ARTICLE IN PRESS

ELSEVIER

Journal of Arid Environments ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Journal of Arid Environments

www.elsevier.com/locate/jnlabr/yjare

Carbon stocks in Senegal's Sahel Transition Zone

P.L. Woomer[a,*], A. Touré[b], M. Sall[b]

[a] SACRED Africa, P.O. Box 79, The Village Market, Nairobi, Kenya

[b] Centre de Suivi Ecologique, B.P. 15532, Dakar-Fann, Senegal

Received 24 November 2003; received in revised form 12 February 2004; accepted 23 March 2004

Abstract

Managing carbon stocks within landscapes is a key mid-term mitigation of atmospheric and climate change. Carbon (C) stocks residing in the vegetation and soils of five sites along a 120 km north–south transect within Senegal's Sahel were determined in degraded grasslands, grasslands with isolated and scattered shrubs, shrubby grasslands, and brushland with isolated trees. Total system carbon to 40 cm soil depth ranged between 12.0 and 31.2 t C ha^{-1} with an overall mean of 20.6 t C ha^{-1} (SEM = 1.8). The canopy cover of woody vegetation was significantly related to total system C to 40 cm (kg ha^{-1}). Total soil organic C (SOC) contents were not significantly different between plant communities despite ranging between 11.6 and 25.3 t C ha^{-1}, an observation that is likely due to under-replication. The overall mean of SOC to 40 cm was 17.2 t C ha^{-1} (SEM = 2.7) with 60 percent of that carbon residing in the top 20 cm. Woody bio-volume (m^3 ha^{-1}) was calculated from canopy coverage and average canopy height, and was significantly correlated with woody biomass ($p = 0.02$), total biomass ($p = 0.03$), SOC ($p = 0.05$) and total system C ($p = 0.02$) and warrants consideration as an indicator of land quality and carbon status in the Sahel. Assuming that degraded grasslands may be restored to woody grasslands over 20 years, then C sequestration rates of 0.77 t C ha^{-1} yr^{-1} may be achieved.
© 2004 Elsevier Ltd. All rights reserved.

Keywords: Africa; Carbon sequestration; Dryland management; Land degradation; Plant communities

1. Introduction

White (1983) describes the Sahel Regional Transition Zone as a 400 km wide band stretching from the Atlantic Ocean to the Red Sea and occupying approximately

*Corresponding author.

E-mail address: plwoomer@africaonline.co.ke (P.L. Woomer).

0140-1963/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jaridenv.2004.03.027

2,482,000 km^2. Wooded grassland is the dominant vegetation in the northern Senegal's Sylvo-Pastoral Ecological Zone, an area that occupies approximately 75,000 km^2 and is representative of the larger southern Sahel (White, 1983; Batjes, 2001). Quantification of carbon stocks for different land conditions of the Sahel allows for better estimates of carbon losses to the atmosphere as dryland vegetation formations or land degradation patterns are compared over time (Lal, 2002).

A confluence of interest exists between African land users and the carbon stocks they manage (Woomer et al., 1997). Soil organic carbon (SOC) and carbon inputs to soil result in greater land productivity and contributes to favorable soil properties such as moisture and nutrient retention, which in turn buffer ecosystems from abiotic stresses (Woomer et al., 1994; Murage et al., 2000). Mortimore and Adams (2001) describe Sahel systems as 'unstable but resilient', implying that the variability is driven by precipitation patterns (Hulme, 2001). The resilience of the system is protected by its biomass and soil carbon, the absence of which is an expression of desertification, a situation that only leads to worsened and more frequent human crises (Squires et al., 1998).

International negotiations continue concerning climate change mitigation under the Kyoto Protocol which focuses upon carbon emissions and stocks resulting from (Article 3.3) "… *human induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation* …" and (Article 3.4) "… *additional human-induced activities related to … agricultural soils and land use change* …" (Noble and Scholes, 2001). Lal (2002) asserts that these Articles provide entry points for the management of drylands as credible carbon sinks and that the restoration of desertified lands and the promotion of perennial woody biomass are two key mechanisms to meet that end. Similarly, Noble and Scholes (2001) argue in favor of more flexible, inclusive definitions of "forests" to include dry woodlands with canopy covers as low as 10 percent. Ojima et al. (1993) describe drylands as having tremendous opportunity for carbon offsets because of their large area and low human populations, despite their relatively low carbon stocks and unfavorable climates.

What are the carbon stocks in the Sahelian landscape and their potentials for increase? The Sahel itself is a transition zone between the Great Sahara Desert to the north and the Sudanese dryland forests to the south (White, 1983). Northern wooded grasslands contain dwarfed shrubs that are many crown-diameters distant, while similar communities to the south support shrubs and trees with canopies that are occasionally touching. Authorities differ in their projections for carbon sequestration in grazed warm drylands with estimates ranging between 0.1 and 1.0 $t\,C\,ha^{-1}\,yr^{-1}$ (Squires et al., 1998; Noble and Scholes, 2001; Lal, 2002). Large differences in the capacity for sandy, dry tropical soils to retain SOC are reported (Woomer et al., 1994; Eve et al., 2001; Feller et al., 2001; Batjes et al., 2001) and often these observations do not account for vegetation and organic inputs to soils. In this study, we describe the carbon stocks occurring in several plant communities within Senegal's Sahelian transition and discuss possible mechanisms to protect and increase that carbon. Studies of this nature allow for more reliable estimates of sub-regional C stocks in the future and provide the foundation for assessment of carbon offset opportunities within the Sahel.

2. Materials and methods

Whole system carbon stocks were characterized and then classified by the density and stature of their woody vegetation (White, 1984) at five locations within Senegal's Sylvo-Pastoral Zone along an approximate 120 km north–south transect (Table 1). The woody species present included *Acacia tortilis* (Savi) Brenan, *Balanites aegyptiaca* (L.) Del., *Boscia senegalensis* (Pers.) Lam. Ex Poir., *Commiphoia* spp. and *Guiera senegalensis* J.F. Gmel. The sites receive between 280 and 400 mm of annual rainfall and have sandy soils classified as Arenosols or Regosols (FAO, 1977). All sites are grazed intermittently and browsed by cattle and goats but only 4.3 percent of Senegal's Sylvo-Pastoral Zone is cultivated (Assize Touré, pers. comm.). One of these sites represented an overexploited (mostly overgrazed) grassland that was considered to be severely degraded. The remaining plant communities represent steps along the continuous gradient from northern grassland to southern shrub land. During the short, annual rains a near-continuous annual grass community forms that is dominated by mixtures and mosaics of *Cenchrus biflorus* Roxb., *Aristida mutabilis* Trin. & Rupr., *Schoenefeldia gracilis* Kunth*, Dactyloctenium aegyptium* (L.) Wild and *Zornia glochidiata* DC. While this area is considered too "dry" for agriculture, it is nonetheless settled and its cultivators experience both periodic crop failure (one year in three) and episodic drought (Hulme, 2001).

Biomass carbon was calculated from the 2000 and 2001 field records of a long-term study originally designed to correlate annual bioproductivity with remotely sensed Normalized Difference Vegetation Index (NDVI) (Diouf and Lambin, 2001). Five sites were selected for analysis with four replicates per site. Each replicate occupied between 0.0625 and 0.25 ha, with smaller plots established at locations with greater densities of woody biomass. The location, vegetation, soils and topography of these sites are described by CSE (1990). Reinterpretation of woody biomass carbon stocks required that basal diameter (BD) measurements be used to estimate the diameter at breast height, then biomass assigned using an allometric equation for dry woodlands (FAO, 1997) with the correction for the over-accounted 1.3 m bole based on geometry and wood density. A value of 0.83 DBH:BD was empirically derived from the paired measurements of 860 trees in the Groundnut Basin by Ndao (2001). Other estimates for this relationship range between 0.78 to 0.9 (O. Diallo, pers. comm.).

Peak-season herbaceous biomass was measured by destructive sampling of 1.0 m quadrats. The proportion of roots to woody biomass (0.38) was derived from the work of Bille and Poupon (1972) who examined subterranean tree biomass for 17 trees of up to 27 cm diameter. Herbaceous root biomass was assumed to be 0.2 of aboveground, a conservative value based upon carbon allocation to roots by annual plants used in the Century model (Metherell et al., 1993). The proportion of C in all biomass pools was assumed to be 0.47. Other vegetation measurements that were calculated from the records of Diouf and Lambin (2001) were woody species canopy cover (percent) and average heights (m) which were further employed to calculate woody biomass volume ($m^3\,ha^{-1}$) and bio-volume C density ($kg\,C\,m^{-3}$).

Table 1
Characteristics of Sahel transitional vegetation in Senegal

Transitional vegetation[a]	Dominant plants[b]	Coordinates		Canopy	
		Longitude (deg)	Latitude (deg)	Cover (%)	Height (m)
Degraded grassland	*Cenchrus biflorus, Eragrostis tremula, Zornia glochidiata*	14.51 W	16.09 N	0.8	1.16
Grassland[c]	*C. biflorus, Schoenefeldia gracilis, Dactyloctenium aegyptium*	13.97 W	16.11 N	4.5	1.22
Grassland w/ shrubs[d]	*C. biflorus, Boscia senegalensis*	14.47 W	16.38 N	6.0	2.53
Shrubby grassland	*Guiera senegalensis, Boscia senegalensis*	14.21 W	15.59 N	15.9	1.74
Shrubland w/ trees[e]	*Pterocarpus lucens, Guiera senegalensis*	14.58 W	15.24 N	27.7	2.16
$LSD_{0.05}$				9.5	0.48
Overall mean (SEM)[f]				10.9 (2.6)	1.76 (0.14)

[a] Vegetation descriptions based upon F. White (1983) *The Vegetation of Africa*, UNESCO, Paris, 356pp.
[b] *sen.* = *senegalensis*.
[c] Grassland with isolated shrubs.
[d] Grassland with scattered shrubs.
[e] Shrubland with scattered trees.
[f] Standard error of the mean in parenthesis.

Total SOC ha^{-1} to 40 cm was calculated from measuring the total soil organic carbon concentrations ($g\,C\,kg^{-1}$) of the 0–20 and 20–40 cm soil layers and soil bulk density at 10 and 30 cm depths (kg soil l^{-1}). Soils were collected along two replicate transects with sub-samples bulked and mixed. Soils were analysed for C in duplicate using wet digestion (sulfuric acid and potassium dichromate) with external heat (150 °C) for 30 min and then absorbance measured at 600 nm using a colorimeter (Nelson and Sommers, 1975). Bulk density was measured by oven drying soil cylinders of known weight and volume for most soils although the volume infill procedure was employed for coarser, sandy soils (Okalebo et al., 2002).

Plant communities were differentiated based upon canopy and woody bio-volume (cover × height) and was subsequently employed as a key parameter for sorting data. These data were inspected and then imported into a computer statistics program where summary statistics (mean and standard errors) were obtained and simple ANOVA performed. Mean values were compiled on a second spreadsheet, and simple linear regressions performed for woody C, biomass C, soil C and total C ($kg\,C\,ha^{-1}$) employing woody bio-volume ($m^3\,ha^{-1}$) and canopy cover (percent) as independent variables.

Carbon dynamics were simulated for a Sahelian savanna under different land use scenarios using the Century Model version 4.0 (Metherell et al., 1993; Parton et al., 1994). Carbon and nitrogen dynamics were first simulated for 162 years, beginning in 1800, as a lightly grazed shrubland (3 months per year of grass without tree leaf removal) established on a sandy soil (91 percent sand) receiving an average 224 mm precipitation $year^{-1}$ (88 percent falling between July and September) with minimum and maximum mean monthly air temperatures of 15.4–25.1 °C and 31.1-41.1 °C, respectively. Between 1962 and 1999, the simulation was based upon available monthly weather records with additional simulations for intensified grazing (with additional tree leaf browsing 4 months per year) with and without soil erosion ($3\,t\,ha^{-1}\,year^{-1}$). In 2000, browsing was eliminated (e.g. livestock were excluded) and "thorn trees" introduced (Metherell et al., 1993) with modest organic fertilization ($200\,g\,m^2$) to simulate a land restoration effort. Outputs were captured for all soil and litter carbon pools and above- and below-ground herbaceous and "forest" (shrubby) biomass C.

3. Results

The Sahelian sites were separated into five different plant communities with woody biomass cover values ranging between <1 and 28 percent with an overall canopy height of 1.6 m (Table 1). These features resulted in approximately 10-fold differences in shrubby bio-volume, from 606 (SEM ± 266) to 6022 (± 1241) $m^3\,ha^{-1}$ with an average woody biomass density of 0.89 (± 0.11) $kg\,C\,m^{-3}$ (data not presented). Total system C averaged across all vegetation types was 20.6 (± 1.8) $t\,C\,ha^{-1}$; 84 percent of that carbon resided in SOC (Table 2).

Woody C was the largest overall biomass C pool (2584 $kg\,C\,ha^{-1}$) and comprised a larger C pool than peak-season herbaceous biomass at four of five sites (Fig. 1) even

Table 2
Peak-season biomass, soil and system carbon stocks in different plant communities within Senegal's Sahel transition zone

Transitional vegetation	Total biomass ($kg\,C\,ha^{-1}$)	Soil C (0–40 cm) ($kg\,C\,ha^{-1}$)	Total C ($kg\,C\,ha^{-1}$)
Degraded grassland	419	11562	11981
Grassland w/ isolated shrubs	905	11728	12633
Grassland w/ scattered shrubs	3068	16333	19401
Shrubby grassland	1983	25347	27330
Shrubland w/ scattered trees	6543	(25347)	31890
$LSD_{0.05}$	1714	n.s.	1715
Overall mean (SEM)[a]	2584 (549)	17254 (2664)	20647 (1825)

[a] Standard error of the mean in parenthesis.

when its coverage was as low as 4.5 percent (Table 1). The 0–40 cm soil profile contained an average 17254 ($\pm$2664) kg SOC ha^{-1}, 60 percent of which resided in the top 20 cm. Significant differences in biomass C pools were observed ($p<0.001$) between vegetation formations but not for SOC (Fig. 1), although this difference may be due to weakness in replication. Average aboveground annual bioproductivity was estimated to be 424 ($\pm$58) $kg\,C\,ha^{-1}\,year^{-1}$ (calculated from Fig. 1). Canopy cover (percent) served as a useful predictor of whole-ecosystem C-storage to a depth of 40 cm. Another useful relationship was established between soil C and woody biomass canopy cover over a range approximately 1–28 percent where *Total C to 40 cm (kg ha*$^{-1}$*)*=11060 + 800 *canopy coverage percent* ($r = 0.97$, $p = 0.01$) (data not presented).

A strong trend in increased system carbon ($p = 0.01$) was observed as vegetation progressed from degraded grassland, to grassland with shrubs to shrub land with isolated trees (Fig. 1). Biomass C became an increasingly larger component of total system C along that same progression. It is difficult to comment upon root carbon as no actual measurements were made, rather this pool is inferred from above-ground measurements. Another weakness in the data is the absence of surface litter C, although this pool tends to be small during peak herbaceous biomass, and then increase as those annual herbs suffer necrosis following the end of the rains (M. Wele, pers. comm.).

The outputs of from the Century Model for different land use and restoration scenarios are presented in Fig. 2. Only the last 20 years of the 162-year ''natural'' land management are presented to allow for better interpretation of the 40-year land degradation and following 20-year land restoration scenarios. Note that the measured C stocks from this study (years 2000 and 2001) of degraded grasslands are similar to the simulated values for heavy grazing combined with soil erosion and that less degraded lands (shrubby grassland and shrub land with trees) have a carbon content that is more comparable to the other two simulations.

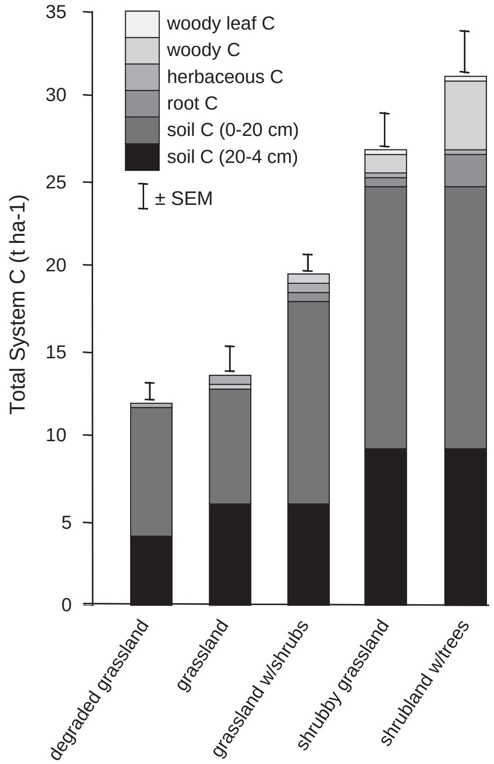

Fig. 1. Carbon pools in different plant communities occurring in sylvo-pastoral areas of Senegal's Sahel.

4. Discussion

Lal (2002) describes four mechanisms to better manage carbon stocks in drylands: (1) better protection of current C stocks, (2) restoration of degraded ecosystems, (3) establishment of biofuel plantations and (4) agricultural intensification. This discussion dismisses the possibility of carbon gains through agricultural intensification within the study area because it lacks sufficient rainfall or access to irrigation that would lead to enhanced biomass yield through improved technologies. The other three technical options have merit and warrant further discussion.

Prevention of further deterioration of existing carbon pools through better controlled stocking rates and the preservation of perennial woody biomass is a prime objective. One of the adjustments made by land managers in the Sahel following the severe drought during the 1970s was the 'integration' of cattle herds by increasing the proportion of small ruminants (Mortimore and Adams, 2001). While this strategy better averts risk, it also places greater pressure upon shrubs because of the browsing habits of goats. Complicating this situation in many areas is the uncontrolled production of charcoal and periodic wildfires. Desertification control is of

ARTICLE IN PRESS

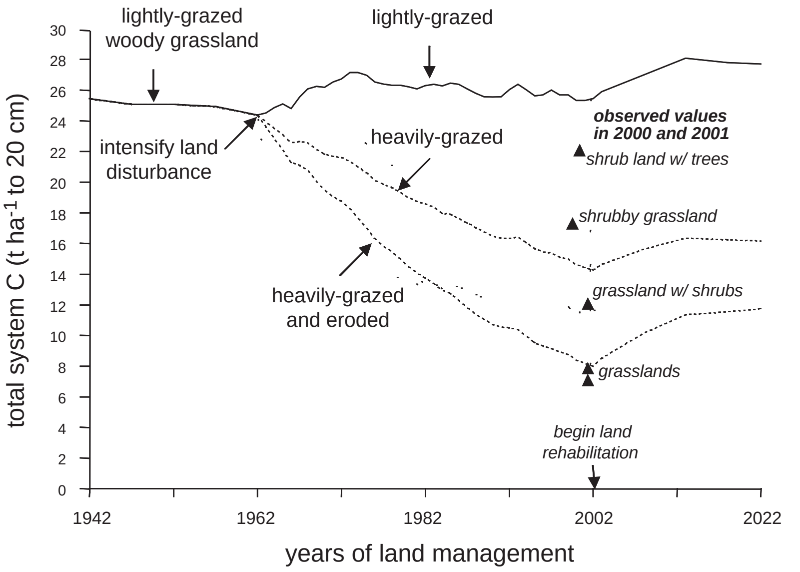

Fig. 2. A Century Model simulation of a Sahelian Woody Grassland in northern Senegal subjected to different intensities of land management and followed by land rehabilitation. Note that the observed values for 2000 and 2001 suggest that carbon status may be attributed to plant communities.

paramount importance within the Sahel for more reasons than carbon management and a key to its control is better understanding by pastoralists and livestock producers with farms of the future consequences of the current management (Squires et al., 1998). Batjes (2001) also raised the technical possibilities of applying fertilizer and establishing improved varieties in moderately degraded lands of the Sahel, but concedes difficulties in the adoption of these practices within pastoral areas. The results of this study indicate that at least 15 t C ha^{-1} are subject to loss as woody grasslands degrade (Table 2, Fig. 1).

Dregne et al. (1991) characterized 53 percent of Africa's 13.4 million km^2 rangelands as moderately to severely degraded. Rangeland rehabilitation includes combinations of physical controls of erosion, soil fertility improvement, plant introduction and seed dispersal, contour and boundary plantings (Lal, 2001) and afforestation where tree introduction is accompanied by grasses and shrubs (Ojima et al., 1993). The costs of land rehabilitation rise disproportionately as land becomes increasingly degraded, with the most degraded land requiring between \$500 to \$4,000 ha^{-1} (Ojima et al., 1993). The results of our study illustrate the advantages of fostering woody biomass within rangelands, with each percent increase in woody canopy cover resulting in 800 kg C ha^{-1} ($p = 0.01$) in woody biomass. Increases in canopy cover by as much as 15 percent (= 12 t biomass C ha^{-1}) appear to be possible as the shrub density increases in grasslands (Table 2). One persistent obstacle to rangeland rehabilitation is the difficulties in protecting young woody vegetation from browsing ruminants after they are introduced and until they reach sufficient stature to resist foraging animals. An alternative is to establish livestock exclosures for several years but this is a practice that divests stakeholders from their lands and consequently risks alienating national planners from carbon offset projects (Trexler, 1993).

Biofuel plantations offer twin advantage with carbon first being sequestered in biomass and soil and then harvested products having potential to substitute for fossil fuels, sinks that are credible within the Kyoto Protocol. Several tree species grow within the studied grasslands (e.g. *Acacia tortilis*, *Guiera senegalensis* and *Pterocarpus lucens*), but their capacity to grow in denser plantation stands is likely to be constrained by moisture availability. Similarly, the capacity of exotic dryland tree species such as neem (*Azadirachta indica*), *Eucalyptus* spp., mango (*Mangifera indica*), tamarind (*Tamarindus indicus*) or *Prosopis* spp. to afforest the Sahel is uncertain. Sudanese dryland forests to the south of Senegal's Sahel contain 45 and 19 t C ha^{-1} as biomass and SOC, respectively (calculated from Ndao, 2001). If such communities could be replicated in the Sahel, then system C gains of approximately 41 t C ha^{-1} above the current C stocks could be achieved. Another option for C management in the Sahel may be biofuel production within the nearly impenetrable deciduous brushland thickets described by White (1983). These stands, consisting primarily of *Commiphora africana* (A. Rich.) Engl., *Boscia senegalensis* (Pers.) Lam. ex Poir. and *Acacia mellifera* (Wahl) Benth., occur elsewhere the Sahel and are likely to contain much more biomass C than their Senegalese grassland counterparts. Clearly, potential exists for carbon gains through biofuel plantations, and many of the technical details concerning their management and profitability should be addressed.

Woody canopy cover correlated well with carbon stocks and pools in this study but measurement based upon canopy alone is dangerous because the stature of woody biomass remains unaccounted. For this reason, woody bio-volume (m^3 ha^{-1}) was calculated by combining canopy coverage and height measurements (Table 1) and then used as an independent variable for multiple regression (Table 3), a procedure that resulted in significant correlation (r) with every system C pool except for herbaceous biomass C. Bio-volume lends a "third dimension" to canopy coverage that can account for the differences in the height of woody vegetation. We suggest that woody bio-volume may provide a useful indicator of land quality and carbon status within different areas of the Sahel. For example, if relationships established in this study (Table 3) are extrapolated to the brushland thickets

Table 3
Regression relationships between woody bio-volume and system carbon stocks

Dependent variable	Regression equation	r	p
Woody biomass C (kg ha^{-1})	$Y = 157 + 0.67$ bio-volume (m^3 ha^{-1})	0.92	0.02
Total biomass C (kg ha^{-1})	$Y = 574 + 0.93$ bio-volume (m^3 ha^{-1})	0.92	0.03
Soil C 0–20 cm (kg ha^{-1})	$Y = 7782 + 1.51$ bio-volume (m^3 ha^{-1})	0.87	0.05
Soil C 0–40 cm (kg ha^{-1})	$Y = 1288 + 2.47$ bio-volume (m^3 ha^{-1})	0.87	0.05
Total C 0–20 cm (kg ha^{-1})	$Y = 8442 + 2.43$ bio-volume (m^3 ha^{-1})	0.95	0.01
Total C 0–40 cm (kg ha^{-1})	$y = 13454 + 3.41$ bio-volume (m^3 ha^{-1})	0.94	0.02

described above, these relationships predict that the thickets contain 14 t C ha^{-1} as woody biomass and 51 t ha^{-1} total system C. Twenty year-old biofuel thickets may have the potential to accumulate 0.6 and 1.5 t C ha^{-1} year^{-1} as woody biomass and total C, respectively (calculated from Tables 2 and 3 and Fig. 1).

Several limitations to this study warrant mention. The study sites do not include examples from the Sahel Semi-Desert Grassland (White, 1983) which occurs to the north of Senegal. This major vegetation type receives <250 mm of annual precipitation and likely contains much less system C per unit area. We speculate, however, that our degraded grassland community type containing approximately 12 t ha^{-1} of system carbon to a depth of 40 cm may be representative of this band across the northern Sahel.

We were unable to determine the extent to which livestock and human activities were responsible for the changes in vegetation formation and the timeframe of these changes. For this reason, we are reluctant to express our measured C data in terms of C flux (e.g. t C ha^{-1} year^{-1}). Land restoration programs for degraded rangelands are estimated to require approximately 20 years (Ojima et al., 1993), however, and if the system C differences observed between the degraded and shrubby grasslands land could be achieved over this interval, then C gains would be approximately 0.77 t C ha^{-1} year^{-1}. We are, however, able to interpret C flux based on historical land use changes using the Century Model (Fig. 2). Simulations using observed monthly climate data between 1960 and 1999 suggested little change in total C stocks due to weather pattern alone. Wind erosion of soil, combined with the climate pattern, resulted in a reduction of total C by 8.2 t C ha^{-1}, with 88 percent of this loss accounted by changes in soil C (which is likely to be re-deposited elsewhere). Intense browsing by goats, and combination of browsing and wind erosion suggests that total system C is steadily reduced to 12.8 and 18.7 t C ha^{-1}, respectively, after 40 years of disturbance. Wood removal for charcoal collection results in the most rapid system C loss but this effect becomes attenuated as the availability of woody biomass decreases (data not presented). Initiation of a desertification control program that excludes livestock and human pressures, replants N-fixing trees and arrests soil erosion results in immediate but modest C gains (<250 kg C ha^{-1} year^{-1} over 20 years), with the 1962 level of system C not obtained for over 100 years (data not presented). It appears more advantageous to protect system C in northern Senegal than to attempt its sequestration following severe disturbance. Data from Tables 2 and 3 suggests that the Century model simulations (Fig. 2) fall within the range of measured carbon stocks in different shrub and grassland formations after the difference in measured total soil C (0–40 cm) and simulated soil C (0–20 cm) are taken into account.

Carbon contained in the surface litter was not considered in this study and work conducted in dry woodlands and savannas elsewhere in Africa suggest that this may be a relatively large C pool. Woomer (1993) reported 3.8 t ha^{-1} of litter carbon in a dry miombo woodland in Zimbabwe, the result of 2.1 t ha^{-1} litterfall C. Manlay et al. (2002) reported an average 980 kg litter C ha^{-1} ($\pm$39) in 11 fallows in southern Senegal. Surface litter was collected by the authors in five grasslands approximately 50 km to the west of this study at the onset of the rains in 2002. The sites contained an average 493 kg ha^{-1} ($\pm$63) surface litter C, but it is unknown how much of this litter would have been accounted as woody leaf and peak season herbaceous biomass during the previous rains in 1991. Clearly, failure to collect surface litter resulted in an underestimate of system C, but we argue that this error is likely to be less than 500 kg C ha^{-1}. Despite the methodological shortcuts employed in this study, we believe that we have estimated the carbon stocks contained in several important vegetation formations established in sandy soils of Africa's Sahel.

Acknowledgements

We thank M. Wele of the Centre de Suivi Ecologique, Dakar for providing insights into the vegetation formations and soils of Senegal's Sahel and making records from the NOAA-CSE NDVI study available for carbon reinterpretation. M. Sène of ISRA-CNRA, Bambey, Senegal provided assistance in the analysis and interpretation of soil analytical results. L.L. Tieszen of the EROS Data Center, Sioux Falls, USA provided encouragement and the means to conduct this study.

References

Batjes, N.H., 2001. Options for increasing carbon sequestration in West African soils: an exploratory study with special focus on Senegal. Land Degradation & Development 12, 131–142.

Bille, J.C., Poupon, H., 1972. Recherches Ecologiques sur une savane sahélienne du Ferlo septentroional, Senegal: biomasse végétale et production primaire nette. Revue d'Ecologie Appliquée 26, 366–382.

Centre du Suivi Ecologique (CSE), 1990. Emplacement et Caractéristiques des Sites de Controle au Sol. CSE, Dakar.

Diouf, A., Lambin, E.F., 2001. Monitoring land-cover changes in semi-arid regions: remote sensing data and field observations in the Ferlo, Senegal. Journal of Arid Environments 48, 129–148.

Dregne, H., Kassas, M., Rosanov, B., 1991. Desertification Control Bulletin (United Nations Environment Programme, Nairobi, Kenya) 20, 6–18.

Eve, M.D., Paustian, K., Follet, R., Elliott, E.T., 2001. A national inventory of changes in soil carbon from national resources inventory data. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Assessment Methods for Soil Carbon. Advances in Soil Science (series). Lewis Publishers, Boca Raton, USA, pp. 593–628.

FAO-Unesco, 1977. Soil Map of the World. Vol. VI. Africa. Unesco, Paris.

Feller, C., Balesdent, J., Nicolardot, B., Cerri, C., 2001. Approaching "functional" soil organic matter pools through particle-size fractionation: examples for tropical soils. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Assessment Methods for Soil Carbon, Advances in Soil Science (series). Lewis Publishers, Boca Raton, USA, pp. 53–67.

Hulme, M., 2001. Climate change perspectives on Sahelian desiccation. Global Environmental Change 11, 19–29.

Lal, R., 2002. Carbon sequestration in dryland ecosystems of West Asia and North Africa. Land Degradation & Development 13, 45–59.

Manlay, R.J., Kaire, M., Masse, D., Chotte, J-L., Ciornei, G., Floret, C., 2002. Carbon, nitrogen and phosphorus allocation in agro-ecosystems of a West African savanna. I. The plant component under semi-permanent cultivation. Agriculture, Ecosystems and Environment 88, 215–232.

Metherell, A.K., Harding, L.A., Cole, C.V., Parton, W.J., 1993. Century Organic Matter Model Environment: Technical Documentation, Agroecosystem Version 4.0. Great Plains System Research Unit, Technical Report No. 4. USDA-ARS Fort Collins, Colorado.

Mortimore, M.J., Adams, W.M., 2001. Farmer adaption, change and 'crisis' in the Sahel. Global Environmental Change 11, 49–57.

Murage, E.W., Karanja, N.K., Smithson, P.C., Woomer, P.L., 2000. Differences in soil properties between productive and non-productive fields identified by smallhold farmers in the Central Highlands of Kenya. Agriculture, Ecosystems and Environment 79, 1–8.

Ndao, M., 2001. Etude d'une zone test du département de Kaffrine (SENEGAL): caractérisation du sol et son occupation. Spatialisation des résultats. M.Sc. Thesis, Ecole Polythechnique Fédérale de Lausanne and CSE, Dakar.

Nelson, D.W., Sommers, L.E., 1975. A rapid and accurate method for estimating organic carbon in soil. Proceedings of the Indiana Academy of Science 84, 456–462.

Noble, I., Scholes, R.J., 2001. Sinks and the Kyoto Protocol. Climate Policy 1, 5–25.

Ojima, D.S., Dirks, B.J., Glenn, E.P., Owensby, C.E., Scurlock, J.O., 1993. Assessment of C budget for grasslands and dryland of the world. Water, Air and Soil Pollution 70, 95–109.

Okalebo, J.R., Gathua, K.W., Woomer, P.L., 2002. Laboratory Methods of Soil and Plant Analysis: A Working Manual, 2nd Edition. SACRED-Africa, Nairobi (128pp).

Parton, W.J., Woomer, P.L., Martin, A., 1994. Modelling soil organic matter dynamics and plant productivity in tropical ecosystems. In: Woomer, P.L., Swift, M.J. (Eds.), The Biological Management of Tropical Soil Fertility. Wiley, Chichester, UK, pp. 171–189.

Squires, V.R., Glenn, E.P., Ayoub, A.T., 1998. Combating Global Climate Change by Combating Land Degradation. United Nations Environment Programme, Nairobi.

Trexler, M.C., 1993. Manipulating biotic carbon sources and sinks for climate change mitigation: can science keep up with practice? Water, Air and Soil Pollution 70, 579–593.

White, F., 1983. Chapter XVI, The Sahel regional transition zone. In: The Vegetation of Africa. UNESCO, Paris, pp. 203–215.

Woomer, P.L., 1993. The impact of cultivation on carbon fluxes in woody savannas of Southern Africa. Water, Air and Soil Pollution 70, 403–412.

Woomer, P.L., Martin, A., Albrecht, A., Resck, D.V.S., Scharpenseel, H.W., 1994. The importance and management of soil organic matter in the tropics. In: Woomer, P.L., Swift, M.J. (Eds.), The Biological Management of Tropical Soil Fertility. Wiley, Chichester, UK, pp. 47–80.

Woomer, P.L., Palm, C.A., Qureshi, J.N., Kotto-Same, J., 1997. Carbon sequestration and organic resource management in African smallholder agriculture. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soils. Advances in Soil Science (series), CRC Press, Florida, pp. 58–78.