percentage of cropping areas in Finkolo is due to the fact that parts of the site fell within the protected area known as "Forêt Classée de Finkolo-Sikasso". That likely explains the high inter-cluster variations of cultivated area, as some of the clusters were not cultivated while those falling on farmers' fields were almost entirely cultivated. Bondigui was the less cropped site although it has no protected area. Plausible explanation lies in the fact that the site is located among the less populated areas in Burkina Faso, where population density is in the range of between 0 and 20 inhabitants per km^2 (Ouédraogo, 2010). In this area fallow systems are still in use with the consequence of sparing woodlands (Devineau & Fournier, 2007), which would have been used for cultivation in other areas. Across sites, the most common land use systems are parklands known as the dominant traditional agroforestry practice that helps farmers to cope with negative impacts of climate change and therefore strengthen their adaptive capacities (Bayala et al., 2014). In both strata, soils were acidic in Finkolo and moderately acidic in Bondigui and Lambussie. This surely had an impact on SOC concentrations that, when compared with the critical limit of 20 g kg^{-1} for an improved soil quality (Musunki et al., 2013; Lal, 2015), was high in Bondigui (25.4±4.2 g kg^{-1}), close in Lambussie (17.8±3.3 g kg^{-1}), and low in Finkolo (10.7±1.7 g kg^{-1}). One can say soils in Bondigui and Lambussie had better quality compared to Finkolo, where their acidic nature seemed to have negatively affected their quality. The better soil quality and fertility in Bondigui might be due to short cultivation phase with possibility to fallow due to low population density and thereby reduced pressure on lands. In such cases, cultivable lands are left uncultivated during a long period that allows the restoration of their fertility. Results obtained in a similar environment with high demographic pressure in Bougouni area, Mali, where fallows used recurrently for agricultural purposes were no longer rich in soil organic matter and nutrients (Benjaminsen et al., 2010) consolidate that assumption.

4.2 SOC stocks change across semi-arid landscapes of West Africa

At site level, only Bondigui showed higher SOC stocks in the topsoil compared to subsoil. This is most likely due to low pressure on lands from both farming and livestock activities that allows the biomass to accumulate on topsoil; therefore contributing to higher soil organic matter in the first 20 cm. However in Lambussie, high agricultural pressure on lands as indicated by the prevalence of cultivated areas has resulted in a reduced average SOC stock in the arable layer of 20 cm. Across sites, SOC stocks in the topsoil varied between 11.2±0.7 and 22.4 Mg C ha^{-1} in line with values ranging from 17.1 from 29 Mg C ha^{-1} and 17.4 from 34.4 Mg C ha^{-1} found in Balé and Ziro provinces with similar environments in Burkina Faso, respectively (Dayamba et al., 2016) though not similar SOC measurement method was used. Also, SOC stocks obtained in subsoil (20-50 cm) were lower compared to similar studies in Burkina Faso, precisely in the provinces of Balé (18.2 from 31.2 Mg C ha^{-1}) and Ziro (18.0 from 32.7 Mg C ha^{-1}) (Dayamba et al., 2016).

At cluster level the presence of SOC stock hotspots with various magnitudes in both soil layers highlights the need to take into account landscape level variations (CV) when planning for land management practices for enhanced SOC accumulation. Moreover, when zooming in on each cluster, high SOC stocks were strongly aggregated in Lambussie, indicating land uses with contrasted impacts on soil organic matter. Combined with wide ranges of within-cluster level variations in SOC stocks (values not shown) that varied from 39.6 to 111.8% in Bondigui, 37.8 to 129.6% in Lambussie and 30.0 to 137.9% in Finkolo illustrating the heterogeneity of clusters; this finding is instrumental in designing site-specific landscape interventions for SOC accumulation improvement. Indeed, SOC stocks might be used as indicators of soil quality and thereby help in prioritizing degraded areas for intervention.

Low values of SOC stocks in soil layers at site and cluster levels are likely caused by the acidity of soils which is known to be a contributory factor to increased crop/plant residue decomposition and fairly high erosion prevalence due to steep landscape (Rajan et al., 2010; Obiri-Nyarko, 2012, Vägen and Winowiecki, 2013). Land cultivation has significantly reduced 40% of SOC stocks in the topsoil of Lambussie and that might be due to the high pressure on lands with 71±0.02% of the area being cultivated. This result is in agreement with findings of Gelwa et al. (2014) in a semi-arid watershed in Tigray, Northern Ethiopia revealing that rainfed crop production was found to store less SOC (16.1±6.6 Mg C ha^{-1}) compared with agroforestry-based crop production (25.8±1.8 Mg C ha^{-1}) and silvopasture (39.1±21.5 Mg C ha^{-1}). The deficit (-19.3%) obtained in Finloko's topsoil was not statistically significant. The same observation applied to hints of surpluses noted in Lambussie subsoil (+6.7%), Bondigui top (+13.1%) and sub (+1.9%) soil, and in Finkolo subsoil (+0.7%). Depletion of up to 50% in SOC stock has been underlined in a similar study in Tanzania and was attributed to soil erosion and unsustainable land management practices (Winowiecki et al., 2016). Likewise, review studies through meta-analyses identified conversion of forest into croplands to be accountable for 25 to 42% reduction in SOC stocks (Guo et al., 2002; Don et al., 2011), a range comprising values found in Lambussie. Bondigui had similar high SOC stocks beneath semi-natural (21.9±2.0 versus 23.4±2.1 Mg C ha^{-1}) and cultivated (22.8±2.2 vs 26.9±2.5 Mg C ha^{-1}) lands indicating that the landscape might be globally less degraded and soils should be responsive to agricultural intensification. As a general rule, rate of SOC accrual is higher in 20-50 cm vis-à vis the topsoil indicating the plausible effect of decomposition and erosion processes that are much more prominent in the superficial layers subjected to moderate tillage and identified as factors influencing SOC accumulation rates (Corsi et al., 2012; Brown and Huggins, 2012; Vägen and Winowiecki, 2013). Regardless of soil layer, SOC accumulation rates in cultivated lands reported in the current study (0.04 to 0.18 Mg C ha^{-1} yr^{-1}) are lower than existing figures reported in the literature under conservation agriculture (1.24 to 1.8 Mg C ha^{-1} yr^{-1}), improved grazing (0.22 - 0.7 Mg C ha^{-1} yr^{-1}), animal manuring (1.5±0.1 Mg C ha^{-1} yr^{-1}) in Brazil, the USA and Europe (Watson et al., 2000; Smith et al., 2000a, 2000b; West and Post, 2002; de Moraes Sà and Seguy, 2008). Moreover, values obtained are by far smaller than the potential soil carbon sequestration rate of 0.25 - 0.5 Mg C ha^{-1} yr^{-1} that can be achieved by changing management options (Lal, 2003). Very few studies have estimated SOC accrual rates in cultivated lands in West Africa Sudanese savannas. Nevertheless, accumulation rate of SOC estimated at 4.3 Mg C ha^{-1} yr^{-1} beneath conservation agriculture in drylands of Western

Nigeria (Ringius, 2002) is indicative of the fact that weathered soils in semi-arid lands can be responsive to improved land management practices that aim at enhancing agricultural production. On the other hand, the depletion rate of SOC stocks (-0.004 to -0.71 Mg C ha^{-1} yr^{-1}) seemed important and expressed the huge potential of agricultural soils in semi-arid areas to have a high sink potential for carbon storage (Corsi et al., 2012). In any case, these figures should be taken with caution as they might not be permanent and any changes in land management or land use might cause a rapid variation undermining or stimulating SOC accumulation (Smith et al., 1996). Baseline data provided across sites should guide further land management decisions to replenish SOC in view of increasing agricultural production.

4.4 Implications of SOC storage for site-specific recommendations for enhanced agricultural production

Depletion in SOC is one of the most insidious and unseen processes of soil degradation that negatively affect agricultural production in most cultivated lands of Sub-Saharan Africa (Lal, 2015; Montanarella et al., 2016). SOC is also used as indicator of soil quality and agricultural sustainability because SOC-enriched soils have the capacity to improve and maintain soil fertility and thereby sustain agricultural production (Loveland and Webb, 2003). One of the most straightforward pathways to mitigating soil degradation in semi-arid drylands is to maintain or replenish SOC concentrations above the critical level of 20 g kg^{-1} (Loveland and Webb, 2003; Musunki et al., 2013; Lal, 2015). While the average SOC concentration in Finkolo (10.7±1.7 g kg^{-1}) was below that threshold, Lambussie (17.8±3.3 g kg^{-1}) was close and Bondigui (25.4±4.2 g kg^{-1}) above, indicating the need for land management prospects that rely on sites' specificities. Likewise, most clusters in Finkolo (81.3%: 13 out of 16) have SOC stocks below 15 Mg C ha^{-1} while the corresponding figure in Bondigui and Lambussie is only 25%. According to figure 7, deficits in SOC stocks are more pronounced in cultivated lands in Lambussie and Finkolo, while only semi-natural lands are concerned in Finkolo. As expected, surplus in SOC stocks was found in uncultivated lands in Lambussie while all land use types experienced that in Bondigui. Thus, Finkolo seems to be the priority site to target in terms of interventions that should consist of firstly raising the pH level prior to selecting the most relevant land management options. In that regard, recommended practices such as liming, application of manure and crop residues, judicious use of acid forming fertilizers including urea, single and trisuperphosphate (SSP and TSP), the use of acid tolerant crops (Cassava, rice, etc.) as well as agroforestry practices should be of interest (Obiri-Nyarko, 2012). As for agroforestry, practices involving leguminous trees and shrubs such as *Albizia zygia*, *Gliciridia sepium* (Baggie et al., 2000), and *Cajanus cajan* (Riddley et al., 1990) might be recommended. In Lambussie, clusters with low SOC stocks should be primarily targeted with conservation agriculture, integrated nutrient management, improved grazing and cover crop farming that are most indicated for SOC accrual in weathered soils (Lal, 2004; 2005; 2006; Bayala et al., 2012).

4.5 Implications for climate change mitigation

Regardless of soil strata, SOC storage in semi-arid landscapes potentially ranged between 112,200±14,000 and 253,000±34,000 Mg C corresponding to 411,400±51,333 Mg CO_2-eq and 927,666.7±124,666.7 Mg CO_2-eq in the target countries. On the other hand, the potential of climate change mitigation through SOC revealed contrasted figures as accumulation rates in cultivated lands ranged from 0.04 to 0.18 Mg C ha^{-1} yr^{-1} and were balanced by higher depletion rates of -0.004 to - 0.73 Mg ha^{-1} yr^{-1} which indicates the potential of semi-arid soils to store carbon. These figures are useful insights for devising improved land management practices that will overcome constraints and enhance SOC storage. In the context of the current study, promising RMPs that have been experimented in the study area should be recommended. They should include agricultural intensification, improved rangelands, agroforestry-led conservation agriculture, and rehabilitation of degraded lands (Reij et al., 2009; Bayala et al., 2012). Indeed, Raji and Ogunwole (2006) reported a rise of 115% in SOC in trials supplemented with manure and NPK over 45 years in semi-arid savannas of Nigeria, while 18 years of application of NPK has resulted in an accrual of 0.28 - 0.41 Mg C ha^{-1} y^{-1}. Moreover, the same authors revealed that improved pastures based on enrichment of *Brachiaria decumbens* contributed to the storage of 0.57 Mg C ha^{-1} yr^{-1} in the soil. At a larger scale, the rehabilitation approach of degraded parklands referred to as farmer-managed natural regeneration (FMNR), a cost-effective agroforestry practice that helped in restoring and sustaining the productivity of 5,000,000 ha of lands in the southern region of Maradi, Niger (Reij et al., 2009) should be upscaled to the entire area of the study. From Niger, where it has been primarily successfully tested, this climate-smart practice, is now being promoted in Ghana over 500 ha with 396,000 trees in Talensi-Nabdam District, Upper-East region (Weston et al., 2013). In Burkina Faso, part of the country is now made up of rejuvenated agroforestry parklands, while in Mali, about 6,000,000 ha of degraded parklands are under regeneration through FMNR (Reij, 2012). Soil fertility enhancement as one of the environmental impacts of FMNR, is strongly linked to SOC build up. In addition to increasing aboveground biomass, FMNR also has the potential of sequestrating up to 5.4 Mg CO_2-eq yr^{-1} as shown recently in Ethiopia (Rob, 2015) with an undeniable impact on SOC stock.

5. Conclusion

This study is the first attempt to demonstrate the carbon sink potential of soils at large scale in semi-arid areas in West Africa using empirical data. Except some constraints due to acidification in Finkolo area in Mali, soils were found to be globally suitable for agricultural intensification as their SOC concentrations ranged between 10.7±1.7 g kg^{-1} and 25.4±4.2 g kg^{-1} with relatively high proportion of clay (35.4±0.4 to 448.8±3.8%). Moreover, low values of SOC accumulation rates magnified by higher depletion rates are indicative of the potential of drylands soils to help in adapting and alleviating climate change effects in semi-arid West

Africa. Site and cluster-level analysis revealed the heterogeneity in SOC stocks distribution at landscape scale, a mandatory finer level analysis prior to decision-making about Recommended Management Practices. Further studies should focus on (i) setting out critical values of SOC stocks beyond which agriculture can be smart and sustain production, and (ii) determining the SOC accumulation potential of the most effective RMPs. These actions seem achievable if long-term agronomic trials across West Africa are gathered and analyzed with relevant approaches. In the same way, assessment of the contribution of FMNR along with land and water conservation practices that have been widely adopted by farmers in West Africa (Reij et al., 2009) to the global carbon budget must be a research priority.

Acknowledgements

This work is part of the Africa Soil Information Service (AfSIS) project funded by the Bill and Belinda Gates Foundation, which is gratefully acknowledged. It has also benefited from the financial support of the CGIAR Drylands Program in West Africa to acquire climate data. Moreover, field surveys and soil samples processing would not have been possible without the great contribution of scientists of the "Laboratoire Sol Eau et Plante" of the "Institut d’Economie Rurale" (IER), Sotuba, Bamako.

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Figure captions

Figure 1. Locaation of Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa.

Figure 2. Standardized Precipitation Index (SPI) of Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa over 41 years (1970-2010) showing alternating of dry and wet years.

Figure 3. Example of a Lambussie sentinel site showing boundaries along with clusters and sampling points allocation, as used in the Land Degradation Surveillance Framework (LDSF) sampling design.

Figure 4. Vertical distribution of average SOC stocks for Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa. Similar bars with different letters are significantly different (Kruskal-Wallis test, p=0.05)

Figure 5. Cluster-level variation of SOC stocks across the soil profile for Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa.

Figure 6. Accumulation rate of SOC stocks (Mg C ha^{-1} yr^{-1}) in cultivated lands across Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa. Similar bars with different letters are significantly different (Kruskal-Wallis test, p=0.05).

Figure 7. Normalized values of SOC stocks at different depths within unclutivated and cultivated areas across Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa.

Figure 1

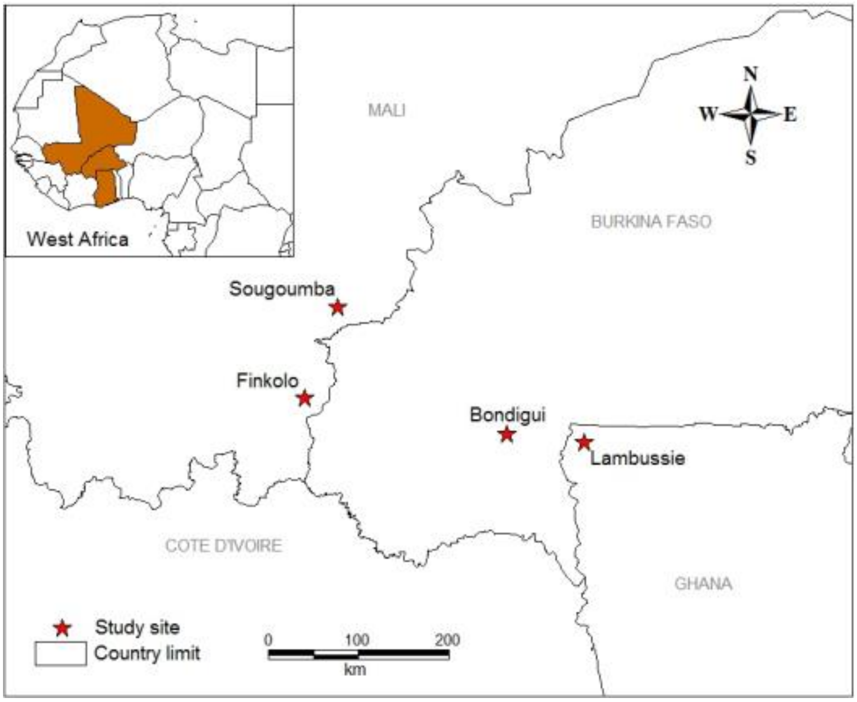
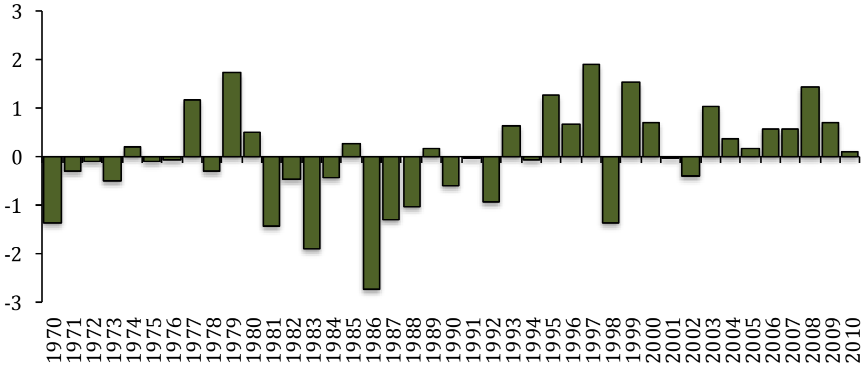
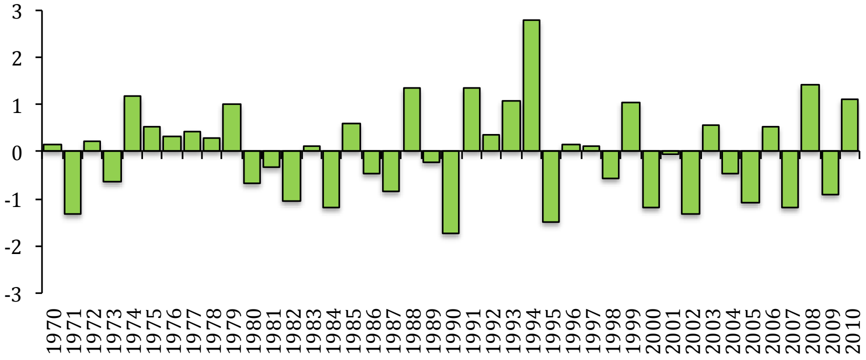

West Africa
MALI
BURKINA FASO
N
W
E
S
Sougoumba
Finkolo
Bondigui
Lambussie
COTE D'IVOIRE
GHANA
Study site
Country limit
0
100
200
km

Figure 2

Lambussie (1014.4 mm)



Bondigui (841 mm)



Finkolo (1109 mm)

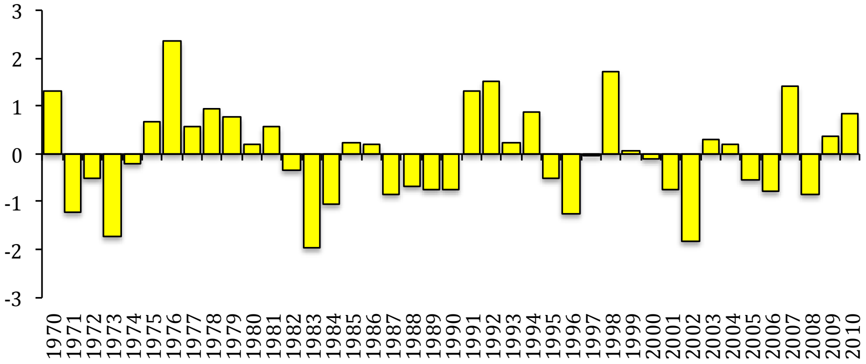
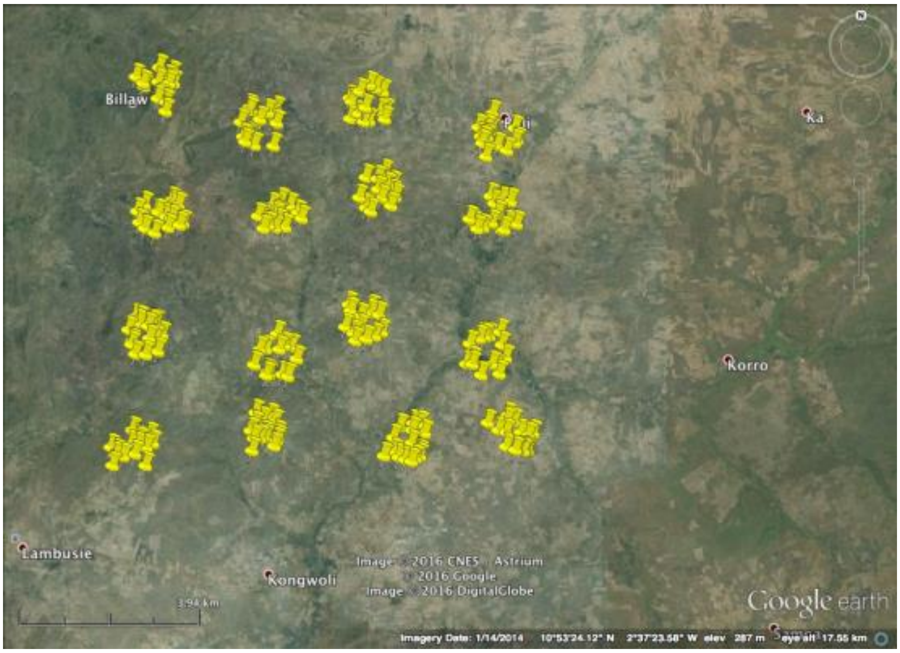


Figure 3


Billaw
Ka
Korro
Lambusie
Kongwoli
Image © 2016 CNES / Astrium
© 2016 Google
Image © 2016 DigitalGlobe
3.94 km
Google earth
Imagery Date: 1/14/2014 10°53'24.12" N 2°37'23.58" W elev 287 m eye alt 17.55 km

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Manuscript under review for journal SOIL
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Figure 4

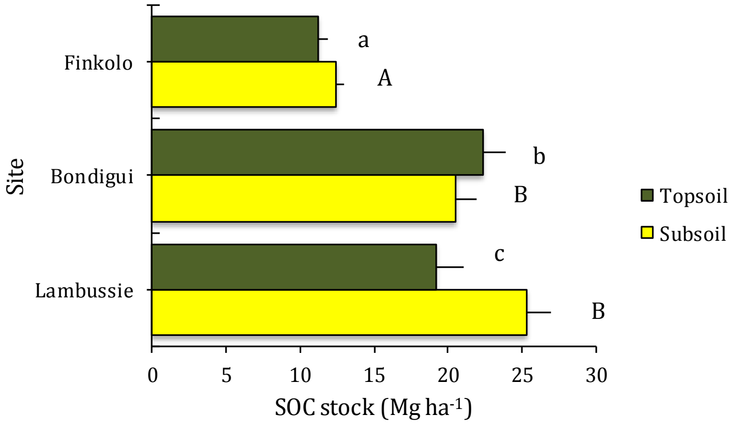


Figure 5

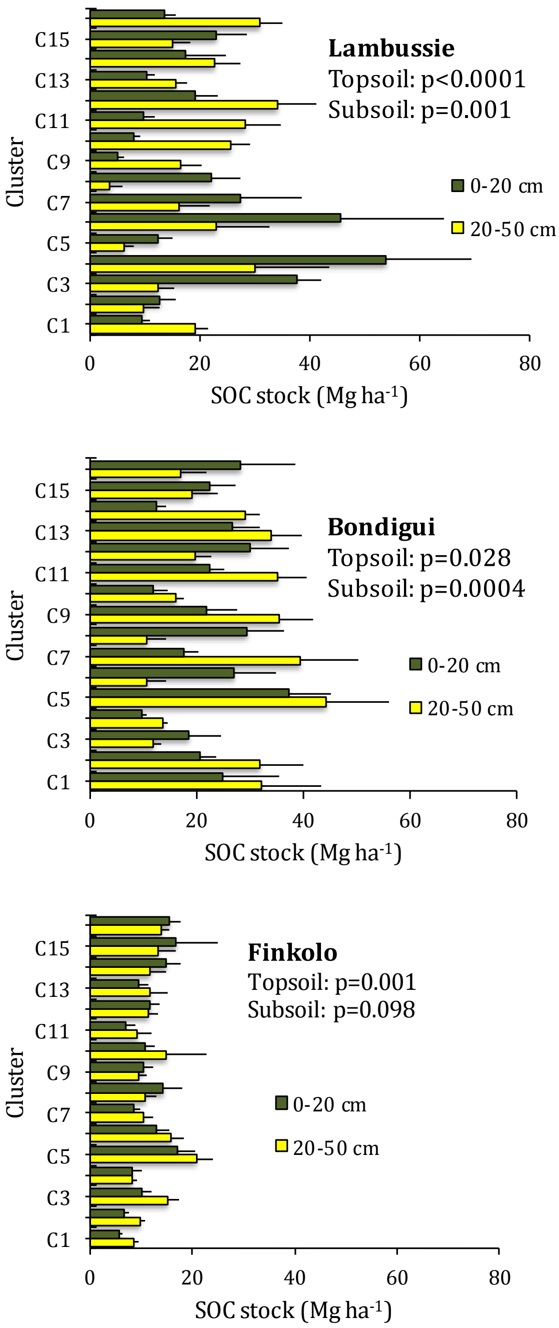

Lambussie
Topsoil: p<0.0001
Subsoil: p=0.001
Bondigui
Topsoil: p=0.028
Subsoil: p=0.0004
Finkolo
Topsoil: p=0.001
Subsoil: p=0.098
■ 0-20 cm
■ 20-50 cm
Cluster
C15
C13
C11
C9
C7
C5
C3
C1
0
20
40
60
80
SOC stock (Mg ha-1)

Figure 6

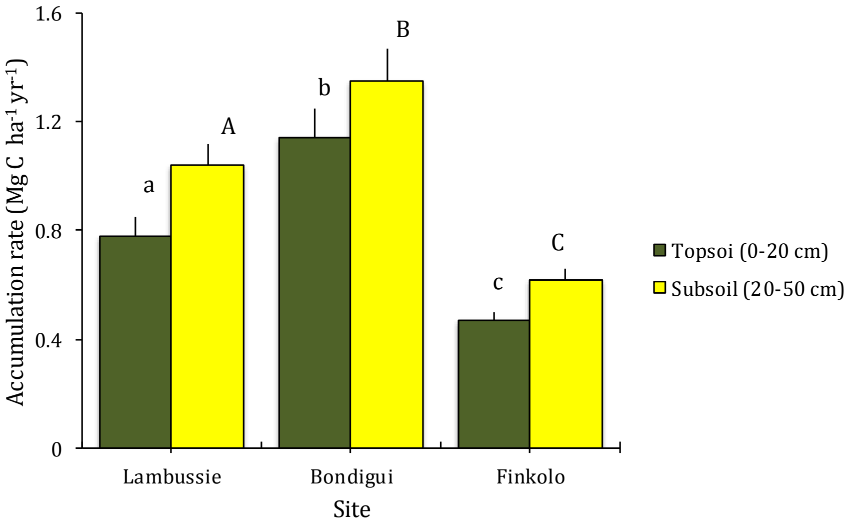
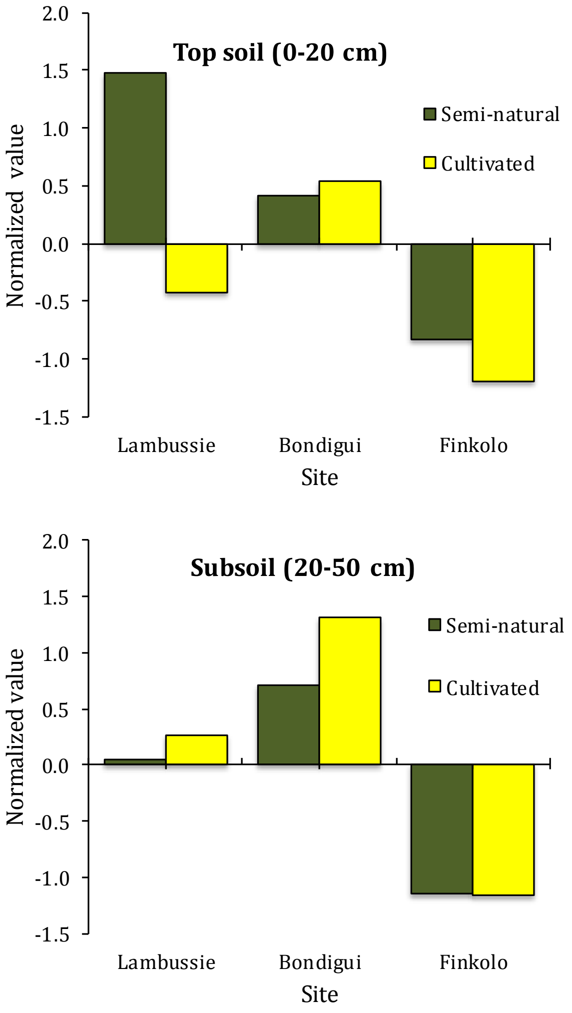

Accumulation rate (Mg C ha-1 yr-1)
1.6
1.2
0.8
0.4
0
a
A
b
B
c
C
Lambussie
Bondigui
Finkolo
Site
Topsoi (0-20 cm)
Subsoil (20-50 cm)

Figure 7


Top soil (0-20 cm)
Normalized value
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
🟩 Semi-natural
🟨 Cultivated
Lambussie
Bondigui
Finkolo
Site
Subsoil (20-50 cm)
Normalized value
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
🟩 Semi-natural
🟨 Cultivated
Lambussie
Bondigui
Finkolo
Site

Table

Table 1. Characteristics of Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa with key land uses and tree and shrub associated.

Sentinel site	Latitude and longitude of 4 corner points	Average altitude (m) ± standard error	Main land use type	Tree or shrub encountered in the landscapes
Lambussie (Ghana)	(10º51'42.96"N, 2º41'27.29"W; 10º56'7.30"N, 2º40'59.18"W; 10º52'3.50"N, 2º36'37.58"W; 10º55'30.32"N, 2º37'2.84"W)	301.5 ± 3.8	Parklands associated with maize, millet, sorghum; association maize+ rice in lowlands; rotation fallow/food crops in parklands; recurrent food crops	*Vitellaria paradoxa, Parkia biglobosa, Afzelia africana, Dyospiros mespiliformis, Detarium microcarpum, Gardenia erubescens, Vitellaria paradoxa, Lannea acida, Annona senegalensis, Ptelopsis ruberosa Piliostigma reticulatum, Ficus gnaphalocarpa, Stericulia setigera*
Bondigui (Burkina Faso)	(10º52'41.85"N, 3º34'55.25"W; 10º56'26.87"N, 3º35'3.01"W; 10º52'35.10"N, 3º30'41.27"W; 10º57'16.66"N, 3º30'43.16"W)	273.2 ± 12.6	Parklands in association with maize, sorghum, millet; association *Mangifera indica*/maize; rotation cotton/maize; rotation	*V. paradoxa, D. microcarpum Bombax costatum, P. reticulata Mitagyna inermis, Mangifera indica, Lannea velutina*

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			millet/beans; recurrent food crops with less fallow	
Finkolo (Mali)	(11º16'28.39''N, 5º32'2.49''W; 11º20'42.46''N, 5º31'50.68''W; 11º16'25.48''N, 5º27'58.07''W; 11º20'47.54''N, 5º28'18.95''W)	431.8 ± 12.6	Maize, millet, sorghum, yam, sweet potato; rotation cotton/maize; association maize/sweet potato/; rotation *M. indica*/food crops; rotation *Citrus lemon*/food crops	*Securidaca longepedonculata V. paradoxa, D. microcarpum Bombax costatum, P. reticulata Mitagyna inermis, Mangifera indica, Citrus lemon*

Table 2. Soil properties (average±standard error) of Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa. Values with similar letters are not significantly different (Kruskal-Wallis test, p=0.05).

	$pH\text{-}H_2O$	SOC ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Ca ($cmolc\ kg^{-1}$)	K ($cmolc\ kg^{-1}$)	Mg ($cmolc\ kg^{-1}$)	ExtP ($mg\ kg^{-1}$)	Clay (%)	Silt (%)	Sand (%)
					0-20 cm					
Bondigui	6.7±0.1a	25.4±4.2a	0.97±0.2a	7.8±1.5a	0.22±0.02a	2.4±0.5a	7.0±0.3a	48.8±3.8a	24.9±1.2a	26.3±4.4a
Lambussie	6.3±0.2a	17.8±3.3a	0.75±0.1a	6.0±2.0a	0.25±0.08a	1.7±0.4a	7.7±2.1a	37.4±3.6b	26.1±1.6a	36.5±4.1b
Finkolo	5.5±0.1b	10.7±1.7b	0.40±0.1b	1.5±0.2b	0.15±0.02b	0.9±0.08a	3.5±0.4a	35.4±3.1b	20.2±2.2a	44.4±4.7b
					20-50 cm					
Bondigui	6.5±0.1a	15.8±3.1a	0.58±0.1a	5.9±1.4a	0.15±0.01a	2.05±0.5a	1.7±0.3a	53.1±4.1a	21.8±1.2a	25.1±3.9a
Lambussie	6.3±0.2a	14.2±3.7a	0.62±0.2a	5.9±2.0a	0.19±0.07a	1.92±0.6a	5.3±2.1a	38.7±3.8b	23.0±1.6a	38.3±4.8a
Finkolo	5.3±0.1b	8.1±1.5b	0.32±0.1b	1.3±0.2b	0.14±0.03a	0.95±0.1a	1.9±0.3a	44.6±3.2ab	23.0±2.5a	32.4±4.1a

Table 3. Average estimated area under cultivation in each of cluster across Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa.

	Bondigui	Lambussie	Finkolo
Cluster		% area	
1	20	40	80
2	30	90	80
3	30	80	80
4	40	30	80
5	40	60	80
6	30	50	10
7	70	90	50
8	30	50	10
9	30	70	90
10	50	90	90
11	70	90	50
12	70	70	80
13	20	90	10
14	80	90	10
15	40	60	20
16	60	90	10
Site	44±0.02a	71±0.02b	52±0.03c
(CV %)	(34)	(28.1)	(63.9)

Table 4. Estimate of average carbon stocks (Mg ha^{-1} ± 95% confidence level) at plot level and total SOC stocks (Mg C± 95% confidence level) at level of Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites

	SOC stock ± 95% confidence level (Mg ha^{-1})	Total SOC stock ± 95% confidence level (Mg C)
Lambussie	19.2±3.7	191,500±37,000
Bondigui	22.4±3	224,000±30,000
Finkolo	11.2±1.4	112,200±14,000
Lambussie	20.5±2.8	205,000±28,000
Bondigui	25.3±3.4	253,000±34,000
Finkolo	12.4±2.8	124,000±28,000

Table 5. Carbon stocks in cultivated and non-cultivated lands of Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa. For a given site, values with similar letters are not significantly different (Mann-Whitney test, p=0.05).

	Topsoil (0-20 cm)		
	Plot	Average±SE	CV (%)
Lambussie	Semi-natural	29.7±5.9a	122.8
	Cultivated	15.7±1.4b	93.7
Bondigui	Semi-natural	21.9±2.0a	82.1
	Cultivated	22.8±2.2a	80.7
Finkolo	Semi-natural	12.7±1.2a	83.3
	Cultivated	10.0±0.7a	66.1
	Subsoil (20-50 cm)		
	Plot	Average±SE	CV (%)
Lambussie	Semi-natural	19.5±3.4a	84.6
	Cultivated	20.7±1.6a	75.1
Bondigui	Semi-natural	23.4±2.1a	69.8
	Cultivated	26.9±2.5a	75.1
Finkolo	Semi-natural	12.4±1.1a	56.6
	Cultivated	12.3±0.8a	56.5

Table 6. Accumulation rate of SOC stocks in cultivated areas at plot level and total cultivated areas across Lambussie (Ghana), Bondigui (Burkina Faso) and Finkolo (Mali) sentinel sites in West Africa.

	Accumulation rate±95% confidence level (Mg C ha^{-1} yr^{-1})	Total accumulation rate±95% confidence level (Mg C yr^{-1})
	0-20 cm	
Lambussie	0.78±0.14	5,538±994
Bondigui	1.14±0.22	5,016±968
Finkolo	0.47±0.06	2,444±312
	20-50 cm	
Lambussie	1.04±0.16	7,488±1152
Bondigui	1.35±0.24	5,940±1056
Finkolo	0.62±0.08	3,224±416