Journal of Arid Environments 59 (2004) 625–642

Journal of Arid Environments

www.elsevier.com/locate/jnlabr/yjare

Land use change and terrestrial carbon stocks in Senegal

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Received 24 November 2003; received in revised form 8 March 2004; accepted 23 March 2004

Available online 15 June 2004

Abstract

Environmental degradation resulting from long-term drought and land use change has affected terrestrial carbon (C) stocks within Africa's Sahel. We estimated Senegal's terrestrial carbon stocks in 1965, 1985, and 2000 using an inventory procedure involving satellite images revealing historical land use change, and recent field measurements of standing carbon stocks occurring in soil and plants. Senegal was divided into eight ecological zones containing 11 land uses. In 2000, savannas, cultivated lands, forests, and steppes were the four largest land uses in Senegal, occupying 70, 22, 2.7, and 2.3 percent of Senegal's 199,823 km^2. System C stocks ranged from 9 $t\,C\,ha^{-1}$ in degraded savannas in the north, to 113 $t\,C\,ha^{-1}$ in the remnant forests of the Senegal River Valley. This approach resulted in estimated total C stocks of 1019 and 727 MT C between 1965 and 2000, respectively, indicating a loss of 292 MT C over 35 years. The proportion of C residing in biomass decreased with time, from 55 percent in 1965 to 38 percent in 2000. Calculated terrestrial C flux for 1993 was -7.5 MT C $year^{-1}$ and had declined by 17 percent over the previous 18 years. Most of the terrestrial C flux in 1993 was attributed to biomass C reduction. Human disturbance accounted for only 22 percent of biomass C loss in 1993, suggesting that the effects of long-term Sahelian drought continue to play an overriding role in ecosystem change. Some carbon mitigation strategies for Senegal were investigated, including potential C sequestration levels. Opportunities for C mitigation exist but are constrained by available knowledge and access to resources.

Keywords: Africa; Carbon sequestration; Deforestation; Land degradation; Sahel; Sudanian savanna; Soil organic carbon

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0140-1963/$ - see front matter
doi:10.1016/j.jaridenv.2004.03.025

1. Introduction

Africa's Sahel, the 400-km-wide band of savanna and bushland spanning the southern edge of the Sahara Desert, has been subjected to repeated periods of drought, especially dramatic in the three decades preceding 1997 (Nicholson, 2001), resulting in a trend referred to as desertification (Squires et al., 1998) that has affected vegetation patterns (Gonzalez, 2001; Woomer et al., 2004) and the livelihood strategies of impacted human populations (Mortimore and Adams, 2001). Senegal rests at the western extreme of the Sahel and was characterized by an approximate 20 percent reduction in rainfall during that decadal period. To the south of Senegal's Sahel are constricted bands of Sudanian zone savanna and dry woodlands and Sudano-Guinean transitional forest (White, 1983). Thus, Senegal is particularly vulnerable to the effects of desertification in that the southern advance of the Sahel has great impacts upon farmers in the densely settled Peanut Basin (Tschakert et al., 2004). A combination of prolonged drought and human disturbance has also affected land use and crop productivity in the southern area of Senegal (Liu et al., 2004). These changes in vegetation and land use surely affected the terrestrial carbon (C) stocks of Senegal, but a detailed description of those stocks has not been done.

Several different approaches to estimating larger-scale carbon dynamics may be undertaken. Shortly after initiation of the Kyoto protocol (Noble and Scholes, 2001), Senegal undertook a rapid inventory to estimate its greenhouse gas emissions (Sokona, 1995). This accomplishment allowed early compliance with its obligation to that international initiative and earned Senegal recognition for its commitment to issues of desertification and climate change, but the study was not performed at sufficient resolution to allow prediction of C losses or gains resulting from specific land management interventions. Computer simulation offers the opportunity to better understand the consequences of climate and land use change on carbon dynamics over larger spatial and temporal scales, including the historical period in the Sahel (Ojima et al., 1993; Stéphenne and Lambin, 2001; Parton et al., 2004). Such efforts serve to support broader planning, but modelers often fail to validate their findings and have difficulty applying results in a site-specific manner. These shortcomings are the result, in part, of a paucity of reliable field measurements of carbon stocks residing in representative ecological zones and land uses in Senegal and in other African countries. Given the demands for national research organizations to support pressing developmental agendas (Eicher, 1999) and the fairly recent emergence of carbon studies within the global change agenda, this lack of information is understandable.

The objective of this study is to describe the effects of climate and land use changes on terrestrial C stocks in Senegal. An inventory of terrestrial carbon stocks was conducted similar to that developed by the Intergovernmental Panel on Climate Change (IPCC, 1997), which established several broad ecological regions, quantified historical land use and land use change within those regions (assigning area weights), established current soil and biomass carbon concentrations for each land use-ecological region unit, and calculated and then aggregated the total C within each unit. Unlike in the IPCC approach applied elsewhere (Eve et al., 2001), soil C estimates were not adjusted by conversion factors on the basis of land management and soil type. Rather, values obtained from recent field measurements at representative locations were gathered. A unit-specific adjustment factor for woody biomass removal was calculated by using aerial photographs and satellite images. This approach allowed the estimation of total C stocks at three times, 1965, 1985, and 2000 and the calculation of C fluxes between those years.

2. Materials and methods

Carbon stocks in 1965, 1985, and 2000 were estimated on the basis of historical land use change within different ecological zones of Senegal, field measurements of standing carbon stocks occurring in soil and plants within those land uses during 2000 (± 2 years), and the decline in woody biomass within land uses over time. Using this approach, the carbon stocks were aggregated to provide a national carbon stock estimate for 2000, and the C fluxes were estimated between the various time points. Not included within this analysis was carbon contained in settlements, wetlands, and open waters, land uses that occupied a relatively small proportion of the country in 2000.

2.1. Carbon estimates

Carbon data were collected from 67 georeferenced locations representing a wide range of ecological conditions and land uses in Senegal. Total system carbon was defined as the sum of the woody biomass, herbaceous biomass, root, litter, and soil carbon pools, with biomass assumed to contain 0.47 C. The locations were also classified by soil texture and severity of land degradation (semidesert grasslands to the north and partially deforested woodlands to the south).

A field protocol was established (Woomer, 2003) that estimated above-ground tree biomass using diameter (D) at breast height (FAO, 1997), where

$$\text{aboveground tree biomass (kg tree}^{-1}) = \exp^{(-1.996+2.32\ \ln D)}$$

with plot size dependent upon tree density (up to 0.25 ha). Herbaceous biomass and litter were destructively sampled from replicated 1.0- and 0.25-m^2 quadrats (Woomer and Palm, 1998), with samples weighed, subsampled, and dried at 65°C to constant weight to correct for moisture content. In agricultural lands, crop C was calculated from time-averaged yield data, where

$$\text{peak biomass C} = \text{crop C content (crop yield/harvest index)} \times (1 + \text{root : shoot ratio})$$

and

$$\text{time-averaged biomass C} = (\text{peak biomass C}/2)/(12/\text{wet months}).$$

Roots were collected by excavating an area $0.2 \times 0.2\,m^2$ to a depth of 40 cm with a narrow, flat-bladed shovel and handsaw. Coarse roots were hand sorted and washed.

The remaining sample was dispersed in tap water, passed through a 2-mm sieve, and roots were collected without an attempt to differentiate live and dead roots. Roots were washed of gross mineral contamination, dried at 65°C to constant weight, weighed, and a subsample ground and ashed to correct mineral content. When not measured, root biomass was calculated as the sum of 0.38 woody and 0.20 herbaceous biomass C. 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, representing several of Senegal's most important tree species.

Soils were recovered in two increments of 0–20 and 20–40 cm using a narrow, flat-bladed shovel. Samples for soil bulk density were recovered by driving a thin-walled metal cylinder of known volume into the vertical face of the excavation with a wooden mallet at two depths (10 and 30 cm, one central to each incremental soil sample), withdrawing the filled cylinder, trimming soil protrusions with a knife, and storing the sample in a plastic bag for later soil moisture and bulk density determination. Organic carbon was determined by the sulphuric acid and aqueous potassium dichromate ($K_2Cr_2O_7$) mixture with external heating (Nelson and Sommers, 1975). This wet digestion was validated with simultaneous dry combustion for inter-laboratory standardization.

Data were collected from 11 locations in the Old Peanut Basin (Tschakert, 2004), the Senegal River Valley, and the Casamance (southern Senegal) using these, or similar, methods. Another study that provided the necessary carbon information for three land uses within a single site in Casamance was reported by Manlay et al. (2002a, b). Vegetation data collected during field campaigns described by Diouf and Lambin (2001) for 23 locations in northern Senegal (Sylvo-Pastoral Zone), the New Peanut Basin, and the south-east Oriental Zone were reinterpreted in terms of standing carbon stocks. Reinterpretation of carbon stocks in northern Senegal required that basal circumference (BC) measurements of woody biomass be used to estimate the diameter at breast height ($DBH = 0.823\,BC/\pi$) and then a carbon proportion (0.47) be assigned. The value of 0.83 was empirically derived from the paired measurements of 860 trees in the Peanut Basin by Ndao (2001), although other estimates for this relationship range from 0.78 to 0.9 (O. Diallo, personal communication). The location, vegetation, soils, and topography of these sites are described in a booklet by *Centre de Suive Ecologique* (CSE, 1990). Soils were collected from these locations and analyzed for soil organic C and soil bulk density at soil depths of 0–20 and 20–40 cm.

Vegetation data from 18 locations in southern Senegal were also reinterpreted from the study of Sankhayan and Hofstad (2001). Woody biomass was estimated using DBH recorded for all trees within 0.25-ha plots. Shrub biovolume was converted to biomass using a factor of 0.38 kg biomass m^{-3}. Carbon stocks were provided for 12 locations in the New Peanut Basin from studies by Touré (2002) and Ndao (2001). Touré (2002) separated the study area (around Kaffrine) into 12 soil types and measured soil bulk density and organic carbon in paired woodlands and cultivated parklands. Ndao (2001) characterized the woody biomass within the same sample areas. The six largest soil units, three sands and three clayey sands, covered

73 percent of the total study area, and these were selected to combine the two studies to calculate the partial carbon budget of ''paired'' wooded-and-cultivated-field land uses. Unfortunately, this dataset lacked information on woodland understorey and surface litter.

2.2. Land use change

The approach considered landscape changes over a regional geographic framework based on distinctive patterns of biophysical and human conditions. This analysis was based on the geographic stratification of Senegal using ecological regions, and areas of relative homogeneity in ecological systems involving interrelationships among organisms and their environment (Omernick, 1987; Tappan et al., 2004).

Analyses of land use change relied on three primary sources: Corona satellite photographs from 1965 (1968 in some areas), Landsat thematic mapper (TM) images from 1984 to 1985, and Landsat enhanced thematic mapper plus (ETM+) images from 1999 to 2000 (Tappan et al., 2000). A stratified random sample of 10×10-km^2-area frames was selected within each ecological region. These frames were selected from a fixed 10-km grid that was placed over the entire country (Tappan et al., 2004). The sample size chosen for each ecological region was similar to the sample design used in an ongoing land cover trends project in the United States (Loveland et al., 2002). The objective was to estimate the percentage of gross change with a margin of error of ± 1 percent for an 85 percent confidence interval. The initial stratum sample sizes generally ranged from 5 to 12, depending on the size of the ecological region. Ninety-three 10-km frames were analyzed, amounting to 4.6 percent of the total land area.

For each 10-km frame, image data were extracted from the full Landsat scenes. False color composite digital and hardcopy images were produced from TM and ETM+ bands 3, 4, and 5. The corresponding 10-km frames were accurately located on Corona black-and-white film positives, and their boundaries were temporarily marked. Next, the area frame Landsat images were interpreted, mainly from the hardcopy prints at a scale of 1:100,000. A manual interpretation approach was used to identify and delineate the land use and land cover classes on image overlays. Identifiable land uses included cultivated lands, bare soil, steppes, savannas, forests, mangrove swamps, plantations, water bodies, wetlands, and settlements.

2.3. Changes in woody biomass

To adjust biomass C over time for the loss of woody cover, we compared detailed satellite images, aerial photographs, and aerial video images between 1965 and 1994 for all ecological regions and major land use/land cover types. The land use/cover included woody cover in agricultural parkland, savannas (open and wooded), forests, and mangroves. The trends in woody cover reflect modifications within land use/cover classes, not conversions from one class to another (Tappan et al., 2004).

The 1965 figures were measured (for the more open vegetation types) and estimated (for the denser vegetation formations) from visual interpretation of percentage of woody cover on the basis of detailed Corona satellite photographs covering 100 percent of Senegal. Corona photographs provide high-resolution (approximately 2-m) historical documentation of surface resources. Measuring percentage of woody cover by shrubs and trees from Corona photographs is straightforward for open vegetation formations, including agricultural parkland and shrub and tree savannas on sandy soils. For denser formations, estimates were made on the basis of canopy structure and qualitative correlation of tree density with film opacity (absorption of visible light). These estimates were cross-checked using medium and high-resolution aerial photographs taken in the 1950s and 1960s in which percentage of canopy cover could be quantified. In addition, we consulted various published reports on vegetation composition and cover from the 1960s. The 1994 woody cover figures were measured on a systematic sample basis from visual interpretation of detailed color aerial video images (Wood et al., 1995). Both vertical and oblique-looking color video images were collected along north–south transects spaced systematically across Senegal, providing high-resolution (0.3-m) coverage along the flight path. The 1994 figures were compared with an extensive map of woody cover of Senegal produced by Rasmussen (1998) using more than 12,000 georeferenced aerial photographs taken in 1990 and 1991. The 1994 figures are very similar to those presented by Rasmussen. Changes in woody cover were assumed to be linear between 1965 and 1994. The cover figures for 1994 were also applied to 2000.

2.4. Data compilation and analysis

Two databases were developed and analyzed. The first database compiled the estimated current C stocks for 67 locations that were categorized by ecological region and land use/land cover as interpreted through satellite imagery. Cases (locations) were rows and C stocks were represented in columns. Two C pools were identified for each case, soil and biomass (+litter), and these were summed to estimate total C. This database was inspected, imported into statistics software, and the mean C stocks (and standard errors) calculated for each ecological region and land use combination.

A second database combined the areas (km^2) of the different ecological regions and land use/land cover combinations over time with their respective C stocks. There were 62 unique combinations of land cover and ecological regions. The areal land cover was determined for 1965, 1985, and 2000. Mean C stocks corresponding to these 62 cases were inserted along with correction factors that adjusted for woody biomass removal. Total C stocks (10^6 t or 1 Mt) within each ecological region and land use/land cover combination were calculated for each year by multiplying the land cover area by the woody-biomass-corrected C stocks (t C ha^{-1}). The resulting data were imported into a statistics program and sorted by land cover or ecological region, and the C stocks for different times were summed. Because each region and land cover combination contained only one estimate of C, estimates of error could not be calculated. National C fluxes ($t\,C\,ha^{-1}\,year^{-1}$) were calculated as the differences between 1965 and 2000 (1984), 1965 and 1985 (1975) and 1985 and 2000 (1993) divided by the number of years and land area and combined with information on domestic forestry production and imports (FAO, 2001, 2002) and petroleum consumption (US Department of Energy, 2003).

A spreadsheet utility was constructed to estimate woody biomass C and resultant soil C gains within tree plantations. The spreadsheet queries users about the conditions of tree planting (land area in ha and number of trees ha^{-1}), which gains are to be considered (above-ground woody biomass only, roots, soil organic C), tree coefficients (C content, root:shoot ratio, proportion of leaves), soil carbon sequestration efficiency, and the price of carbon ($ per ton). The online support tool displays output as $t\,C\,ha^{-1}$ in woody biomass, soil, or both, CO_2 emission reductions, and total project value over time in 0.25-year increments. The Senegal projections were initialized for the sum of C in shoots, roots and soil with values of $+2.2\,cm\,year^{-1}$ DBH, 0.35 root:shoot ratio, 0.3 annual leaf and fine root turnover, 0.08 soil carbon sequestration efficiency, and 0.8 soil organic carbon turnover.

3. Results

By combining land use changes documented by satellite imagery with field-based carbon measurements adjusted for reduction in woody biomass over time, we generated estimates of total terrestrial carbon stocks within Senegal and in its component land uses and ecological regions. Savannas, cultivated lands, forests, and steppes were the four largest land uses in Senegal, occupying 70, 22, 2.7, and 2.3 percent of Senegal's 199,823 km^2, respectively, in 2000 (Table 1). The coverage of cultivated lands, steppes, and barren land grew over time ($+11{,}516\,km^2$) and nearly equals the reduction in savannas and forest during that same interval ($-11{,}662\,km^2$).

Table 1
Area (km^2) of different land use/land cover types in Senegal between 1965 and 2000 and the treatment of carbon estimates in this paper

Land use/land cover	Cover (km^2)			Carbon stocks considered
	1965	1985	2000	
Savanna	147,258	142,505	138,927	Yes
Agricultural parkland	34,030	39,573	42,660	Yes
Dryland and gallery forests	8765	5808	5434	Yes
Shrubland	3584	4735	4487	Yes
Open water	1969	1933	2193	No
Bare sand and soil	1528	2868	3511	Yes
Mangrove forest	1189	819	837	Yes
Marsh and wetland	1067	1116	1222	No
Human settlements	431	463	552	No
Total	199,823	199,823	199,823	

Carbon stocks within open waters, wetlands, and human settlements were not considered in this study, but these three land uses constituted less than 2 percent of Senegal's area throughout the study (Table 1).

Carbon stocks ranged from 9 t C ha^{-1} in degraded savannas in the Sylvo-Pastoral Zone to 113 t C ha^{-1} in the remnant forests of the Senegal River Valley (Fig. 1). When those forests are excluded, C stocks within land use tend to increase in a north–south direction. Conversion of woody savanna and forest to agriculture results in a large decline in total C, but many of these areas are cultivated as tree parklands, with as much as 32 t C ha^{-1} remaining as woody biomass. Soil C tends to vary less within land uses of a given vegetation zone than does vegetation C. Note that the vegetation zones presented in Fig. 1 conform to the Sahelian–Sudanian–Guinean transition sequence that characterizes the northern part of sub-Saharan Africa (White, 1983).

This approach resulted in estimated total C stocks of 1019, 839, and 727 MT C during 1965, 1985, and 2000, respectively, indicating a loss of 292 MT C over 35 years. The proportion of C residing in biomass decreased with time, from 55 percent in 1965 to 38 percent in 2000, suggesting large-scale reduction of vegetation was driving C loss (Table 2). As of 2000, the largest C stocks continued to reside within savannas, particularly in savanna soils. Total forest C greatly decreased over time, with 67 and 39 percent reduction in biomass and soil C, respectively, between 1965 and 2000. Despite a 26 percent increase in the area of cultivated lands between 1965 and 2000 (Table 1), their total C stocks declined by 18 percent (26 MT C), mostly owing to woody biomass removal in parklands (Table 2, Fig. 1). Mangrove swamps contain a disproportionately high amount of Senegal's C (1.4 percent), as both biomass and sediments, given their relatively small coverage (0.4 percent from Table 1). Calculating these C stocks showed that mangrove forests contained between 31 and 44 t biomass C ha^{-1} (data not presented).

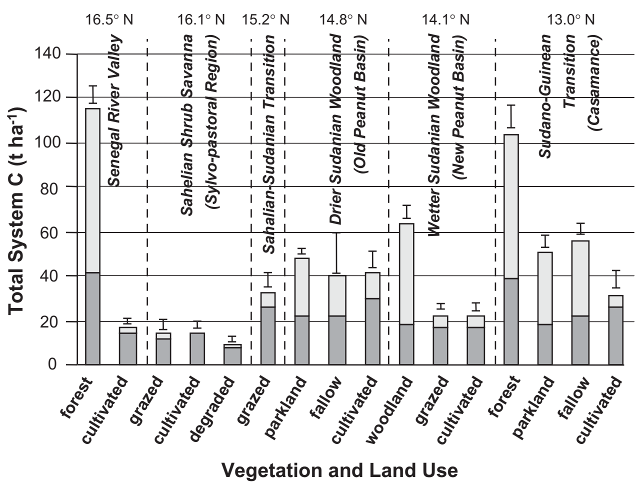

Fig. 1. Carbon stocks in different vegetation zones and land use/land cover types in Senegal.

Table 2
Estimated terrestrial C stocks (million t) in Senegal between 1965 and 2000 after adjusting for land use/cover change and the depletion of woody biomass

Land use	Estimated carbon stocks ($t\,C \times 10^6$)					
	1965		1985		2000	
	Biomass	Soil	Biomass	Soil	Biomass	Soil
Savanna	368.05	342.30	264.19	331.51	199.01	324.40
Dryland and gallery forests	99.10	31.60	50.19	20.78	32.85	19.37
Agriculture and parkland	82.52	68.79	65.97	79.75	39.51	84.85
Mangrove swamp	5.20	10.72	3.07	7.39	2.61	7.54
Shrub and grassland	1.07	5.77	1.42	7.62	1.34	7.21
Bare sand and soil	0.58	3.22	0.78	6.39	0.80	7.61
Total	556.51	462.39	385.62	453.43	276.08	451.00

Table 3
Area (km^2), estimated terrestrial carbon stocks (million t) after adjusting for land use/cover change and the depletion of woody biomass during 1965 and 2000 and the resulting annual C flux ($kg\,C\,ha^{-1}\,year^{-1}$) in different ecological regions of Senegal

Ecological region	Area (km^2)	Carbon stocks ($t\,C \times 10^6$)		C flux ($kg\,C\,ha^{-1}\,year^{-1}$)
		1965	2000	
Sylvo-pastoral	66,523	219.02	174.57	−190.9
Oriental transition	56,529	253.42	230.47	−116.0
Old peanut basin	25,915	189.67	110.51	−872.7
Casamance	24,540	205.23	124.97	−934.4
New peanut basin	14,849	97.97	49.94	−924.2
Senegal river valley	6323	27.93	13.82	−637.6
Estuaries	4095	21.51	17.33	−291.6
Northern coast	1049	4.16	4.91	204.3
Senegal total	199,823	1,018.91	726.52	−418.1

For purposes of analysis, Senegal was separated into eight ecological regions (Table 3). The eight ecoregions are based on an aggregation of 13 original ecoregions presented by Tappan et al. (2004). The largest zone is the Sylvo-Pastoral, containing 33 percent of Senegal's land area, followed by the Oriental Region (28 percent), the Old Peanut Basin (13 percent), Casamance (12 percent), the New Peanut Basin (7 percent) and three smaller regions (6 percent). Together, the Sylvo-Pastoral Region and Oriental Region contained 56 percent of Senegal's C stocks (Table 3), with 70 percent of this contained in the soil (284 MT C, data not presented). These two relatively undisturbed regions have the lowest calculated C fluxes between 1965 and 2000 ($<200\,kg\,C\,ha^{-1}\,year^{-1}$). On the other extreme, the three regions with greater

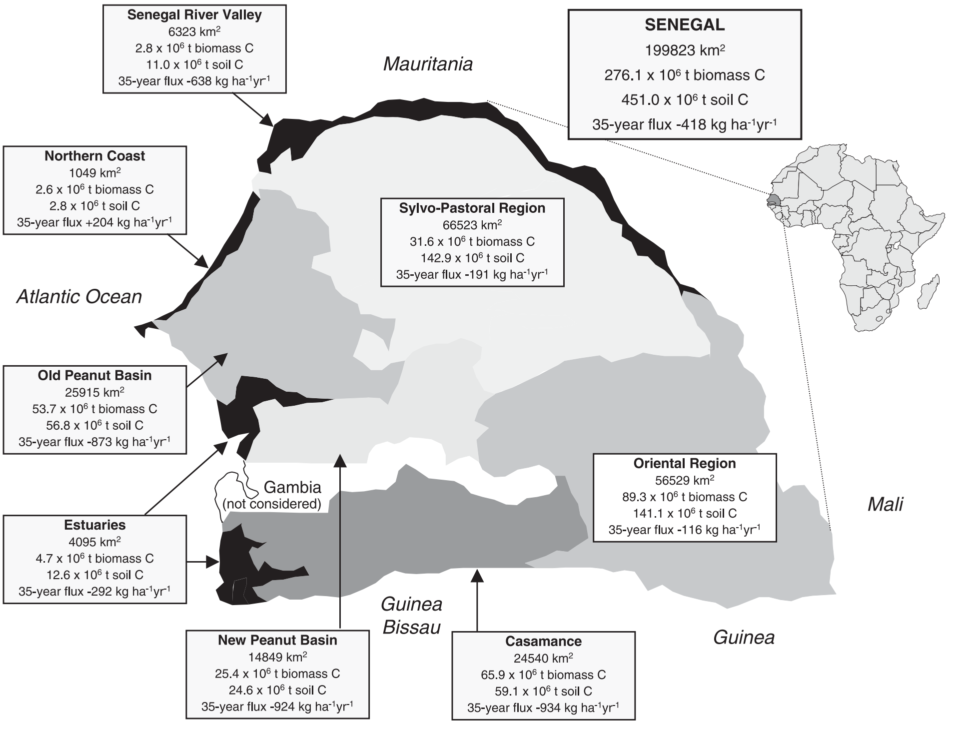

Fig. 2. Land area, carbon stocks and average carbon flux in Senegal and its major geographical zones.

woody biomass in their original natural vegetation (Fig. 1) that were then widely converted to agriculture (Table 1) have much larger calculated C fluxes (873–934 kg C ha^{-1} year^{-1}). These three regions are the Casamance and the New and Old Peanut Basins. The overall C flux of Senegal over the 35-year period was estimated to be about 418 kg C ha^{-1} year^{-1}.

Land areas, biomass, soil C stocks, and calculated carbon fluxes of the different ecological regions of Senegal are presented as a map in Fig. 2. Note that the Estuary Region is non-continuous and separated by Gambia, a country that is not considered in this analysis despite its forming an enclave within Senegal. Also, note that the Northern Coast is the only ecological region of the country that has a positive calculated carbon flux. Terrestrial C fluxes are presented for different ecological regions (Fig. 2) and human activities (Table 4).

4. Discussion

This study suggests that terrestrial carbon losses from Senegal were 293 Mt between 1965 and 2000, an average 418 kg C ha^{-1} year^{-1} (Table 3), with >95 percent of this loss resulting from vegetation disturbance, both by land use conversion and

Table 4
National terrestrial C flux during 1975, 1984, and 1993 calculated for Senegal using data in this study and other information sources

Year	Units	1975	1983	1993
Total terrestrial C	Mt C	929	873	783
Total biomass C	Mt C	471	416	331
Total soil C	Mt C	458	457	452
Total terrestrial C loss	$Mt\,C\,year^{-1}$	−9.0	−8.3	−7.5
Soil C loss	$Mt\,C\,year^{-1}$	−0.5	−0.3	−0.2
Biomass C loss	$Mt\,C\,year^{-1}$	−8.5	−8.0	−7.3
From land use change	$Mt\,C\,year^{-1}$	−1.7	−0.9	0.1
From wood fuel burning	$Mt\,C\,year^{-1}$	−1.2	−1.3	−1.5
From timber harvest	$Mt\,C\,year^{-1}$	−0.1	−0.2	−0.2
From other effects	$Mt\,C\,year^{-1}$	−5.5	−5.6	−5.7
Petroleum C consumption	$Mt\,C\,year^{-1}$	−0.6	−0.7	−0.9
Wood C production and imports	$Mt\,C\,year^{-1}$	0.2	0.2	0.3
National annual C loss	$Mt\,C\,year^{-1}$	−9.4	−8.8	−8.1
National average C flux	$t\,C\,ha^{-1}\,year^{-1}$	−0.47	−0.44	−0.41

by decreases in woody cover (Table 2). These are large losses, now clearly documented with intensive ground and aerial data, and most likely reflect the combined impacts of human pressure and protracted aridity. Desertification within the Sahel has resulted from 50 years of poor rains, especially in the three decades preceding 1997, the most substantial and persistent rainfall decline ever recorded (Nicholson, 2001). This "super-drought" has caused a marked shift in woody species composition in north-western Senegal, with vegetation zones moving 25–30 km toward the south at a rate of 0.5–0.6 $km\,year^{-1}$ (Gonzalez, 2001).

Conspicuous victims of this shift were trees, with a pronounced shift from mesic Guinean forest to Sudanian savanna and xeric Sahelian shrubland. Semidesert grasslands described by White (1983) as occurring in the Sahel to the north are now found in Senegal's Sylvo-Pastoral Region (Fig. 2). Evidence of these changes is found in the dead stands of trees in north-western Senegal, seemingly from natural causes, in the failure of tree planting projects because of lack of water (Gonzalez, 2001), shrinking lakes, reduced stream flow and lower water tables (Baumer, 1990), and in changing survival strategies by pastoralists and farmers victimized by decades of drought (Gonzalez, 2001; Mortimore and Adams, 2001; Squires et al., 1998).

Much of the calculated decline in total C in Senegal between 1965 and 2000 resulted from the estimated decline in woody biomass within land use, particularly savannas, woodlands, and cultivated lands. When total carbon losses are calculated on the basis of 1965 and 2000 surface area but using current (2000) estimates of biomass, without adjustment for woody biomass depletion over the 35-year interval, the estimated loss of terrestrial C is 44 MT C (data not presented) rather than the 293 MT C as calculated from Table 3. Alternatively stated, an estimated loss of

249 MT C has resulted from woody biomass removal within current land cover use in Senegal.

The steady loss of woody biomass throughout Senegal is well documented. Gonzalez (2001) characterized the removal of trees from north-western Senegal, reporting that tree numbers (> 3.0 height) fell from 10 to 8 trees ha^{-1} between 1954 and 1989, resulting in a woody biomass decline of approximately 1.0 t C ha^{-1}. Overexploitation of trees for fuel was described as a driving factor because the carrying capacity of firewood collection (13 persons km^{-2}) was exceeded by a factor of 3.5 in 1993, approximately 195 kg C ha^{-1} $year^{-1}$ (at 0.47 biomass C), and a production-removal imbalance had existed since 1956. Woomer et al. (2004) described the land degradation process in which woody biomass C declines from 6.5 t ha^{-1} in Sahelian shrublands to 0.4 t C ha^{-1} in degraded savanna. Accounted "roundwood" harvests in Senegal, including fuelwood extraction, steadily grew from 3.4 million m^3 in 1965 (about 1.1 MT C $year^{-1}$) to 5.9 million m^3 in 2000 (about 1.8 MT C $year^{-1}$) (FAO, 2001, 2002). A large amount of localized fuelwood gathering presumably remains uncounted.

Tschakert et al. (2004) state that natural woody savannas have disappeared from the Old Peanut Basin, and villagers must now rely upon trees remaining in cultivated parklands. These vanished woody savannas formerly contained 60–75 large trees ha^{-1}, mostly *Faidherbia albida* (M. Khouma, personal communication), but after several decades following conversion to agriculture, this density ranges from 0 to 28 trees ha^{-1} containing 5.7 ± 6.3 t C ha^{-1} (Tschakert et al., 2004). Touré et al. (2003) describe "protected" woodlands in central Senegal containing only 1.8–5.8 t biomass C ha^{-1} with average C depletion of 190 kg C ha^{-1} $year^{-1}$. Mbow et al. (2000) reported herders in south-eastern Senegal routinely burning the woodland understory to secure better grazing. Sankhayan and Hofstad (2001) described the process of woodland depletion for fuel and structural materials adjacent to villages in southern Senegal. Manlay et al. (2002a, b) described a secondary forest near Sare Yorobana Village in southern Senegal containing "at best" 14 t woody biomass C ha^{-1}, compared with much higher reports for less disturbed dry woodlands of 28 t C ha^{-1} (Breman and Kessler, 1995) and 52 t C ha^{-1} (see Fig. 1).

The assumption that biomass carbon stocks have steadily declined within land use/land cover is supported by many of these accounts, but it is difficult to quantify these declines over time for historical carbon stocks to be estimated. The approach in this study of comparing satellite and aerial images over time to estimate the reduction of woody biomass from savannas and dry woodlands tended to produce proportionately large, overly rounded estimates as land uses with relatively few trees were subjected to disturbance over a 29-year interval (data not presented). For example, percentage of woody cover in savannas of the northern Sylvo-Pastoral Region changed from 12 percent in 1965 to 3 percent in 1994 (a four-fold decline). Similar declines were noted for other major land uses in various ecological regions, including the western Sylvo-Pastoral savannas (15–8 percent), southern Sylvo-Pastoral savannas (17–7 percent), New Peanut Basin savannas (25–8 percent), cultivated parkland (5–2 percent), and Casamance wooded savannas (50–25 percent). If these declines are exaggerated (Gonzalez, 2001), then the historical biomass C was overestimated, particularly during 1965 (Table 2).

The opposite trend is likely to have resulted from historical estimates of soil C as studies in Senegal, and elsewhere in West Africa, have often focused only on C losses caused by conversion from natural vegetation to agriculture (Batjes, 2001; Elberling et al., 2003), including long-term cultivation (Siband, 1974) or during shifting cultivation (Manlay et al., 2002b). Rarely have projects used data sources that allowed them to determine changes within individual land uses as they were steadily degrading. For this reason, suitable soils-within-land use adjustment factors could not be developed, and total carbon losses from soil were only captured by comparing different soil C contents arising from land use change (Fig. 1). As a result of this approach, it is likely that historical changes in total soil C were underestimated. Historical soil C changes within degrading savannas and woodlands would most likely be better appreciated through plant–soil simulation modeling (Parton et al., 2004).

Calculated C fluxes based upon differences in terrestrial C stocks between 1965, 1985, and 2000 suggest terrestrial C losses of 7.5 MT C $year^{-1}$ in 1993 and that the rate had declined by 17 percent over the previous 18 years (Table 4). When averaged across Senegal's land area (Table 1), C fluxes of -0.47, -0.44, and -0.41 MT C ha^{-1} $year^{-1}$ were calculated for 1975, 1984, and 1993, respectively. Most of the total C flux in 1993 (8.1 MT C $year^{-1}$) was attributed to biomass C depletion (90 percent). Attempts to sum components of biomass C loss caused by human disturbance (land use change, wood fuel burning, and timber harvest) accounted for only 35 and 22 percent of C loss in 1975 and 1993, respectively. Gonzalez (2001) maintains that climatic factors override anthropogenic effects in explaining the changes in vegetation in north-western Senegal, and the partial budget of biomass C flux (Table 4) supports this contention for C changes as well because the effects of long-term rainfall declines are presumably embedded within the remaining, unaccounted "other" category. Biomass C losses due to land use/land cover change were attenuated in 1993, in large part because the amount of new agricultural lands derived from woody savanna and dry forest had diminished (Table 1). Petroleum consumption is increasing with time (0.9 MT C in 1993) but remains a relatively small component of total C emissions (11 percent in 1993).

It is one thing to estimate historical carbon stocks and the resultant fluxes, and yet another to devise strategies to reaccumulate lost terrestrial C. To offset annual C losses of 8 MT C requires that 40 carbon sequestration projects yielding 0.2 MT C at maturity be started each year. If 0.2 MT C accumulates on 2500 ha over 12 years (roughly equivalent to a 2.2 cm annual DBH gain by 400 trees ha^{-1}), then 12,000 km^2 of C sequestration projects must be established over 12 years, which represents 28 percent of Senegal's total agricultural lands in 2000 (Table 1). Although technically feasible, this enterprise would require a massive commitment by Senegalese authorities and the fossil fuel industry, and it calls into question the livelihoods of villagers presently occupying these lands. Carbon gains could result from large offset projects, and these should not be discouraged, but they are more likely to accompany better management of existing land uses.

Gonzalez (2001) suggests that natural regeneration by more drought-tolerant Sahelian species under current, drier climatic conditions has not yet reached its climax. This suggests that savannas in north-western Senegal that are not overexploited will increase their C stocks and that this approach will offer greater advantage than attempts to establish potentially more productive but less adapted exotics in tree plantations. Our study indicates that Senegal's Sylvo-Pastoral Region has 1761 km^2 of semidesert savanna containing very few woody species (data not presented). If these lands were effectively regenerated to the status of grasslands with scattered shrubs (6 percent woody biomass cover) described by Woomer et al. (2004), the increase of 7.4 t C ha^{-1} would yield 1.3 MT C over an unknown period, a modest step in the right direction that results from "merely" convincing pastoralists and fuelwood collectors not to degrade their available land resource. Establishing exclosures (protected areas) would accelerate this process but would most likely impinge on the livelihoods of current land users. Batjes (2001) maintains that applying fertilizers and establishing exotic cover crops offer a "medium" opportunity for C gains in Senegal's degraded pasture lands, but amounts of C and feasibilities of the interventions were not discussed in detail.

The Old Peanut Basin has been largely converted from wooded Sudanian Zone savanna (White, 1983) to cultivated parklands containing increasingly fewer *F. albida*. By 1985, 80 percent of this region's 25,915 km^2 (Fig. 2) was cultivated, although some of its marginal lands (3311 km^2) were withdrawn from production over the next 15 years (data not presented). Let us assume that options for C sequestration in this region must consider the potential for gains by modifying farmers' practices in a manner that meets their household objectives and available resources. Tschakert et al. (2004) simulated 25 candidate land managements to explore their potential to increase soil organic C in sandy soils of the Old Peanut Basin. Nine of those managements, those involving current practices or different rotations of current crops, resulted in C decline over 24 years. Eight of those with simulated soil C gains resulted in a localized effect that would probably have depleted C stocks elsewhere, such as through composting, crop residue transfer, or application of livestock manures. Four of the remaining options abandoned agriculture in favor of grassland or tree systems. The two remaining systems practiced short- and midterm improved fallows through agroforestry, resulting in gains of 4–6 t soil C ha^{-1} over 24 years. If these systems were adopted throughout the Old Peanut Basin, as much as 0.4 MT C $year^{-1}$ could be sequestered over 24 years. The feasibility of this C gain is nested in accompanying crop production increases, however, because the value of the increased C per ha is negligible. Furthermore, difficulties have been experienced in the adoption of these systems because they are knowledge and labor-intensive and require rapid dissemination of germplasm (Diop, 1999).

A more straightforward approach to sequestering C in cultivated parklands is to increase the stands of *F. albida* within them. If 20 additional trees ha^{-1} were established within all of the cultivated lands of the Old Peanut Basin in 2000 (17,344 km^2), and if those trees grew at a rate of 2.2 cm $year^{-1}$ for 24 years, then

21 t ha^{-1} C would accrue, amounting to 1.6 MT C year^{-1} across the region. The adoption of *F. albida* by farmers is less at issue as this species is already the dominant parkland species, and its benefits are widely recognized by land managers (Vandenbeldt, 1991). The feasibility of this action would, however, require resolving by government ministries and substantial financing because 3.5 million tree seedlings must be established in parklands where current livestock management practices include intensive stubble grazing during the 8-month dry season. On the other hand, such an initiative would stimulate local economies through the establishment of tree nurseries, fabrication of protective enclosures, and commissioning of local livestock wardens.

It is not the intent of this paper to explore every mechanism for C offsets through land management in Senegal, but merely to highlight that many such opportunities exist. Over 12 million Casuarina trees were planted in the Northern Coast Region starting in the early 1980s to stabilize 22,000 ha of sand dunes, and this effort has sequestered approximately 1.8 MT C (data not presented). Inadequately protected dunes remain and offer the potential for subsequent conservation actions. Large irrigated rice schemes that were developed by clear-cutting dry woodland at Anambé (near Velingara) in the Casamance have failed, and these lands offer the potential to sequester 0.12 MT C over 24 years (under conditions previously described), a venture that could reduce deforestation in adjacent lands. Mangrove swamps in Senegal are dominated by *Rhizophora racemosa* (RHZ) and *Avicennia africana* P. Beauv., species with little commercial value except as charcoal and poles (FAO, 2001), and the coverage of mangroves in Senegal's southern estuaries increased slightly between 1985 and 2000 (Table 1) resulting in biomass C gains of about 0.05 MT C over 15 years (data not presented). Estimates of mangrove swamp sediments in Senegal, containing an average 90 t C ha^{-1} to a depth of 40 cm, were based on a paucity of samples amid reports by Batjes (2001) of much higher values (257 t C ha^{-1} to a depth of 1.0 m), suggesting that our C estimates in the Estuary Region may be low. Terrestrial carbon stocks in Senegal were considerably reduced by a combination of decades-long drought and "management" associated with survival strategies of the poor. However, it must be emphasized that opportunities for C gains exist and can be integrated with practices to achieve enhanced agricultural fertility and sustainability. These opportunities are constrained only by available knowledge and understanding, site- and cultural-specific management options, supportive policies, and access to resources.

Acknowledgements

M. Wélé and O. Diallo of the Centre de Suivi Ecologique, Dakar, provided insights and information on the vegetation formations of Senegal's Casamance, Sahel, and Northern Coastal Zones. M. Sène and M. Khouma of ISRA-CNRA, Bambey, Senegal, assisted through the analysis and interpretation of soil analytical results. P. Tschakert provided field results from her study of C in agricultural systems in west-central Senegal. We thank all of these individuals for their valuable assistance. This study was funded through an interagency agreement to the USGS-EROS Data Center by USAID.

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