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Carbon stocks and patterns in native shrub communities of Senegal's Peanut Basin

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ABSTRACT

Accurate and reliable estimates of carbon (C) storage in landscapes are critical to the development of effective policies and strategies to mitigate atmospheric and climate change. Carbon stocks of two native woody shrub (*Guiera senegalensis* J.F. Gmel and *Piliostigma reticulatum* (DC.) Hochst) communities and associated soils within Senegal's Peanut Basin were determined and the spatial structure of soil C quantified. These shrubs are of interest because they dominate semiarid sub-Sahalien Africa and commonly coexist with row crops but have been largely overlooked as a key vegetative component of this landscape. Peak-season shrub biomass C was measured in forty-five 0.81 ha plots at 8 locations using allometric relationships along with soil sampling (0 to 40 cm depth) and analysis for organic C and bulk density. Soil samples to a depth of 20 cm were taken every 2 m in 24×20 m grids and every 0.5 m in four nested 3 m×3 m grids containing at least one shrub or tree canopy, and geostatistical techniques were then used to quantify scale and degree of soil C spatial dependence. Estimates of peak-season biomass C ranged from 0.9 Mg C ha^{-1} to 1.4 Mg C ha^{-1} with an overall mean of 1.12 Mg C ha^{-1} (SEM=0.079) in the *G. senegalensis* sites and from 1.3 to 2.0 Mg C ha^{-1} (mean=1.57 Mg C ha^{-1}; SEM=0.18) in the *P. reticulatum* communities. The overall mean of SOC to 40 cm was 17 and 17.2 Mg C ha^{-1} respectively, at the *G. senegalensis* and *P. reticulatum* sites with 57% of that C residing in the top 20 cm. Semivariograms of soil C showed moderate spatial dependence and spatial autocorrelation at distances of less than 0.56 and 1.34 m at the *G. senegalensis* and *P. reticulatum* sites, respectively. Comparison across the different grids showed that the presence of shrub canopies at either site had much closer relationship to soil C levels than trees.

1. Introduction

Assessment and improved understanding of total system carbon (C) stock and its individual components in Senegal's Old Peanut Basin is important for understanding biogeochemical processes in this ecosystem, improving soils for crop productivity, and practical strategies to sequester C in soils. Carbon lost from the Parkland agroforestry systems in this basin significantly contributes to atmospheric change, particularly increases in carbon dioxide concentrations (Houghton et al., 1993). Therefore a quantification of C stocks for different land management systems allows for better estimates of these C losses to the atmosphere as land degradation patterns are compared over time (Lal, 2002). Besides the global goal of mitigating elevated atmospheric carbon dioxide, sequestering C in soils would be of interest to land managers by improving soil properties (Woomer et al., 1997). These benefits could include increased land productivity, better yields and also contribute to improved overall soil quality and health, which in turn can help buffer these inherently fragile ecosystems (Bationo and Mokwunye, 1991; Brouwer and Bouma, 1997) from abiotic stresses (Elliot et al., 1993; Woomer et al., 1994; Murage et al., 2000).

The policies and scientific research/actions concerned with C cycling depend on accurate information about spatial distribution of C in vegetative and soil components of terrestrial ecosystems. The Kyoto Protocol (1997) presents an internationally negotiated framework for guiding these policies. Lal et al. (1999), and Lal (2002) argue that Article 3.3 and Article 3.4 of the protocol provides rationale for the importance of managing drylands to sequester C via two key mechanisms: restoration of desertified lands (Lal et al., 1998a,b) and the promotion of perennial woody biomass (Manley et al., 1995).

The Peanut Basin of Senegal is located on the Sahel's north/south vegetative gradient between the sparsely wooded grasslands of the north and tree-dominated ecosystems to the south. It is characterized by intensively cultivated Parkland systems (Freeman, 1992) comprising mainly of randomly dispersed trees and woody shrubs in farmers' fields (Weber and Major, 1984). Depending on geological substrate,

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temperature and rainfall amounts, the woody shrub component covers the entire landscape in some areas and normalized difference vegetation indices (NDVI) show it is the single largest vegetation component in this region (A. Lufafa pers. comm., 2005; M. Dièye pers. comm., 2005). *Guiera senegalensis* J.F. Gmel and *Piliostigma reticulatum* (DC.) Hochst dominate this shrub species. In farmers' fields these shrubs are normally pruned back to the soil surface and the residue is burned in the spring of every year prior to cultivation but the shrubs will continue to grow if left uncut. Consequently, because of their dominance in the landscape and coexistence with cropping activities, these shrubs have the potential to be a significant source or sink for C within the global cycle, depending on land use and management.

A number of studies of C stocks in the Peanut Basin have been done that have had a range of estimates for the vegetative component (Woomer, 1993; Bationo et al., 1998; Manlay, 2000; Bationo and Buerkert, 2001; Batjes, 2001; Manley et al., 2002; Liu et al., 2004; Tschakert et al., 2004; Woomer et al., 2004a,b). However, these studies have had various levels of resolution and generally neglected the importance of the shrub component. We hypothesized that the shrubs, because of their abundance, are more important than the tree component or other sources of C such as animal manure in regulating the C stocks of the Peanut Basin. The objective of this study was to quantify shrub biomass C and evaluate the relative influence of the shrubs and trees on the spatial dependence of soil C levels.

2. Materials and methods

2.1. Study area characteristics

The study area is the Peanut Basin in Senegal, West Africa. Located east of Dakar, the area center lies approximately at 16°W, 14.7°N with a spatial coverage of ~44,000 km^2. The climate is semiarid, with on average more than 85% of precipitation falling between August and October. Mean annual precipitation is approximately 540 mm, skewed towards the south and with high variability from year to year (Dacosta, 1989). The mean annual minimum and maximum temperatures are 20 °C and 34 °C, respectively, with a marked seasonal variation. Geological substrates in the area include mainly aeolian deposits of Harmattan wind sand (Herrmann, 1996) of Quaternary age over sedimentary rocks of Cretaceous to Miocene age (Monciardini, 1966), and highly eroded colluvial–alluvial ferruginous sediments derived from paleosols (Neogene) and Precambrian bedrock (Renaud, 1961; Michel, 1973). Basin soils are sandy, classifying as Psamments (FAO: Arenosols or Regosols) and Calcids (FAO: Calcisols) according to Soil Survey Staff (2003) and fall broadly into two indigenous types, i.e. Dior and Deck (Badiane et al., 2000). Basin vegetation is shrubland with scattered trees (Diouf and Lambin, 2001).

2.2. Carbon stock estimation

2.2.1. Biomass C estimation

The peak-season standing biomass of shrubs in farmers' fields occurs in late spring just before the shrubs are pruned back to prepare for the summer cropping season. Thus we assessed shrub C stocks at this time of year. The procedure was to develop allometric equations that use easily measured shrub properties to estimate biomass. In turn, plot scale inventories of shrub densities in combination with allometric equations were done to estimate shrub biomass.

2.2.1.1. Allometric equations. The allometric equations were developed based on 75 shrubs (49 *G. senegalensis* and 26 *P. reticulatum*) sampled from eleven sites that captured the north–south rainfall gradient in the Peanut Basin. Measurements of maximum height (*maxht*), mean crown diameter (*mcd*), mean diameter of the shrub base (*mbd*), and total number of stems (*stems*) were recorded for individual shrubs at their peak growth in March (Breman and Kessler, 1995; Ker, 1995). The shrubs were clipped and roots were excavated to measure biomass in the above- and belowground components. Samples (leaves, stems and roots) of the biomass components were oven dried at 105 °C for 48 h to determine biomass on a dry weight basis. The data set obtained was randomly split to create an independent set of 12 *G. senegalensis* and 6 *P. reticulatum* samples that was used for validation of the biomass predictive models. Linear ($\log Y=\beta_o+\beta_1*X_1$), logarithmic ($Y=\beta_o+\beta_1*\log X$), exponential ($\log Y=\log \beta_o+X^{\beta 1}$), log–log ($\log Y=\log \beta_o+\beta_1*\log X$), and quadratic ($Y=\beta_o+\beta_1*X+\beta_1*X^2$) regression models ($Y=$ dry weight of biomass in grams, $X_1 \ldots X_n$ are the respective explanatory variables in each model e.g. maxht, mcd, mbd) were used as the pool of independent variables to build optimized models. Optimal equations were selected based on adjusted R^2 values and independent variables that maximized the significance (*p*-value) of the regression coefficients. The validation data set was used to evaluate the predictive capacity of the regression estimators (Neter et al., 1996) and to select the final equations.

2.2.1.2. Shrub biomass inventories. Shrub biomass inventories were performed in 90×90 m plots that were originally designed to derive relationships between remotely-sensed shrub abundance and landscape-level biomass C stocks (Lufafa et al., 2008). Eight sites (6 for *G. senegalensis* and 2 for *P. reticulatum*) with varying number of plot replicates (more plots at sites with great variation in shrub density) were selected for the inventory. The location, elevation and number of replicates at each of the sites are provided in Table 1. Measurements of biomass predictive variables (as adduced from the allometric equations) were recorded on all shrubs encountered in each plot and used to assign biomass to each shrub. The proportion of C in all biomass pools was assumed to be 47% of the biomass dry weight (Skog and Nicholson, 1998).

2.2.2. Soil C estimates

Total soil organic C (Mg ha^{-1}) to 40 cm depth in the plots was calculated from measurements of C concentrations (g C kg^{-1}) of the 0–20 and 20–40 cm soil layers and soil bulk density at 15 and 30 cm depths. In each of the 90×90 m plots, 15 sampling points were located along three transects positioned approximately 30 m apart. Soils were collected from the 15 sampling points with four sub-samples at each point bulked and mixed to obtain a composite sample. Bulk density was measured as described by Okalebo et al. (2002) at 15 and 30 cm depths. Samples for soil C were air dried and analyzed for total C by combustion on a LECO C-144 C analyzer (LECO Inc., St. Joseph, Michigan). No attempts were made to correct for carbonate as near-surface soil horizons in the study area are predominantly acidic (pH<7) (Tschakert et al., 2004).

Table 1
Location, elevation, number of plot replicates and average number of shrubs at the biomass inventory sites

Shrub species	Location, latitude/longitude	Elevation (m)	Replicates	Shrubs/ha[a]
G. senegalensis	Keur Asanulo N14.78, W16.74	34.3	3	275 (59.7)
	Keur Mandiemba N14.75, W16.67	46.7	4	409 (35.7)
	Keur Matar Aram N14.77, W16.86	50.5	7	239 (74.6)
	Keur Ibra Fall N14.75, W16.76	25.1	2	312 (162.0)
	Ndiagne N14.76, W16.77	22.5	5	407 (36.0)
	Thilla Ounte N14.79, W16.68	27.3	3	228 (42.0)
P. reticulatum	Sikatrou N13.98, W15.99	24.0	8	134 (20.9)
	Sanguel N14.03, W16.04	23.5	13	288 (22.4)

[a] Standard error of the mean in parentheses.