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Biophysical potential for soil carbon sequestration in agricultural systems of the Old Peanut Basin of Senegal

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Abstract

Carbon sequestration in soil organic matter is increasingly advocated as a possible win–win strategy in the rehabilitation of degrading dryland agro-ecosystems because it simultaneously contributes to the reduction of global atmospheric greenhouse gas concentrations while enhancing local land productivity. A study was conducted in Senegal's Old Peanut Basin to assess current carbon stocks and to examine management options for their increase. Average soil and woody biomass carbon contents were 11.3 and 6.3 t carbon (C) ha^{-1}, respectively. CENTURY, a biogeochemical model, was used to simulate soil and biomass carbon over a period of 25 and 50 years under a series of land use and management options. These simulated practices resulted in C dynamics ranging from -0.13 t C ha^{-1} yr^{-1} from a worst-case millet–sorghum rotation to $+0.43$ t C ha^{-1} yr^{-1} on intensively managed agricultural fields. Agroforestry simulations involving *Faidherbia albida* (Del.) Chev. and *Leucaena leucocephala* (Lam.) deWit. also resulted in promising carbon gain ($+0.22$ and $+0.12$ t C ha^{-1} yr^{-1}, respectively), suggesting that improving agricultural practices is key to enhancing food production and mitigating climate change. Results from a sensitivity analysis suggest that woody biomass carbon is more sensitive to long-term changes in precipitation and temperature than soil carbon. Other management strategies likely to result in lower rates of soil carbon sequestration, including short-term improved fallows, should also be considered viable opportunities because promoting too narrow a set of 'best management practices' risks

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weakening local adaptability and opportunistic management regimes, both of which are crucial elements in small-scale farming systems in drylands.

Keywords: Soil management; CENTURY model; Carbon sequestration; Dryland farming systems; West Africa

1. Introduction

Carbon sequestration in soil organic matter (SOM) is increasingly advocated as a potential win–win strategy for reclaiming degraded lands, particularly in semi-arid regions of the developing world, mitigating global climate change, and improving the livelihoods of resource-poor farmers (Lal et al., 1999; Batjes, 2001; FAO, 2001; Lal, 2002; Ringius, 2002). Soil organic carbon and carbon inputs to the soil are expected to improve soil properties such as nutrient uptake, moisture retention, and tilth (Woomer et al., 1994) and, as a consequence, increase land productivity and crop yields and contribute to the restoration of degraded agro-ecosystems.

In drylands, especially in the Sudano-Sahelian zone, soils are inherently low in organic carbon (SOC) (Bationo and Buerkert, 2001). For Senegal, estimates in the West-Central part of the country range from 4.5 t C ha^{-1} for continuously cultivated areas without manure input to 18 t carbon (C) ha^{-1} for non-degraded savannas (Tiessen et al., 1998; Ringius, 2002). The amount of C that is likely to be sequestered in semi-arid regions is 0.05–0.3 t C ha^{-1} yr^{-1} on croplands, through improved management practices or changes in land use, and 0.05–0.1 t C ha^{-1} yr^{-1} on grasslands and pastures (Lal, 1999).

Despite these overall low sequestration rates, the technological potential to increase current soil carbon levels through rehabilitation of drylands is considered to be relatively high. This is primarily due to the fact that the SOM content in severely degraded areas is usually low and the extent of these degrading lands is vast. Improved land management practices such as reduced tillage, mulching, crop rotations, composting, manure application, fallowing, agroforestry, and soil salinity control as well as changes in land use patterns are not only expected to increase the rate of carbon dioxide (CO_2) uptake from the atmosphere but also to contribute to erosion and desertification control and enriched biodiversity (Lal et al., 1999; Lal, 2002). As such, carbon sequestration in soils could provide the vital link between three international conventions: the UN Framework Convention on Climate Change (UNFCC), the UN Convention to Combat Desertification (UNCCD), and the UN Convention on Biodiversity (UNCBD).

There are at least two important advantages of sequestering carbon in SOM of degraded agro-ecosystems rather than above-ground biomass. First, carbon sinks in degraded agro-ecosystems are more likely to secure carbon storage in the long run, primarily because of the longer residence time of carbon in soils. Also, smallholders who depend on soil fertility as the basis for their livelihoods are likely to have a greater incentive to protect this resource (Olsson and Ardö, 2002). Second, direct environmental, economic, and social benefits are expected to accrue for local populations inhabiting and cultivating degraded agro-ecosystems that are now perceived as potential carbon sinks. In areas where subsistence agriculture constitutes an important source of income for farmers, higher soil fertility and crop yields as well as restored grass and grazing lands could all directly enhance local food security and livelihoods.

Nonetheless, controversy surrounding the notion of carbon sequestration in soils remains. Many development practitioners are skeptical, arguing that carbon brokers, national ministries, and local leaders rather than needy rural populations will benefit from carbon offset projects. Another argument cited refers to important hidden 'costs' some management practices promoted for carbon sequestration might carry, increasing rather than reducing atmospheric CO_2 emissions (Schlesinger, 2000). Moreover, soil carbon sequestration will not be eligible during the first commitment period of the Kyoto Protocol, although political pressure has been growing (Ringius, 2002).

This paper is a contribution to the scientific debate on carbon sequestration in dryland farming systems. We assess the current carbon status in soils and biomass in the Old Peanut Basin of Senegal. These values are then used as key input data for carbon simulations performed with the CENTURY model (Parton et al., 1993, 1994). A series of improved management practices and land use changes, as identified through discussions with farmers in three villages, are tested through model simulations for their short and long-term carbon sequestration potential and their impact on agricultural yields. Finally, the longer-term sensitivity of soil and biomass carbon stocks and the stability of crop productivity were evaluated through a series of model simulations involving alternative climate change scenarios.

2. A case study in the Old Peanut Basin

2.1. Description of study area

The study, part of the SOCSOM project (Sequestration of Carbon in SOM), was conducted in the West-Central Agricultural Region of Senegal, also known as the 'Old Peanut Basin'.[1] It is characterized by a fairly flat landscape resulting from leveled old sand dunes between interspread dunal depressions. The two major soil types are described as *dior*[2] and *deck* (Badiane et al., 2000). *Dior* soils have a sandy texture containing more than 95 percent sand. Their organic matter content is very

[1] The name goes back to the introduction of peanuts (groundnuts) by the French colonial power at the end of the 19th century in an area initially overlapping with today's administrative regions of Diourbel, Louga, and Thiès (Pélissier and Laclavère, 1980). Nowadays, the term "Peanut Basin or "Bassin Arachidier" reflects a certain socio-economic entity in Senegal (Stomal-Weigel, 1988).

[2] Common names (in italics) are in Wolof, the most widely used local language in the Peanut Basin.

low (0.2 percent on average) as well as their content in total nitrogen (0.01 percent). Their exchangeable bases are of 0.9 cmol kg^{-1} with 0.07 cmol kg^{-1} for K and 0.1–1 cmol kg^{-1} for Mg. *Dior* have a pH between 6 and 7, and a low buffer capacity. These soils are usually white-gray in color, found in interdunal areas, and are composed of accumulated materials from aeolian and hydraulic origin, constituted of sand, clay, and silt.

In contrast, *deck* soils are hydromorphic with temporary water-clogged parts during most of the rainy season. They are sandy but more clayey than *dior* with clay contents from 3 to 8 percent and approximately 2 percent silt. The hydromorphic properties can be observed for topsoils or deeper horizons in the profile. They are usually found in lowlands with sand underlying marl-limestone deposits. *Deck* soils sometimes contain Montmorillonite clay. Therefore, they are usually heavier and better structured than *dior* soils. The available water content is about 5 percent on surface soils and 8 percent in deeper horizons and their pH between 5 and 7). Their content in organic matter, although higher than for *dior* soils, remains lower than 1 percent (between 0.5 and 0.8 percent) while total nitrogen varies between 0.02 and 0.04 percent. The phosphorus content is inherently low and, thus, constitutes the major deficient nutrient for these soils. The content of exchangeable bases in *deck* soils is higher than those of *dior* soils.

Annual precipitation in the Old Peanut Basin ranges from 350 to 700 mm, making this part of the country, where 90 percent of all arable lands are used for cultivation, just barely suitable for rain-fed agriculture (*Centre de Suivi Ecologique*, 2000). The main crops are millet (*Pennisetum typhoides* (L.) R. Br.), groundnuts (*Arachis hypogaea* L.), sorghum (*Sorghum bicolor* (L.) Moench), and cowpeas (*Vigna unguiculata* (L.) Walp.). The rainy season lasts from July to September or October, although both spatial and temporal variation of rainfall are high and episodic droughts and crop failures well known.

Today, mainly because of a long agricultural history and increasing population densities, the natural vegetation, including woody species primarily from the families of *Mimosaceae* and *Combretaceae*, has become increasingly under pressure. The major woody shrubs comprise *Balanites aegyptica* (Desert date) (L.) Del. and *Guiera senegalensis* (Guiera) J.F. Gmel. The most common tree species, according to the authors' observations, are *Acacia raddiana* (Twisted Acacia) (Savi) Brenan, *Acacia nilotica* (Black Thorn) (L.) Willd. ex Del., *Adansonia digitata* (Baobab) L., and *Faidherbia albida*.

Population density in the Old Peanut Basin is higher than in any other agricultural zone in Senegal, ranging from 150 to 225 inhabitants km^{-2} (*Centre de Suivi Ecologique*, 2000). Land use and land cover within farming systems have changed considerably over time. A comparison of remotely sensed imagery suggests that land under fallow has decreased from over 30 percent to less than 5 percent in most areas, although patches of new fallow in the north-east of the study area can be identified (Tschakert and Tappan, 2004). The scope of agricultural intensification varies depending on, inter alia, population pressure, availability of and access to land, and ethnic group affiliation (Pélissier, 1966; Copans, 1988; Stomal-Weigel, 1988; Lericollais et al., 1998).

2.2. Field and laboratory methods

2.2.1. Soil and biomass carbon measurements

Biomass and soil carbon measurements were obtained from seven fields in each of three different villages: *Thilla Ounté* (*Communauté Rurale de Touba Toul*), *Ngodjilème* (*Communauté Rurale de Ngoye*), and *Thiaytou* (*Communauté Rurale de Dinguiraye*). The sample fields included both infields and outfields of different sizes (<0.5 to 11 ha). Infields (*champs de case*) are directly adjacent to the village compounds and typically receive more organic matter inputs, including household waste, ashes, and manure from penned animals, than the more remote outfields (*champs de brousse*). Trees were counted and measured at diameter at breast height within a 0.25 ha (50×50 m) plot, established in the center of each field. Herbaceous biomass, litter, and roots were recovered from 42 randomly positioned 1, 0.25, and 0.04 m^2 replicate quadrates within the main plot. A total of 84 soil samples were collected from the 0–20 and 20–40 cm soil profile with the 0.04 m^2 quadrats. Accompanying bulk density samples from 10 and 30 cm soil depths were also collected, allowing C contents to be expressed on an area basis. Individual field histories were recorded in presence of field owners. All samples were analysed at the *Centre National de la Recherche Agronomique de l'Institut Sénégalais de Recherches Agricoles* (ISRA/CNRA) in Bambey. Total soil carbon was obtained using the Walkley and Black method (Walkley, 1947). Soil bulk density was determined from oven-dried core samples at 105°C for 24 h. Soil texture was measured using a Bouyoucos Hydrometer.

Data were standardized on a hectare basis. A conversion factor of 0.47 was used to reflect the proportion of C in all biomass pools. This factor represents the mean of the 0.45–0.5 range recommended to infer carbon content of biomass and intact litter from mass (Woomer et al., 2001). Due to the nonexistence of functions for species in the study area, tree biomass was calculated based on an allometric equation proposed for dry woodlands (FAO, 1997).

2.2.2. Simulation modeling with CENTURY

CENTURY, a biogeochemical ecosystem model that simulates fluxes of C, nitrogen (N), phosphorus, and sulfur (Parton et al., 1993, 1994, 2004), was used: (1) to estimate historic, present, and future carbon levels; and (2) to evaluate the impact of a series of candidate land management options on soil C dynamics and crop yields. The main output variables of interest were total soil C ($g\,m^{-2}$) in the upper 20 cm soil horizon and crop yields ($g\,m^{-2}$) for millet and groundnuts. C values obtained through ground measurements served to validate present C values as simulated with the model.

Due to the high sand content in the soils of the research area (95 percent), the "charcoal version" of CENTURY, a monthly version used by collaborators at Colorado State University (Keough, personal communication), was used instead of the standard monthly CENTURY . According to Skjemstad et al. (1996), the majority of protected soil C, analogous to the passive pool in CENTURY, can be in the form of charcoal in systems that are or were frequently burned. Input data for the model were obtained through the *Direction Nationale de la Météorologie* in

Table 1
Assumptions for future for climate change scenarios in CENTURY

Climate change scenarios	2020	2050	2080
Increase in temperature (°C) "LOW"	0.8	0.8	1.8
Decrease in precipitation (mm) "LOW"	−2	−10	−14
Increase in temperature (°C) "HIGH"	2	3.8	5.8
Decrease in precipitation (mm) "HIGH"	−30	−48	−48

Dakar, field measurements, and from the literature (Sagna-Cabral, 1989; Badiane, 1993). Recorded precipitation and temperature data from the Bambey station were used to initialize the climate and as a basis for future scenarios. Historic periods prior to 1960 were based on long-term (60 years) climate means. Land use and management changes after 1945 were reconstructed based on remotely sensed data and field interviews and then used to simulate historic C levels. Earlier periods were approximated using similar, less disturbed environments in adjacent parts of Senegal. Details on the historic scenario can be found in Tschakert (2004). The model was run to equilibrium for 1850 years before the first scenario was introduced.

Future land use and management options, specified in 25 scenarios, were also simulated with CENTURY using data from field investigations and the literature (Sagna-Cabral, 1989; Lekasi et al., 2001). These scenarios include conversion of cropland to grassland, various fallow periods with and without external inputs, grazing, organic matter inputs from manure, agro-forestry and tree plantation options with nitrogen-fixing *F. albida* and *Leucaena leucocephala*, and optimal agricultural intensification with manure application, green manure, mineral fertilizer, and 1-year fallowing (Table 3). Improved management practices were simulated for 1 ha of land over a 25-year and a 50-year period.

Finally, a sensitivity analysis was performed to explore the effect of changes in temperature and precipitation on both the historic and the future simulation scenarios (base case). For the historic part of the analysis, monthly temperature means was changed by −1°C, +1°C, +3°C, and +5°C. For precipitation, a departure of −50 percent, −20 percent, +20 percent, and +50 percent was calculated. Finally, two future climate change scenarios, a low and a high estimate, were tested for the period 2002–2100. The assumptions are presented in Table 1. These high and low estimates represent the draft emissions scenarios presented in the Intergovernmental Panel on Climate Change's Third Assessment Report and the modeled future climates as summarized for the Sahel and other areas by Hulme et al. (2001).

3. Results

3.1. Soil and biomass carbon measurements

Total system carbon among the 21 sites ranged from 12.7 to 59.3 t ha^{-1} (mean 28.2, S.D. = 12). Considerable variation was observed between sites, both for total

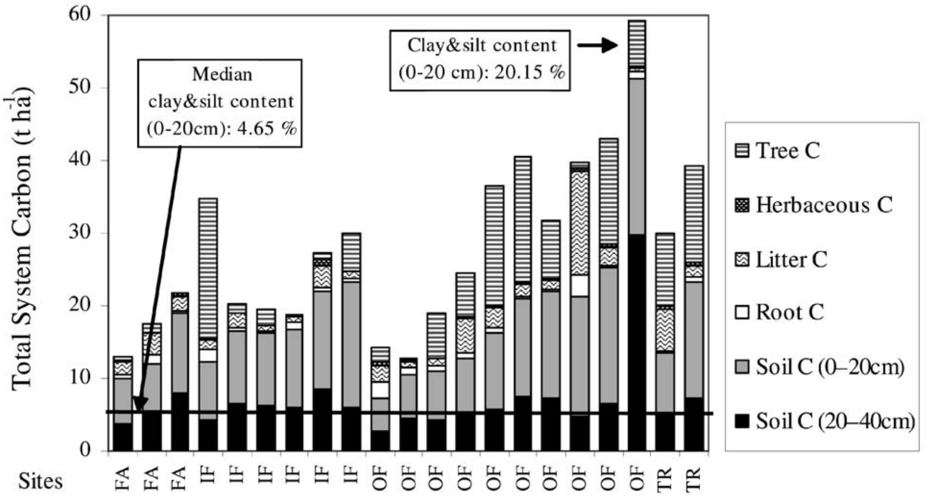

Fig. 1. Total system carbon (t ha^{-1}) for 21 sites in the Old Peanut Basin. FA = field in fallow; IF = infield; OF = outfield; TR = trees (parkland field). Source: Tschakert (fieldwork, 2001).

system carbon and individual carbon pools (Fig. 1). One of the sites (#11), in close proximity to a pond, contained 20.2 percent combined clay and silt in the 0–20 cm soil horizon (compared to <10 percent for all other sites) and 28.3 percent for the 20–40 cm horizon (compared to <15 percent for all other sites). Six of the seven other sites with high total system C (>34 t ha^{-1}) had a few old or several young trees, primarily *F. albida*, that accounted for tree C as high as 15–20 t ha^{-1} while roughly half of all sites showed $<$ 5 t ha^{-1}.

On average, combined soil and tree C accounted for 86 percent of total system carbon (S.D. = 11) while root, litter, and herbaceous C accounted for the remaining 14 percent. The 20–40 cm soil pool contained on average 37 percent of the total measured soil C, compared to 63 percent found in the upper 20 cm. Soil C (for 0–20 and 20–40 cm layers combined) varied from 6 to 50 t ha^{-1}. The mean soil bulk density was 1.6 g cm^{-3} (measurement results range from 1.5–1.79 g cm^{-3}, $n = 21$) and the SOC content 0.1–0.8 percent. The mean soil C in the top 0–20 cm reference depth was 11.3 t ha^{-1}. The same value was used later as a base comparison for carbon simulations with CENTURY. Values for soil C in the 20–40 cm horizon were 2.8–29.8 t ha^{-1} (mean 6.9, S.D. $\pm$5.4).

The mean value for tree C was 6.3 t C ha^{-1}, with large variation between sites (S.D. $\pm$6.4). Root and herbaceous C were almost insignificant, accounting on average for only 3.7 percent and 1.2 percent of the total, respectively. The paucity of herbaceous C is most likely related to the time of sampling (November–December). Litter C was of 0.5–14.2 t ha^{-1} (mean 2.5, S.D. $\pm$3), accounting for roughly 10 percent of the total system carbon.

Grouping the data by land use type (Table 2) reveals highest total system C for cultivated lands (29.5 t C ha^{-1}, S.D. $\pm$13.4). However, the mean obscures the

Table 2
Soil and biomass carbon by land use type, West-Central Agricultural Region, 2001

Land use type	*n*	Clay + silt	Clay + silt	Carbon (t ha^{-1})							
		% 0–20 cm	% 20–40 cm	Tree C	Herb. C	Root C	Litter C	Soil C 0–20 cm	Soil C 20–40 cm	Total soil C 0–40 cm	Total system C
Cultivated infields	6	3.84	5.43	4.80	0.29	0.75	1.42	11.59	6.22	17.81	22.68
		(0.81)	(1.00)	(7.30)	(0.42)	(0.51)	(1.11)	(4.25)	(1.42)	(5.22)	(8.01)
Cultivated outfields[a]	10	6.68	9.41	7.79	0.27	1.11	3.12	11.99	7.83	19.82	28.22
		(5.29)	(7.97)	(6.32)	(0.23)	(1.43)	(4.75)	(6.91)	(9.27)	(14.91)	(15.59)
Fallow	3	5.10	6.45	0.58	0.30	0.72	2.11	7.99	5.70	13.69	17.40
New parkland	2	5.70	6.73	5.85	0.44	0.58	3.62	12.09	6.23	18.32	28.81

Standard deviation in parentheses.

[a] Includes one field with high clay content (20.3% and 28.4% for the 0–20 cm and the 20–40 cm soil horizon, respectively).

differences between poorly and well-managed fields. "New parklands", fields with trees planted during the last decade, show a mean of 28.8 t C ha^{-1}. Lowest values were found on fields in fallow (17.4 t C ha^{-1}), most likely indicating the slow recovery rate of degraded areas.

3.2. CENTURY soil carbon and crop yield simulations

The simulation results (Fig. 2) suggest that the initial total system carbon in the native savanna environment amounted to 60 t ha^{-1}. During this pre-cultivation period, tree C accounted for 34.7 t C ha^{-1} and soil C for 20.1 t C ha^{-1}. With the introduction of agriculture, tree C decreased rapidly, dropping to 34 percent of its initial C content by 1900, which corresponds to a loss of 0.47 t C ha^{-1} yr^{-1}. Soil C declined more slowly (0.084 t C ha^{-1} yr^{-1}), resulting in a loss of 21 percent in 1900. Both SOC and tree C continued to decrease until 2001, due to a combination of agricultural expansion, biomass removal, periodic fire events, pruning, browsing, episodic drought events, and low organic matter inputs.

Current (2001) soil C values simulated with CENTURY amounted to 11.9 t ha^{-1} for the upper horizon (0–20 cm), which corresponds well with the 11.3 t ha^{-1} obtained through field measurements. Simulated tree C was 4.2 t ha^{-1}, comparable to the measured tree C of 6.3 t ha^{-1}. Overall, the model suggests that total system C has decreased by 71 percent (42.7 t ha^{-1}) from 1800 to present day. Losses of soil C amounted to 8.2 t ha^{-1} over 150 years (−41 percent) and those for tree C to 29.4 t ha^{-1} (−87 percent). In terms of crop yields, CENTURY simulated millet yields at an average of 653 kg ha^{-1} for the 1980–2001 historic scenario, which is higher than the official mean for the Bambey region (527 kg ha^{-1} reported by the *Direction de l'Agriculture*, unpublished document). Simulated groundnut yields were 707 kg ha^{-1}, close to the official 665 kg ha^{-1}.

The results of CENTURY simulations with respect to future management scenarios suggest that, after 50 years, total system carbon could be increased by 244 percent, from a mean present level of 17.3 t ha^{-1} to a maximum of 40.8 t ha^{-1}

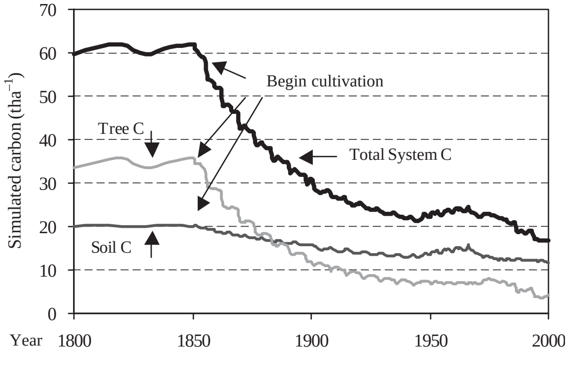

Fig. 2. Total system C, soil C, and tree C as simulated by CENTURY for the period 1800–2000. Source: Tschakert (2004).

(see also Tschakert, 2004). This would involve the conversion of agricultural land into a grassland-tree plantation with *F. albida (kad)*. Under an assumed worst-case scenario with annual millet–sorghum rotation and no external inputs, total system C would decline to an absolute low of 8.7 t ha^{-1} (−27 percent). A description of all 25 management scenarios as well as results for soil C, tree C, and total system C after a 50-year treatment period are listed in Table 3.

The largest gain in soil C (+115 percent) is expected to occur under an optimal intensification scenario (from 11.9 to 25.4 t C ha^{-1}). Soil C increases from *kad* plantations would be nearly as high as those under the intensification scenario, although the rate of increase is expected to be significantly lower. Other practices that are likely to result in increases in soil C include the application of cattle and sheep manure (4–10 t ha^{-1}) with 28–42 percent C (Lekasi et al., 2001) with or without fertilizer and 3–10 year fallow periods with organic matter input in rotation with 4–6 year cropping cycles. Management options involving short-term crop rotations with or without fallow and no organic matter input other than from grazing animals show a decrease in soil C of 1–4 t C ha^{-1} over 50 years. As for improvements in tree C, the grassland-tree plantation represents the best option, showing an increase of 4.2–11.8 t C ha^{-1}, which is comparable to C in woody biomass before 1900. Under the worst-case scenario, almost no tree C would be available in 50 years (0.6 t C ha^{-1} or loss of 86 percent).

Note that for all simulated management practices, with the exception of *kad* plantations, the largest changes in C, primarily with respect to soil C, occur during the first 25 years. Fig. 3 depicts annual changes in soil C for two 25-year periods (2002–2025 and 2026–2050). Simulated annual gains during the first management period range from 0.02 to 0.43 t C ha^{-1} yr^{-1} and losses from 0.02 to 0.13 t C ha^{-1} yr^{-1}. Increases >0.1 t C ha^{-1} yr^{-1} can be expected for management practices involving 4–10 t of manure, cropping cycles with 10-year fallow periods and organic matter support as well as agricultural intensification and the conversion of cropland to a *kad* plantation. On the other hand, losses >0.1 t C ha^{-1} yr^{-1} are likely to occur under annual rotation patterns that do not include nitrogen-fixation through groundnuts nor any organic matter inputs. Such worst-case options will result in further nutrient mining and decline of soil C. Changes in soil C during the second 25-year period are less significant, ranging from −0.03 to +0.1 t C ha^{-1} yr^{-1}. The only exception is the increase of 0.2 t C ha^{-1} yr^{-1} under the *kad* plantation scenario.

Finally, changes in crop yields as a result of simulated management options for a 25-year period varied from −62 percent to +200 percent for millet and −45 percent to +133 percent for groundnuts compared to historic (1980–2000) values. These predicted values correspond well with the simulated changes in soil C under worst and best management scenarios. Maximum gains in both millet (from 613 to 1959 kg ha^{-1}) and groundnuts (from 707 to 1647 kg ha^{-1}) were achieved under the optimum intensification scenario. Increases in groundnuts exceeded those in millet when significant amount of manure was simulated on millet fields (4–10 t ha^{-1}), reflecting the 1-year lag effect of manure on millet, as explained by farmers in the study area. Under the worst-case scenario (millet–sorghum rotation without any

Table 3
Soil C (0–20 cm soil depth), tree C, and total system C under 25 management scenarios as simulated with CENTURY for 2002–2050 ($t\,C\,ha^{-1}$)

Number	Scenario	Description	Soil C ($t\,ha^{-1}$)	Tree C ($t\,ha^{-1}$)	Total system C ($t\,ha^{-1}$)	Change total system C compared to 2001 mean ($t\,ha^{-1}$)[a]	Feasibility (smallholder perspective)
1	Rotation millet–sorghum (1:1)	Annual rotation; no inputs, browsing, increased pruning	8.0	0.6	8.7	−8.7	High
2	Rotation millet–groundnuts (4:1)	5-year rotation cycle; no inputs, browsing, increased pruning	8.0	0.6	8.7	−8.7	High
3	Rotation millet–groundnuts (2:1)	3-year rotation cycle; no inputs, browsing, increased pruning	8.1	0.4	8.6	−8.8	High
4	Rotation millet–groundnuts	Annual rotation; no inputs, browsing	9.8	4.8	16.2	−1.1	High
5	Rotation crops–fallow + 80 sheep (4:3)	Millet–groundnuts rotation; sheep summer grazing on fallow land; only inputs from grazing animals	10.2	5.3	16.7	−0.6	Medium
6	Rotation crops–fallow (4:3)	Millet–groundnuts rotation; 7-year rotational cycle; no inputs	10.5	4.7	16.4	−0.9	Medium
7	Rotation crops–fallow + 30 cows (4:1)	Millet–groundnuts rotation; 5-year rotational cycle with cows summer grazing on fallow land; only inputs from grazing animals	10.3	5.0	16.8	−0.5	Medium
8	Rotation crops–fallow + mixed animals (2:2)	Millet–groundnuts rotation; 4-year rotational cycle with low intensity grazing on fallow land; only inputs from grazing animals	10.4	5.2	17.3	0.0	Medium
9	Crops with protection of *kad*	Annual rotation millet–groundnuts; reduced pruning, no other inputs	10.9	4.8	17.6	0.3	High
10	Stubble grazing (20 cows)	Millet–groundnuts rotation with high intensity grazing November–December after millet; only inputs from grazing animals	10.2	4.7	16.4	−0.9	Medium

Table 3(*continued*)

Number	Scenario	Description	Soil C ($t\,ha^{-1}$)	Tree C ($t\,ha^{-1}$)	Total system C ($t\,ha^{-1}$)	Change total system C compared to 2001 mean ($t\,ha^{-1}$)[a]	Feasibility (smallholder perspective)
11	Horse manure 1.5 t	Rotation crops (millet–groundnuts)–fallow with manure (4:1); manure applied before June	10.7	4.6	16.7	−0.6	High
12	Grassland + grazing	All cropland converted to grassland with native grass; summer grazing with moderate intensity; only inputs from grazing animals	13.9	2.4	18.2	0.9	Medium
13	Compost	Millet–groundnuts rotation + 2 t of compost on millet; 4 t of millet stalks and 1.8 t of manure	12.2	4.5	18.5	1.2	Medium
14	Grassland	All cropland converted to grassland with native grass; no inputs	14.7	2.1	18.8	1.5	Medium
15	Grassland + protection *kad*	All cropland converted to grassland with native grass; *kad* trees protected; reduced pruning, no other inputs	15.3	4.0	18.6	1.3	Medium
16	Rotation crops–fallow + manure (4:3)	7-year rotational cycle; millet–groundnuts rotation; 2 t organic matter input on fallow land; 1 t of manure + 1 t of household waste	14.1	4.5	19.7	2.4	Medium
17	Cow manure 4 t	Millet–groundnuts rotation; manure on millet before June	14.5	4.8	21.0	3.7	Low–medium
18	Cow manure 4 t + fertilizer	Millet–groundnuts rotation; manure + 150 kg fertilizer (14-7-7) + 100 kg urea on millet; 150 kg fertilizer (8-18-27) on groundnuts	15.0	4.3	21.1	3.8	Low–medium

19	Sheep manure 5 t	Millet–groundnuts rotation; manure on millet before June	15.3	4.4	21.4	4.1	Low–medium
20	Rotation crops–fallow + leucaena prunings (4:3)	7-year rotational cycle; millet–groundnuts rotation; 2 t leucaena prunings on fallow land before June	15.3	4.6	21.1	3.8	Medium
21	Sheep manure 10 t	Millet–groundnuts rotation; manure on millet before June	16.5	4.4	22.6	5.3	Low
22	Rotation crops–fallow + manure (6:10)	16-year rotational cycle; millet–groundnuts rotation; 2 t organic matter input (1 t of manure + 1 t of household waste) on fallow land	17.1	4.9	23.5	6.2	Low–medium
23	Rotation crops–fallow + leucaena prunings (6:10)	16-year rotational cycle; millet–groundnuts; 2 t leucaena prunings on fallow land every 2nd year in July	17.3	5.0	23.9	6.6	Low–medium
24	*Kad* plantation	Cropland converted to grassland, native grass, 250–300 *kad* planted; only input from *kad* trees	23.0	11.8	40.8	23.5	Medium
25	Optimum agricultural intensification	3-year rotation cycle with groundnuts–millet–fallow; 150kg fertilizer (8-18-27) on groundnuts; 4 t manure on fallow; 5t sheep manure + 2 t leucaena prunings on millet; animal traction, reduced pruning, improved millet seeds	25.4	5.0	32.2	14.9	Low–medium

[a] 2001 simulated mean.

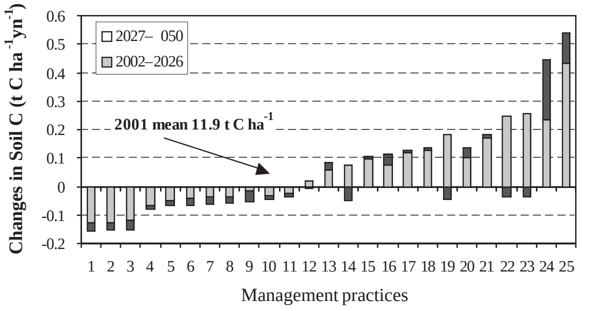

Fig. 3. Annual changes in soil C (t C ha^{-1} yr^{-1} for the 0–20 cm horizon) as a result of soil management practices and land use options, as simulated with CENTURY for two 25-year periods (2002–2026 and 2027–2050). Losses and gains are compared to the simulated mean for 2001. Bars with the 2002–2026 segment above zero and the 2027–2050 segment below zero represent non-sustainable practices over the long run. Numbers of management practices as in Table 3.

external inputs), the model suggests a drop in average millet yields to <300 kg ha^{-1}, which would be insufficient to satisfy basic household food needs.

3.3. CENTURY sensitivity analysis

Climate change scenarios indicate that, overall, forest C is more sensitive to modifications in precipitation and temperature than soil C. For the historic (1900–2000) scenarios (Table 4), the model simulates a loss of forest C of 33–71 percent compared to the base case as a result of increased monthly temperature (+3–5 °C), reduced annual precipitation (20–50 percent), and a combination of both. Losses in soil C for the same climate scenarios varied between 17 and 25 percent. On the positive side, the model indicates that a slight reduction in temperature (−1 °C) during the historic time period would have been favorable for all C pools while increased precipitation would have benefited forest C (10–24 percent change) but not soil C. Crop yields appear highly sensitive to changes in both precipitation and temperature. Under the worst-case (*P*–50 percent, $T+5$ °C) climate change scenario crop yields would have been 86 percent lower than under recorded climate conditions.

The results from the two future climate change scenarios ("LOW" and "HIGH"), based on a series of assumptions (Table 1), are presented in Tables 5 and 6. As for the historic scenarios, forest carbon is more sensitive to changes in precipitation and temperature than soil carbon. Slight changes in these two input variables, as assumed under the "LOW" scenario, will not have a significant impact on the carbon pools during the first half of the century. However, during the second 50-year period, losses in carbon across all pools would amount to 3–68 percent, with the largest impact on *kad* plantations. Larger changes in precipitation and temperature, as assumed under the "HIGH" scenario, are expected to cause losses in all carbon pools, being more

Table 4
Percent change in soil carbon, forest carbon, total system carbon, and carbon in grain ($g\,m^{-2}$) for various climate scenarios compared to the historic base case scenarios (1800–2000)

Climate scenarios	Year	Soil carbon	Forest carbon	Total system carbon	Carbon in grain
Base case ($g\,m^{-2}$)	1950	1426.6	687.0	2306.9	61.6
	2000	1176.8	405.1	1680.4	27.3
$P+50\%$, $T-1\,^{\circ}C$	1950	−1.7	30.9	8.8	−8.9
	2000	−2.6	32.4	6.8	8.4
$P-50\%$, $T+5\,^{\circ}C$	1950	−17.8	−39.1	−25.8	−86.3
	2000	−19.0	−70.6	−34.0	−86.4
$T-1\,^{\circ}C$	1950	4.4	6.7	5.5	−3.7
	2000	7.0	14.0	9.4	28.1
$T+1\,^{\circ}C$	1950	−4.2	−5.4	−4.9	−5.6
	2000	−6.4	−11.9	−8.4	−26.6
$T+3\,^{\circ}C$	1950	−13.4	−15.9	−15.3	−29.9
	2000	−17.4	−33.0	−22.8	−62.8
$T+5\,^{\circ}C$	1950	−20.2	−16.1	−20.5	−50.2
	2000	−25.1	−41.0	−30.9	−84.6
$P-20\%$	1950	−2.5	−17.2	−7.4	−20.1
	2000	−0.8	−23.7	−7.0	−16.5
$P-50\%$	1950	−5.0	−43.9	−18.0	−61.3
	2000	−3.7	−69.5	−21.8	−32.8
$P+20\%$	1950	0.2	13.2	4.4	1.7
	2000	−3.0	10.3	0.4	−10.4
$P+50\%$	1950	−5.6	23.9	3.5	−11.3
	2000	−8.4	17.9	−1.9	−14.7

P, annual mean precipitation; *T*, monthly mean temperature.

than twice as high as under the "LOW" scenario. The model suggests that by 2100 total system carbon would be 12–72 percent lower than under an average climate scenario. The smallest impacts are expected to occur under the millet–sorghum rotation scenario, primarily because current carbon values are already very low.

4. Discussion and conclusion

The results from the soil and biomass field measurements and the simulations performed with CENTURY for the Old Peanut Basin constitute a first step in a national carbon assessment for Senegal. Overall, carbon stocks in this semi-arid part of Senegal are relatively low and, without adequate management strategies, are likely to remain at risk.

The low SOC range (0.12–0.87 percent) is very common for soils in the Old Peanut Basin, as indicated by various authors investigating the effects of soil

Table 5
Percent change in soil carbon, forest carbon, total system carbon, and carbon in grain ($g\,m^{-2}$) for selected future management practices under an assumed climate scenario ("LOW") compared to the future base case scenarios (2002–2100)

	Time	Base case ($g\,m^{-2}$)				Climate change LOW (% change)			
		Soil carbon	Forest carbon	Total system carbon	Carbon in grain	Soil carbon	Forest carbon	Total system carbon	Carbon in grain
Worst case (millet–sorghum rotation)	2010	997	145	1168	11	0.0	0.0	0.0	0.0
	2025	884	55	952	7	−0.9	9.2	−0.4	−6.1
	2050	788	76	875	4	−0.4	15.7	−1.8	11.3
	2100	714	71	796	4	−2.8	−18.5	−4.5	1.6
Grassland	2010	1256	385	1810	0	0.0	0.0	0.0	n/a
	2025	1377	263	1817	0	−0.8	9.7	1.4	n/a
	2050	1485	183	1864	0	−2.0	−8.8	−3.6	n/a
	2100	1533	116	1801	0	−10.0	−56.8	−13.7	n/a
Kad plantation (*F. albida*)	2010	1425	633	2386	0	0.0	0.0	0.0	n/a
	2025	1720	610	2726	0	0.2	−0.6	−0.1	n/a
	2050	2325	1050	4075	0	−0.8	−6.7	−2.8	n/a
	2100	2796	1439	5072	0	−31.2	−67.8	−45.2	n/a
Optimum agricultural intensification	2010	1858	544	2549	90	0.0	0.0	0.0	0.0
	2025	2127	465	2775	62	−0.8	11.0	0.8	44.1
	2050	2438	520	3155	96	−5.1	−2.4	−4.9	−5.5
	2100	2430	431	3047	64	−15.0	−28.1	−17.7	−26.5

Climate change assumptions:
2020: temperature + 0.8 °C, precipitation − 2%;
2050: temperature + 1.8 °C, precipitation − 10%;
2080: temperature + 1.8 °C, precipitation − 14%.

Table 6
Percent change in soil carbon, forest carbon, total system carbon, and carbon in grain ($g\,m^{-2}$) for selected future management practices under an assumed climate scenario ("HIGH") compared to the future base case scenarios (2002–2100)

	Time	Base case ($g\,m^{-2}$)				Climate change HIGH (% change)			
		Soil carbon	Forest carbon	Total system carbon	Carbon in grain	Soil carbon	Forest carbon	Total system carbon	Carbon in grain
Worst case (millet–sorghum rotation)	2010	997	145	1168	11	0.0	0.0	0.0	0.0
	2025	884	55	952	7	−1.0	18.3	−2.1	−8.4
	2050	788	76	875	4	−0.7	34.7	−3.9	1.3
	2100	714	71	796	4	−5.0	−74.0	−12.0	−45.8
Grassland	2010	1256	385	1810	0	0.0	0.0	0.0	n/a
	2025	1377	263	1817	0	−3.1	3.7	−2.3	n/a
	2050	1485	183	1864	0	−10.5	−30.4	−13.2	n/a
	2100	1533	116	1801	0	−36.5	−68.8	−41.7	n/a
Kad plantation (*F. albida*)	2010	1425	633	2386	0	0.0	0.0	0.0	n/a
	2025	1720	610	2726	0	−7.2	−34.8	−15.2	n/a
	2050	2325	1050	4075	0	−34.3	−73.9	−49.3	n/a
	2100	2796	1439	5072	0	−60.7	−84.8	−71.6	n/a
Optimum agricultural intensification	2010	1858	544	2549	90	0.0	0.0	0.0	0.0
	2025	2127	465	2775	62	−5.0	−3.1	−5.3	−5.5
	2050	2438	520	3155	96	−15.6	−48.9	−22.6	−68.6
	2100	2430	431	3047	64	−40.3	−71.4	−46.7	−92.9

Climate change assumptions:
2020: temperature + 2 °C, precipitation − 30%;
2050: temperature + 3.8 °C, precipitation − 48%;
2080: temperature + 5.8 °C, precipitation − 48%.

organic amendment on soil C (Charreau and Vidal, 1965; Sédogo, 1981; Rabot, 1984; Badiane, 1993; Pérez et al., 1996; Badiane et al., 2000). It is also consistent with a SOC average of 0.76 percent for soils in the Sudano-Sahelian zone (Manu et al., 1991) and global values for dryland soils, ranging from 0.2 to 0.8 percent (Lal, 2002).

The highest measured SOC contents on sandy soils (0.73 and 0.74 percent C) can be directly linked to favorable management practices as recorded through field histories (application of 570 kg ha^{-1} of household waste on an infield and stubble grazing with 25 cows over 6 months in addition to 600 kg of 10-10-20 fertilizer on an outfield of 11 ha, respectively). The above SOC values are within the documented upper limits of 0.47 percent on continuously cultivated fields with manure input (Tiessen et al., 1998; Ringius, 2002) and 1.05 percent reported for an infield (Badiane et al., 2000) within the same area. The outlier with 0.87 percent SOC and 20.15 percent clay and silt content (see also Fig. 1) can be explained by the fact that higher clay contents usually also result in higher soil carbon levels (Pieri, 1992). Sites with 0.12–0.23 percent SOC (4–8 t C ha^{-1}) showed poor management histories, with 0.12 percent representing the lowest limit known for the Old Peanut Basin.

The fact that cultivated fields show, on average, higher soil C contents than fields under fallow confirms Ringius' assertion (2002) that short fallow periods are insufficient to restore SOM in degraded savannas of West Africa. The young fallows sampled (<3 years) constitute fields that have been temporarily taken out of production due to their degraded state and most likely require additional management input in order to recover. Unimproved fallows, even if left out of production for 10–15 years, are likely to cause continued degradation and nutrient mining rather than soil restoration, mainly as a result of combined grazing pressure, tree removal, and wind erosion.

Carbon losses since the introduction of agriculture around 1850, as simulated with CENTURY, have been considerable. This is particularly true for C in woody biomass (0.2 t C ha^{-1} yr^{-1}). However, relatively pristine and undisturbed control sites, required to accurately estimate historic carbon, no longer exist in the Old Peanut Basin. In fact, the study area is the only large region in Senegal without any protected (forest) areas. Hence, maximum historic C levels had to be approximated based on savanna woodlands and protected forests farther south and corrected for higher precipitation. Simulated decreases in SOC, especially for the period 1950–2000, are lower than the 4.3–7 percent annual losses reported by Pieri (1992) for 3–5 years of observation. This might be related to a temporary increase in soil C between the 1950s and the mid-1970s that can be interpreted as the result of above long-term average precipitation combined with intensified agriculture and inputs subsidized by the national government (Gaye, 2000). Actually, measured soil C contents do not deviate significantly from the 0.1–0.3 percent SOC range reported by Bonfils and Faure (1956) for matching field sites. This suggests that farmers have invested in soil fertility management and that, on average, C stocks have remained relatively stable over the last 50 years. In some cases, particularly on infields, SOC has in fact increased (Badiane et al., 2000).

The results from C dynamics simulations indicate that it is possible to increase C stocks through appropriate management and land use options but that the overall rate is likely to be modest compared to other agro-ecosystems. Annual soils C gains over 25 years ranging from 0.02 to 0.43 t ha^{-1} yr^{-1} on croplands are slightly higher than existing estimates of 0.1–0.3 t C ha^{-1} yr^{-1} (Lal, 1999; Batjes, 2001). Nevertheless, the expected C increase after a 25-year management period is unlikely to exceed 10.5 t ha^{-1}. This is roughly half of the upper limit estimated for tropical areas (Lal, 1999). Simulated climate change scenarios suggest that, without appropriate actions to preserve and improve existing C stocks today, these resources might be seriously threatened in the future. Crop yields are likely to be affected by both increase in temperature and a decrease in precipitation, putting additional pressure on smallholders depending to a large extent on subsistence agriculture.

'Best management practices' as modeled with CENTURY include the use of *L. leucocephala* as green manure, longer-term fallow periods in rotation with millet–groundnuts cropping cycles and converted cropland to grazing land or tree plantations as well as the use of mineral fertilizer and large amounts of manure, although the latter two remain contested in terms of their net C contributions (Schlesinger, 2000). None of these practices is new to smallholders in central Senegal. Most farmers actually protect *F. albida*, a tree with the capacity to fix nitrogen and stimulate litterfall from leaves at the beginning of the rainy season (Seyler, 1993). Simulated increases in soil C due to the use of compost (2 t ha^{-1} every other year) were modest and cannot be expected to be sustainable. Stubble grazing with no other inputs, the option preferred by most farmers, is predicted to result in C losses rather than gains over the long run.

Despite their recognition of the possible benefits of these 'best management practices' for local soil fertility management, it should be stressed that the majority of smallholders in the research area would most likely not be in the position to afford these strategies that, in addition, also sequester C, due to their limited resource base. Most of them seem simply unrealistic from a production perspective. For instance, 10 t of manure, recommended for one hectare every other year on the Basin's degraded soils (Sagna-Cabral, 1989), clearly exceeds the maximum usage of 3 t ha^{-1} (Badiane et al., 2000) and 4 t ha^{-1} among smallholders, the latter reported for one out of 180 fields visited for this study in 2001. Fallow periods longer than one year are officially prohibited by the law on land tenure (*Loi du* 19 *Decembers* 1975) (Lo and Dione, 2000), even though the law has been unevenly and incompletely applied (Golan, 1994) and long-term fallow exists in villages with low population pressure. What practices might make most sense from a farming system and livelihood perspective is described in Tschakert and Tappan (2004).

Additional caution is required when interpreting the simulation results. Model simulations are often fraud with uncertainties. Falloon and Smith (2003) estimate that data sets without estimates of error about the mean of SOC values used in models produce errors of 6.8–8.5 percent for site-specific calibrations and up to 34 percent for regional default input values. Thus, as the authors suggest, using error as an indicator for uncertainty could improve model predictions. Also, for future analysis, historic simulations should be performed for each of the 21 sites in the Old Peanut Basin for which measurements are available in order to improve model validation. Although CENTURY has been tested extensively in cropped soils, only few studies so far have used it for simulations in the Sahel (Olsson and Ardö, 2002; Parton et al., 2004). Hence, performance verification remains difficult.

Another shortcoming of the paper is that, for the purpose of the analysis, the same piece of land (1 ha) is assumed to undergo the same improved management practice or land use change for the duration of the simulation. In order to estimate sequestration potentials, monitor carbon improvements, and calculate remuneration schemes, this evidently constitutes the most convenient approach. In reality, such a management strategy would be in conflict with farmers' major production and livelihood objectives. Small-scale farmers, confronting highly "complex, diverse, dynamic and unpredictable" realities (Chambers, 1997), are more concerned with adapting to their constantly changing environment, seizing opportunities and evading hazards when they emerge (Mortimore and Adams, 1999) rather than to strive for C gains and new steady states as assumed by the model. Decisions regarding land use and management as well as production are not determined by profit (or C) maximization but by risk management and a variety of complex factors (Scoones et al., 1996). These factors include the availability of and access to land, labor, seeds, organic matter, means of transportation, the timely availability of cash, soil types and conditions, crop rotation patterns, location of the fields, animal pressure throughout the year, and economic side benefits of management practices. Institutional networks and agricultural policies, access to credits and subsidies, and land tenure arrangements also influence local decisions (Berry, 1993; Hart, 2000; Ayuk, 2001). Thus, focusing one single management practice for a given plot seems simplistic and, thus, somewhat misleading.

Based on the results from this analysis, it can be concluded that C gains through improved management practices and land use change in small-scale farming systems in dryland regions of Senegal may serve common goals of rural stakeholders and global society. Improving agricultural practices may be the key to simultaneously enhance food production and mitigate climate change. Whether or not farmers will be able and willing to implement most promising technological practices depends on a whole set of economic, institutional, social, and policy factors that all need to be taken into account before designing potential carbon offset programs. Other management strategies likely to result in lower rates of soil carbon sequestration, including short-term improved fallows and lower rates of manure applications, as well as a mix of management sequences on the same piece of land should also be considered viable opportunities. Promoting too narrow a set of 'best management practices' risks weakening local adaptability and diverse and opportunistic management regimes, both of which are crucial elements in small-scale farming systems in drylands.

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