UNDERSTANDING THE DISTRIBUTION OF SOIL CARBON IN GABON, CENTRAL AFRICA

by

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April 24, 2015

Masters project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University
ABSTRACT

Soils are the largest reservoir of carbon in terrestrial ecosystems. The top meter is estimated to contain 1,500 Gt of carbon, which is three times the amount held in the world’s vegetation. Despite the importance of these pools to the carbon cycle, research on soil carbon stocks is lacking in many regions worldwide. This is especially true in parts of Africa, such as the Congo Basin.

There is a great need to understand soil carbon pools in Central Africa because these carbon stocks are labile and susceptible to depletion from land use change. Historically, tropical forests in the Congo Basin of Central Africa were spared from massive deforestation. However, there is evidence that such practices are intensifying. Industrial logging has become the most widespread land use in the Congo Basin; more than 30% of the forests are under logging concessions.

This study centers on Gabon, one of six countries in the Congo Basin. Over eighty percent of the country is covered in dense tropical forest. Currently, the government is increasing pressure on these lands for agricultural development and cash crop plantations. Because of these expected land use changes, it is important to know the contemporary amount of carbon held in the soils of Gabon. The objectives of this study are to 1) quantify Gabon’s soil carbon stocks down to two meters in depth and 2) examine how environmental controls influence soil carbon.

The first part of the study involves measuring soil carbon and texture in 78 one-hectare plots located across Gabon. Plot samples were collected as part of an ongoing national forest carbon assessment. Soil carbon was measured for all depths, and soil texture was determined for the 0-10 cm and 50-75 cm depths. The second part encompasses a geospatial analysis of soil carbon predictor variables in sub-Saharan Africa. For this large-scale analysis, data on topography, climate, soil properties, and land cover type was taken from geographic information system (GIS) databases. A series of points were generated across the region, and a regression was used to assess the relationship of soil carbon to different environmental factors.

On average, there were 162 megagrams (Mg) of carbon per hectare in the top 2 meters of soil in Gabon. The top meter had 110 Mg and the second meter had 52 Mg. Carbon content in the plots varied widely, ranging from 56 to 1,000 Mg C per hectare. Soil carbon stocks were correlated with texture in both the surface and subsurface depths. Fine-textured plots had the highest percent carbon in the 0-10 cm depth, and subsequently had higher percent carbon in the lower depths. In terms of land-use, plots with logged forests had higher levels of soil carbon than plots with old growth and successional forests. Altogether, soil carbon stocks in Gabon were influenced by soil texture.

The broad geospatial analysis revealed that soil texture, topography, and climate were significant predictors of soil carbon in sub-Saharan Africa. In the surface soil layer, precipitation and bulk density had the most explanatory power. In the subsurface layer, texture and elevation had the most explanatory power. These models suggest that climate is a controlling factor on soil carbon at the surface. With increased depth, texture and lithology are of greater importance for soil carbon pools.
This study’s estimate of soil carbon for the top meter (110 Mg/ha) is lower than estimates from previous studies (123 to 186 Mg/ha). This discrepancy is due to the inclusion of non-forested plots that have lower amounts of soil carbon in the upper layers. The estimate for the second meter (52 Mg/ha) aligned more closely with past estimates (54 to 74 Mg/ha). The sizable subsoil C pool found in this study (over 30% of total soil C was estimated to be beneath the 1st meter) supports the notion that soil carbon sampling needs to go deeper in order to avoid underestimating soil carbon stocks.

To conclude, this study provides the first national estimate of soil carbon stocks in Central Africa to a 2-meter depth. Most of Gabon’s soil carbon pools rest under forested lands. Increasing pressure on uncultivated soils suitable for agriculture and cash crop production means that these soil carbon stocks will be affected, especially those stocks in the surface layers. Without efforts to replenish and conserve soil carbon through conservation practices, anticipated land-use conversions in Central Africa will result in substantial releases of soil carbon.
I. INTRODUCTION

Soils are the primary reservoir of carbon in terrestrial ecosystems (Post and Kwon, 2002). The top meter of soil is estimated to contain 1,500 gigatonnes (1 gigatonne (Gt) = 1 petagram (Pg) = 10^{15} grams) of organic carbon (SOC), approximately three times the amount held in the world’s vegetation. When accounting for inorganic carbon, the top meter is estimated to store 2,200 Gt of carbon, nearly triple the amount of carbon contained in the atmosphere (Batjes, 1995). There is considerable variation in global soil carbon estimates. The median estimate of global SOC stocks from 27 studies was 1,460 Gt, and the range was 504 to 3,000 Gt (Scharlemann et al., 2014).

Increases in soil sampling have led to revisions of these global approximations. Several studies have estimated soil carbon stocks down to two or three meters on global and regional scales (Jobbégy and Jackson, 2000, Batjes, 1995, Bernoux, 2002, Yu, 2007). Other studies have correlated soil carbon pools with world life zones, land-use changes, and climate change (Post et al., 1982, Guo and Gifford, 2002, Davidson and Janssens, 2006). There is also a growing body of literature on soil carbon sequestration, marked by differing opinions on the potential for climate change mitigation (Lal, 2004, Powlsen et al., 2011, Wiesmeir et al., 2014).

In the tropics, limited soil and climatic data hinder knowledge of soil carbon stocks and dynamics (Schwartz and Namri, 2002). Figure 1 on the following page shows the discrepancy between increases in the number of studies on soil carbon worldwide and in the tropics.

Globally, the amount of papers on soil carbon has grown by a factor of 10 from 2000 to 2014. Yet less than 3% of the studies in 2014 referenced soil carbon in Africa. Much remains to be answered about Africa’s contribution to the global soil carbon budget due such a lack of regional research. Forest carbon data is sparse for many African countries, and lowland tropical forests constitute one of the biggest gaps of knowledge on SOC pools (Ciais et al. 2011, Dieleman et al., 2013, Gautum and Pietsch, 2012). In recent years, several papers have called for more inventories and monitoring of soil and vegetation carbon stocks in Africa (Ciais et al., 2011, Gautum and Pietsch, 2012).
The deficient of soil carbon studies in Africa stems from the belief that areas in the northern latitudes, such as permafrost regions, store the majority of soil carbon. Nearer to the equator, aboveground biomass, especially in tropical forests, is believed to hold more carbon than the soils (Scharlemann et al., 2014). Soil carbon stocks are determined by the difference between plant production and decomposition. Since tropical climates promote rapid decomposition, global maps estimating SOC distributions depict low soil carbon in equatorial Africa (Hiederer and Kochy, 2011). On the following page, Figure 2 shows this supposed exchange between carbon in the soil and carbon in biomass across climatic regions. Tropical forests store the greatest amounts of carbon in aboveground vegetation, whereas the permafrost regions of Russia and North America hold the largest amounts of soil carbon. Nevertheless, the depth of tropical soils (some more than 10 meters in depth) suggests that these soils are capable of storing sizable pools of carbon. However, the scarcity of soil carbon sampling below one meter constrains estimates for subsoil carbon pools (Schwartz and Namri, 2002).

Figure 1. Difference in the number of studies on soil carbon worldwide and on soil carbon in Africa.

Source: Web of Science (search terms - For global studies: soil carbon (title) AND carbon stocks (topic); for Africa: soil carbon (title), AND carbon stocks (topic), OR Africa (topics)).
Regardless of size, soil carbon stocks are labile and susceptible to depletion from land use and land cover change. In Central Africa, degradation and deforestation of tropical forests are the primary drivers of soil carbon loss. Globally, land-use change in the tropics accounts for 12 to 20 percent of anthropogenic greenhouse gas emissions (IPCC, 2007). During the late 20th century, carbon dioxide emissions from deforestation and agricultural development averaged 1.5, 1.1, and 0.5 Pg C per year in South America, Asia, and Africa (Richter and Houghton, 2011). Much of the emissions from land-use change in the tropics has been due to deforestation in countries such as Brazil and Indonesia.

Historically, tropical forests in the Congo Basin of central Africa were spared from massive deforestation. The Congo Basin includes all of Gabon and Equatorial Guinea, along with parts
of the Congo, Cameroon, the Democratic Republic of Congo, and the Central African Republic. The region is home to the world’s second largest dense humid tropical forest, which stretches over 2 million square kilometers. Unlike deforestation in the Amazon Basin and the islands of Southeast Asia, deforestation in Central Africa has not been dominated by large-scale clearcutting. Rather, deforestation occurs on a smaller scale for either agricultural practices of communities or for highly selective commercial logging (Hansen et al., 2008). However, there is evidence that the practice of clearcutting is intensifying. Since the 1990s, the region has experienced increased pressure on lands suitable for agriculture, livestock grazing, and cash crops such as palm oil (IPCC, 2014). Industrial logging has increased to become the most widespread land use; more than 30% of the forests are under logging concessions (Laporte et al., 2007).

The study centers on Gabon, one of six countries in the Congo Basin. Currently, the Gabonese government with help from private companies is increasing pressure on forested lands for agriculture and cash crops such as palm oil. Because these expected land-use changes will diminish forest and soil carbon stocks, it is important to know the contemporary amount of carbon held in these lands. For this study, the objectives were to 1) quantify Gabon’s soil carbon stocks down to two meters in depth and 2) examine how environmental controls influence the distribution of soil carbon. The first part of the study involved measuring soil carbon and texture in 78 one-hectare plots across Gabon. The second part encompassed a geospatial analysis of soil carbon predictor variables in sub-Saharan Africa. This study provides the first national estimate of soil carbon stocks in Central Africa to a 2-meter depth.
II. METHODS

Gabon Analysis

Site description

Gabon, which sits on the Atlantic coast of Central Africa, has a moist, hot climate typical of equatorial areas. January is the warmest month, with an average high of 31 Celsius (°C) and low of 23°C. In Libreville, Gabon’s capital, mean annual precipitation (MAP) averages 2,540 millimeters (mm). Further north along the coast, MAP exceeds 3,810 mm. Over eighty percent of the country is covered in dense tropical forest. The country is marked by mountain ranges rising to more than 1,000 meters (m). The most notable range is the Du Chaillu range, which contains the highest point in Gabon, Mount Iboudjji at 1,575 m (Hickendorff, 2014). The landscape is heavily influenced by the Ogooué River, Gabon’s largest river, which creates a delta of wetlands and lakes along the coast (McShane, 1990).

The soils of Gabon are dominated by or associated with the Ferralsol soil group (Oxisols in the United States). Ferralsols are deeply weathered red or yellow soils characteristic of the humid tropics, found in relatively old landscapes. Low activity clays such as kaolinites and sesquioxides dominate these soils. High soil temperatures and moist precipitation regimes remove weatherable primary minerals over time, leaving behind only the most insoluble chemical compounds. Ferralic soils are usually acidic (pH < 4.5) and have variable organic matter concentrations. Within this soil order, edaphic soil characteristics vary according to morphology and mineralogy in the parent material.

Plot sampling and collection in Gabon

The study included 78 one-hectare plots organized across Gabon in a randomized complete block design, sampled from 2012 to 2013 (Figure 3). The sampled plots were

Figure 3: Location of sample plots.
part of an ongoing national forest carbon assessment being spearheaded by John Poulsen at Duke University. For each plot, three soil pits were dug to a meter depth. Sampling consisted of five to seven depth increments, composited into one sample per depth per plot. Bulk density values were determined in Gabon. Composited soil samples were collected and shipped to the Richter soils lab at Duke University, North Carolina for analysis.

**Soil analysis**

A subsample of 2-mm sieved soil was ground using a shatterbox. Subsamples were measured for total carbon and total nitrogen by dry combustion on an automatic C/N analyzer (Perkin-Elmer 2400 Elemental Analyzer). For the analysis of soil texture, soil samples (< 2 mm) were dispersed with Calgon (NaPO₃)₆. The soil solution was agitated for one minute and transferred to a sedimentation cylinder. The distribution of sand and silt particles (>50 microns and >2 microns respectively) was determined by removing two volumetric aliquots after different temperature-dependent settling times (20 to 22 seconds for sand, 4:00 to 3:38 hours for silt). Soil carbon stocks were estimated using the following equation: 

$$C_T = C_F \times BD \times V$$

where $C_T$ is total carbon in metric tons, $C_F$ is the fraction of carbon, $BD$ is the bulk density in g cm⁻¹ (see following section) and $V$ is the volume of the soil layer (m³).

**Bulk density analysis**

Bulk density is the dry mass of soil per unit volume of soil (g cm⁻¹), and can be thought of as a measure of compaction. A bulk density value is required for any estimation of soil carbon by mass. Oven-dried bulk density measurements were taken for 59 of the 78 plots in Gabon, shown in Figure 4. For the remaining 19 plots, bulk density values were estimated using a stepwise multiple regression procedure. An overall regression equation for predicting bulk density at the surface was calculated from percent clay and

![Figure 4. Bulk density measurements taken in Gabon (Poulsen, 2014). Average bulk density values are in black.](image-url)
depth, with $R^2 = 0.56$ ($p < 0.001$). Figure 5 shows the predicted values from the bulk density model against the measured bulk density values taken in Gabon. Bulk density values for the remaining depth increments were based on surficial bulk density and an exponential decay curve derived from bulk density measurements taken in Gabon.

![Figure 5](image.png)

**Figure 5.** Results of bulk density regression.

*Additional data*

Data for aboveground biomass carbon was acquired from the Poulsen forest carbon assessment mentioned previously. A geospatial layer of elevation, at a 30-meter resolution, was taken from the Satellite Remote Sensing (SRTM) project. Precipitation and temperature data were drawn from WorldClim (Hijmans, 2005). Table 2 on the following page gives a summary of the layers. Lithology and land surface layers were modeled by the USGS (Table 1). Land surface form was determined with a methodology that used finer-resolution slope and local relief data. The lithology dataset was modeled based off twelve digital geology, soil and lithology databases (USGS, 2009a and 2009b). Geospatial analyses were conducted using ArcGIS 10.1 (ESRI, 2011).

**Table 1.** Cover classes for land surface and lithology USGS layers.

<table>
<thead>
<tr>
<th>Data Layer</th>
<th>Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface land form class</strong></td>
<td>Smooth plains, irregular plains, escarpments, hills, breaks, low mountains, and high mountains/deep canyons</td>
</tr>
<tr>
<td><strong>Lithology</strong></td>
<td>Carbonate, karst, non-carbonate, metasedimentary, alkaline intrusive volcanic, silicic, metaigneous, ultramafic, extrusive volcanic, colluvium, hydric – organic, Aeolian sediments, alluvium – fan deposit, alluvium – fluvial, alluvium – beach, alluvium – saline, alluvium – gypsum, alluvium – other, volcanic</td>
</tr>
</tbody>
</table>
Table 2. Summary of Gabon data.

<table>
<thead>
<tr>
<th>Data</th>
<th>Units</th>
<th>Source</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil carbon</td>
<td>kg/kg</td>
<td>Author</td>
<td>Point data</td>
</tr>
<tr>
<td>Soil texture</td>
<td>%</td>
<td>Author</td>
<td>Point data</td>
</tr>
<tr>
<td>Aboveground biomass</td>
<td>kg/m³</td>
<td>Poulsen</td>
<td>Point data</td>
</tr>
<tr>
<td>Land-use status</td>
<td>Categorical</td>
<td>Poulsen</td>
<td>Point data</td>
</tr>
<tr>
<td>Mean annual precipitation (MAP)</td>
<td>mm</td>
<td>WorldClim</td>
<td>30 arc seconds (0.86 km²)</td>
</tr>
<tr>
<td>Mean annual temperature (MAT)</td>
<td>°C * 10</td>
<td>WorldClim</td>
<td>30 arc seconds (0.86 km²)</td>
</tr>
<tr>
<td>Potential evapotranspiration (PET)</td>
<td>cm/yr</td>
<td>MODIS</td>
<td>30 arc seconds (0.86 km²)</td>
</tr>
<tr>
<td>Elevation</td>
<td>meters</td>
<td>SRTM</td>
<td>3 arc seconds (30 m²)</td>
</tr>
<tr>
<td>Slope</td>
<td>%</td>
<td>SRTM (derived)</td>
<td>3 arc seconds (30 m²)</td>
</tr>
<tr>
<td>Lithology</td>
<td>17 classes</td>
<td>USGS</td>
<td>3 arc seconds (90 m²)</td>
</tr>
<tr>
<td>Land surface</td>
<td>7 classes</td>
<td>USGS</td>
<td>3 arc seconds (90 m²)</td>
</tr>
</tbody>
</table>

Statistical analysis

Given the non-normality of some of the data, a generalized linear model was used to determine a suitable regression model. Variables were tested for collinearity, and variables with Akaike information criterion (AIC) values greater than 10 were discarded. Model variables deemed significant (p < 0.05) were retained and an ANOVA test was used to check the parsimonious nature of the model. All analyses were carried out within the RStudio software package (v. 0.98.434). The soil carbon profiles for each plot were fit with a modified three-parameter exponential decay function using SigmaPlot (Systat Software, San Jose, CA). The intercept and decay coefficients were tested for correlations with surface percent carbon and percent clay.

Geospatial Analysis

Data description

Data was drawn from three databases: soil property maps from the International Soil Research Institute Center (ISRIC), climate data from the WorldClim database, and topographic and ecosystem data from the United States Geological Survey (USGS). Four tiles of elevation data...
from the GTOPO30 DEM model were mosaicked together. Potential Evapotranspiration (PET) data was taken from the MODIS Global Evapotranspiration Project (MOD16), drawn from average PET values from 2000 to 2010. The 250-meter resolution maps from ISRIC were predictions of soil properties, generated from an automated mapping framework that used 3D regression-kriging based on random forests. Average temperature and precipitation maps had 1-km resolutions, and were interpolated from average monthly climate data from weather stations. Table 3 gives a summary of the layers.

**Table 3. Summary of data for regional analysis.**

<table>
<thead>
<tr>
<th>Data layer</th>
<th>Units</th>
<th>Source</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic carbon*</td>
<td>g/kg</td>
<td>ISRIC</td>
<td>250-m interpolated map</td>
</tr>
<tr>
<td>Soil texture*</td>
<td>%</td>
<td>ISRIC</td>
<td>250-m interpolated map</td>
</tr>
<tr>
<td>Bulk density*</td>
<td>g/cm³</td>
<td>ISRIC</td>
<td>250-m interpolated map</td>
</tr>
<tr>
<td>MAP</td>
<td>mm</td>
<td>WorldClim</td>
<td>30 arc seconds</td>
</tr>
<tr>
<td>MAT</td>
<td>°C * 10</td>
<td>WorldClim</td>
<td>30 arc seconds</td>
</tr>
<tr>
<td>PET</td>
<td>cm/yr</td>
<td>MODIS</td>
<td>30 arc seconds</td>
</tr>
<tr>
<td>Elevation</td>
<td>meters</td>
<td>USGS</td>
<td>30 arc seconds</td>
</tr>
<tr>
<td>Slope</td>
<td>%</td>
<td>USGS</td>
<td>30 arc seconds</td>
</tr>
<tr>
<td>Lithology</td>
<td>Classes</td>
<td>USGS</td>
<td>3 arc seconds</td>
</tr>
<tr>
<td>Land surface</td>
<td>Classes</td>
<td>USGS</td>
<td>3 arc seconds</td>
</tr>
</tbody>
</table>

* = Data from both the 0-5 cm and 60-100 cm depths were used

**Data analysis**

Six sets of random points were generated across sub-Saharan Africa. Values from the various geospatial layers were extracted to each set of points. Geospatial analyses were conducted using ArcGIS 10.1 (ESRI, 2011). A generalized linear model was used to generate a regression model in the RStudio package (v. 0.98.434). Variables were tested for collinearity, and variables with AIC values greater than 10 were discarded. Model variables significant (p < 0.05) were kept and an ANOVA test was used to check the parsimonious nature of the model.
III. RESULTS

Soil carbon in Gabon

On average, there were 162 Mg (1 Mg = 1 metric ton) of carbon per hectare. The first meter contained 110 Mg (70% of the total) and the second meter held 52 Mg (30%). Carbon content in the plots varied widely. Soil carbon ranged from 56 to 1,000 Mg C per hectare. Variability in the amount of carbon depended on depth. The surface layer (0-10 cm) encompassed the greatest amount of variability: carbon ranged from 0.33% to 28%. In the lowest three depths, 75 cm to 200 cm, soil carbon was below 1% for all samples with the exception of one plot. Figure 6 shows percent carbon by depth, averaged across the plots. Below the surface layer, percent carbon declined rapidly and leveled off around 0.4% in the second meter.

Figure 7 shows the average mass of carbon (in metric tons) per hectare. Total carbon stocks differed from percent carbon measurements due to the inclusion of bulk density in calculations. Proportionally, more carbon was contained in the surface layers; the top 10 cm of mineral soil stored approximately the same amount as the bottom 50 cm.

![Figure 6. Average percent soil carbon in Gabon plots.](image1)

![Figure 7. Average mass of soil carbon.](image2)
Soil texture

Texture analysis of the surface soil layers (0-10 cm) revealed that half of the plots were fine-textured soils, defined as being at least 35% clay (Figure 8). Of the remaining plots, 16% were coarse-textured (sand > 50% and clay < 20%) and 34% were medium-textured (clay < 40%). Subsoil texture analysis, at 50-75 cm, was carried out on a selection of 36 plots that had varying amounts of surficial clay (Figure 9). Clay also dominated in these subsoil layers; over half of the plots were fine-textured.

![Figure 8](image1.png)

**Figure 8.** Texture results for the 0-10 cm layer. Nearly half of the plots were fine-textured.

![Figure 9](image2.png)

**Figure 9.** Texture results for the 50-75 cm layer. Fine-textured soils were also abundant in the subsurface depth.
Texture in the surface soils related to texture in the subsurface soils (Figure 10). A Pearson-product moment correlation coefficient confirmed this, showing that clay in the 0-10 cm layer was correlated with clay in the 50-75 cm layer, with an $R^2 = 0.86$ ($p < 0.05$). Sand in the 0-10 cm layer was strongly correlated with sand in the 50-75 cm layer, with an $R^2 = 0.82$ ($p < 0.05$).

![Figure 10](image.png)

**Figure 10.** Texture correlations between the surface (0-10 cm) and subsurface (50-75 cm).

Some profiles exhibited signs of an argillic horizon in the subsoil layer (Figure 11). Argillic horizons occur when the upper soil profile is leached of fine clays, and lower soil layers are enriched in them. The presence of this subsurface horizon is diagnostic of the Ferralsol order. There are different requirements depending on surface percent clay to determine whether or not a soil has an argillic diagnostic horizon.

![Figure 11](image.png)

**Figure 11.** Likelihood of the presence of an argillic horizon based on differences in % clay between in the surface and subsurface layers.
Soil carbon stocks were correlated with texture in both the surface and subsurface depths. In the 0-10 cm layer, percent carbon was positively correlated with percent clay, with $R^2 = 0.30$ ($p < 0.001$). Percent carbon was negatively correlated with percent sand, with $R^2 = -0.31$ ($p < 0.05$). The relationship between texture and soil carbon was greater in the 50-75 cm layer (Figure 12). In the 0-10 cm layer, the correlation between soil carbon and clay was 30% ($p < 0.05$). At the subsurface, the 50 to 75 cm depth, the correlation was 60% ($p < 0.001$).

![Figure 12](image)

**Figure 12.** A) Percent carbon and percent clay in the 0-10 cm layer  
B) Percent carbon and percent clay in the 50-75 cm layer.

Percent soil carbon followed a similar exponential decay curve across fine, medium, and coarse-textured plots (Figure 13, following page). Fine-textured plots had the highest average percent carbon in the 0-10cm layer, and subsequently had higher percent carbon in the lower depths. An analysis of variance showed that fine-textured plots had significantly higher levels of percent carbon than coarse-textured soils in the top meter, with the except of the top 10 centimeters.
\( F(2,70) = 5.69, p < 0.05. \) There was no significant difference in percent carbon between medium and coarse-textured plots in any of the depths.

![Figure 13. Average percent carbon by depth for fine-, medium-, and coarse-textured plots.](image)

There were no significant trends in total C by mass along the soil textural gradient. Figure 14 shows the total amount of carbon (in metric tons) per 50 cm increment. In the 0-50 cm depth, fine-textured plots contained over 3 Mg of carbon more than coarse-textured plots. This difference in carbon storage between fine- and coarse-textured soils was over 9.5 Mg in the 100-150 cm and 150-200 cm depths.

![Figure 14. Average carbon by mass for fine-, medium-, and coarse-textured plots.](image)
Relationship of soil carbon with vegetation and land-use

Vegetation

Figure 15 shows the soil carbon stocks and aboveground biomass (AGB) carbon stocks for each plot. Figure 16 shows the soil carbon stocks for the 0-10 cm layer plotted against AGB carbon stocks. No relationship was found between soil carbon stocks and AGB carbon stocks (p > 0.05) either across the soil profile or in the surface layer. This finding mirrors the conclusions drawn from Figure 2, which had worldwide maps of soil carbon and vegetation carbon stocks. On a global scale, increases in aboveground carbon stocks do not translate to increases in belowground carbon pools.

Figure 15. Total soil carbon stocks (brown) and carbon in AGB (green) for each plot. Plots are organized by increasing AGB carbon from left to right.

Figure 16. Soil carbon in the 0-10 cm layer and carbon in AGB for each plot. Note the spatial variability. Some surface soil carbon pools had nearly 50% the amount of carbon stored in AGB, while other plots had 3 or 4%.
Land-use

Soil profiles were classified according to land-use status: logged forests, old-growth forests, or successional forests. These classes were based on field observations from the national forest carbon inventory: logged plots had fresh logging tracks or downed trees, successional plots had old tracks, and old-growth plots showed few signs of logging. According to these observations, 18 plots were logged forests, 13 were old-growth forests, and 21 were successional forests. The remaining 26 plots were not classified according to land use.

Figure 17 shows the average amount of carbon stored in 50-cm depth increments. An analysis of variance (ANOVA) showed that the land-use classes had significant differences in carbon storage in the top 50 cm, \( F(2, 153) = 6.64, p < 0.01 \). In the 50-100 cm depth, logged and old-growth plots were different in terms of carbon storage, \( F(2, 101) = 5.0, p < 0.01 \). Land-use classes showed no differences in carbon storage in the second meter.

![Figure 17](image)

**Figure 17.** Average amount of carbon (metric tons/ha) for each land-use class.

Figure 18 (following page) shows the average percent carbon by land-use class. Standard error was the greatest in the surface depth, reflecting the variability of labile soil carbon in surface soils. ANOVA tests showed that there were significant differences in percent carbon in the top 50 centimeters. In the 10-30 cm layer, logged plots had higher levels of percent carbon than successional plots, \( F(2, 49) = 3.02, p < 0.05 \). In the 30-50 cm layer, percent carbon was significantly greater in the logged plots than in old-growth plots, \( F(2, 49) = 2.78, p < 0.05 \).
Reflective perhaps of selective logging practices, Figure 19 shows that land-use status was not tied to AGB carbon stocks. An analysis of variance showed that the logged plots were not different from the old-growth plots or successional plots in terms of biomass, $F(2, 49) = 2.75, p > 0.05$. The old-growth plots (mean = 360, SD = 88) had higher amounts of AGB carbon stocks than the successional plots (mean = 268, SD = 133), $t(32) = 2.44, p < 0.05$. 

Figure 18. Average percent soil carbon by land-use class.

Figure 19. Average AGB carbon stocks according to land-use class
Geospatial analysis

Of the environmental variables in Table 3 (page 12), five were significant predictors of carbon in the 0-5 cm layer and 6 were significant predictors in the 60-100 cm layer (Tables 4 and 5). These factors were texture (symbolized by clay), bulk density, precipitation (MAP), evapotranspiration (PET), land surface, and lithology (subsurface only). The GLM built with these variables had an adjusted $R^2$ of 0.686 (p-value < 0.001) for the surface and an adjusted $R^2$ of 0.380 (p-value < 0.001) for the subsurface layers.

Table 4. Results for surface soil carbon, averaged for six models.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. error</th>
<th>t-value</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.30</td>
<td>0.025</td>
<td>13</td>
<td>2 x 10^{-16}</td>
</tr>
<tr>
<td>Bulk density</td>
<td>-0.17</td>
<td>2.4</td>
<td>-7.8</td>
<td>4 x 10^{-6}</td>
</tr>
<tr>
<td>MAP</td>
<td>0.0078</td>
<td>0.00048</td>
<td>18</td>
<td>2 x 10^{-16}</td>
</tr>
<tr>
<td>PET</td>
<td>-0.0055</td>
<td>0.0013</td>
<td>-4.5</td>
<td>3 x 10^{-4}</td>
</tr>
<tr>
<td>Land surface</td>
<td>1.6</td>
<td>0.17</td>
<td>10.0</td>
<td>1.6 x 10^{-14}</td>
</tr>
</tbody>
</table>

p-value: < 0.001
R-squared (average): 0.686

Table 5. Results for subsurface soil carbon, averaged for six models.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. error</th>
<th>t-value</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.061</td>
<td>0.017</td>
<td>7.2</td>
<td>3.9 x 10^{-5}</td>
</tr>
<tr>
<td>Bulk density</td>
<td>-4.2</td>
<td>1.03</td>
<td>-4.4</td>
<td>4.4 x 10^{-3}</td>
</tr>
<tr>
<td>MAP</td>
<td>0.0010</td>
<td>0.00024</td>
<td>4.6</td>
<td>7.3 x 10^{-3}</td>
</tr>
<tr>
<td>PET*</td>
<td>-0.0027</td>
<td>0.00054</td>
<td>-5.2</td>
<td>1 x 10^{-6}</td>
</tr>
<tr>
<td>Land surface</td>
<td>0.70</td>
<td>0.091</td>
<td>8.2</td>
<td>2 x 10^{-16}</td>
</tr>
<tr>
<td>Lithology</td>
<td>0.10=</td>
<td>0.022</td>
<td>4.9</td>
<td>6.4 x 10^{-3}</td>
</tr>
</tbody>
</table>

p-value: < 0.001
R-squared (average): 0.380
Figure 20 shows that average correlations for the environmental variables (p < 0.005) were greater in the surface layer than in the subsurface layer. In the surface layer, mean precipitation and bulk density had the most explanatory power in predicting soil carbon. Mean annual precipitation was the most positively correlated with soil carbon at the surface ($R^2 = 0.66$, $p < 0.001$), and percent sand was the most negatively correlated ($R^2 = -0.53$, $p < 0.001$). For the subsurface layers, texture and elevation had the most explanatory power. Percent clay was the most positively correlated ($R^2 = 0.48$, $p < 0.001$) and bulk density was the most negatively correlated ($R^2 = -0.64$, $p < 0.001$). These models suggest that climate is a controlling factor on soil carbon at the surface. With increased depth, climatic effects are diluted, and texture and lithology are of greater importance for soil carbon pools.

**Figure 20.** Correlations between environmental variables and soil carbon for the ISRIC interpolated maps.
IV. DISCUSSION

Comparison with earlier estimates

Estimates of soil carbon stocks in sub-Saharan Africa are scarce. This study’s estimate of soil carbon for the top meter – 110 Mg/ha – appears to be lower than estimates from previous studies (Table 6). The Intergovernmental Panel on Climate Change (IPCC) estimated tropical forest soils to contain 123 Mg/ha to a 1-meter depth (2007). In 2000, Jobbágy and Jackson estimated that tropical evergreen and deciduous forests contain 186 and 158 Mg/ha of soil carbon to a depth of 1 meter. A 2012 study in Gabon’s Mount Birougou National Park found results in close agreement with those in Jobbágy and Jackson (2000), estimating the forests in the park to contain 186 Mg/ha in the first meter (Gautam and Pietsch, 2012). This discrepancy in soil carbon for the first meter between this study and previous estimates is likely due to the inclusion of non-forested plots, such as plots under palm oil concessions or along sandy beaches, that have lower amounts of soil carbon in the upper layers. The addition of these non-forested plots explains why the observed 1.8% mean soil carbon fraction in this study was lower than 2.3%, which was the mean soil carbon fraction for the intact forests in Mount Birougou National Park (Gautam and Pietsch, 2012).

Table 6. Comparison of results.

<table>
<thead>
<tr>
<th>Study area</th>
<th>Study</th>
<th>Mg/ha, 0-1 m</th>
<th>Mg/ha, 1-2 m</th>
<th>Sample size, 0-1 m</th>
<th>Sample size, 1-2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical evergreen</td>
<td>Jobbágy &amp; Jackson, 2000</td>
<td>186</td>
<td>54</td>
<td>35</td>
<td>27</td>
</tr>
<tr>
<td>forest</td>
<td></td>
<td>158</td>
<td>74</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>Tropical deciduous</td>
<td>Jobbágy &amp; Jackson, 2000</td>
<td>123</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>forest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical forest soils</td>
<td>IPCC, 2007</td>
<td>186</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gabon national park</td>
<td>Gautam and Pietsch, 2012</td>
<td>110</td>
<td>52</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>Gabon</td>
<td>This study</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This study’s estimate for the 1-2 m depth aligned more closely with those from Jobbágy and Jackson (Table 6). Both studies suggest that substantial pools of carbon are stored in the subsoil horizons despite low percent carbon concentrations. The sizable subsoil C pool found in this
study (over 30% of total soil C was estimated to be beneath the 1st meter) supports the notion that soil carbon sampling needs to go deeper than the first meter in order to avoid underestimating soil carbon stocks.

Estimating soil carbon stocks in Gabon

Controls on soil carbon

Among thirteen environmental factors analyzed using a regression analysis, the only detectable influence on soil carbon in Gabon was from soil texture (p < 0.05). The environmental variables considered in the regression were elevation, slope, precipitation, temperature, bulk density, texture (sand, clay), lithology, landform, terrestrial ecosystem, topographic convergence index, land-use, and aboveground biomass. Aside from soil texture, none of these factors could be used to help predict soil carbon stocks (p > 0.05). The series of charts in Figure 19 show the variability in soil carbon with climate: neither temperature nor precipitation showed a clear linear relationship with soil carbon. Elevation had a positive correlation with soil carbon, but not one strong enough to signal a direct effect. Surface soil texture, represented in Figure 21 by percent clay, did have a significant positive effect on soil carbon stocks, with $R^2 = 0.30$ (p < 0.05).

![Figure 21. Percent soil carbon in Gabon plots versus environmental factors](image-url)
Based on the results from the two regression analyses of soil carbon – the broad geospatial analysis of sub-Saharan Africa and the more narrow analysis of the Gabon plots – the ability to generate a soil carbon model with environmental variables appears to be scale-dependent. On a larger continental scale, soil carbon can be hypothesized to vary with climate and topography. Previous studies have identified climate as being a primary determinant of soil carbon pools (Jobbágy and Jackson, 2000, Amundson, 2000). Figure 22 shows the relationship of global soil carbon to changes in temperature (MAT) and precipitation (MAP). In Gabon, average temperature ranges from 23 to 31°C, and average rainfall from 3,050 to 3,810 mm. This climatic variability, limited by spatial scale, is not large enough to draw a detectable response in soil carbon. On the national scale in Gabon, soil texture exerts the greatest control on soil carbon storage.

![Image](image_url)

**Figure 22.** Relationship of soil carbon to mean annual temperature and mean annual precipitation. Source: Amundson, 2000.

**Carbon decay rates**

Another method was more successful in estimating soil carbon stocks in Gabon. Figure 23 shows that, on average, declines in percent soil carbon in the plots followed an exponential decay curve ($y = a * e^{-B*D}$; $y$ = percent soil carbon, $a$ = intercept, $B$ = decay rate, and $d$ = depth). Exponential decay curves were fit to 66 of the 74 plots, and the decay rate and intercept coefficients for each plot were analyzed with percent carbon and clay in the 0-10 cm layer.
When both log-transformed to be normally distributed, decay rate and soil carbon were negatively correlated, with $R^2 = -0.43$, $p < 0.001$ (Figure 24). Additionally, the log-transformed decay rate was negatively correlated with percent clay, with $R^2 = -0.46$, $p < 0.001$ (Figure 23).
Carbon concentrations of surface soils have been found to strongly correlate with those of deeper soils (Jobbágy and Jackson, 2000). The analysis of carbon decay rates above supports this fact. Soil profiles with either higher percent carbon or higher percent clay in the 0-10 cm layer had lower decay constants, and therefore higher levels of soil carbon at depth. Because surface soil carbon was correlated with the decay constant, and the decay constant was correlated with the intercept, an exponential decay curve predicting carbon stocks across the entire soil profile could be built based on one measurement of soil carbon at the surface. Digging 2-meter deep soil pits is laborious and expensive. Only needing one surface soil sample would enable more plots to be measured without sacrificing estimates for subsoil carbon pools. However, this hypothesis needs to be tested with a greater sample size in order to generate more accurate relationships between soil carbon and exponential decay rates.

Implications for land-use changes

The majority of Gabon’s soil carbon pools rest under tropical forests, which comprise 80% of the country. The development of forested areas suitable for agriculture and cash crop production has the potential to affect these soil carbon pools, especially in the surface layers. However, the degree to which these anticipated land-use conversions impact soil carbon depends on the intensity of the land use, stability of subsoil carbon pools, and conservation practices to mitigate soil carbon losses.

Deforestation in Central Africa is dominated by selective logging, meaning that companies harvest a limited number of important timber species rather than clear-cut patches of forest (CARPE, 2005). So far, the Congo Basin has not experienced the development of large-scale plantations for agriculture and biofuels, as seen in Southeast Asia and the Amazon. However, because Central Africa stands out as a region with some of the highest potential for agricultural development in the world, it is possible that the region will experience more large-scale forest conversion (Megevand, 2013). Land clearing for agriculture and cash crops such as palm oil would deplete soil carbon in the surface layers, where carbon stocks are the greatest. Regardless of the effects of logging, conservation practices to mitigate soil carbon losses should be implemented. Management strategies include controlling soil erosion, reducing tillage, and
limiting burning and residue removal in the beginning stages of land clearing (Banwart et al., 2014).

In this study, plots on logged forests had higher soil carbon stocks in the top 50 cm than plots on old growth and successional forests. Several reasons could explain this. Given the nature of selective logging, soils on these logged plots may have been largely undisturbed. This hypothesis is supported by the fact that old growth and logged sites had similar aboveground biomass. Second, the soils of the logged plots may be inherently more carbon-rich (and therefore more fertile) than the other plots; hence why they were suitable to be forest concession stands. Finally, other studies have found evidence of soil carbon redistribution within the profile after forest harvests due to physical mixing, dissolved organic carbon, priming effects, and decaying roots (Vario et al., 2014).

CONCLUSION

This study found 162 Mg of carbon per hectare in the top two meters of soil in Gabon. The highest amounts of soil carbon were in the surface layers: the 0-1 meter depth contained 110 Mg, and the top 30 cm alone held approximately 50 Mg. Yet the 1-2 m depth contained a substantial portion of these carbon stocks (30% of the total), suggesting that soils in Central Africa have sizable reservoirs of stable, subsoil carbon. A geospatial analysis of sub-Saharan Africa revealed that climate, topography, and soil texture influence soil carbon stocks. A similar analysis using this study’s soil carbon data specifically for Gabon yielded different results: only soil texture had a notable effect on belowground carbon storage. These regression analyses showed that estimating soil carbon stocks with environmental factors becomes more difficult on finer scales. However, exponential decay curves have the potential to approximate subsoil carbon pools when surface soil carbon values are known. To conclude, this study provides the first national estimate of soil carbon stocks in Central Africa to a 2-meter depth.
REFERENCES


Figure 1. Maps of interpolated 250-m data from ISRIC. These data layers were used for the broad geospatial analysis of sub-Saharan Africa.

Figure 2. USGS maps of lithology (left) and land surface classes (right).
Figure 3. Random point locations for analysis with ISRIC 250-m interpolated maps. A. Locations of first 5 sets of random points (average 700 points per set). B. Location of sixth set of random points (3,000 points).
Figure 4. Results from surface analysis (0-5cm) of ISRIC 250-m interpolated maps, used for geospatial analysis. Models performed poorly above 40 g/kg soil organic carbon (4% carbon). However, the models did well predicting the bulk of the random points, whose values were below 3% SOC.
Figure 5. Results from subsurface analysis (60-100 cm) of ISRIC 250-m interpolated maps, used for the geospatial analysis. The models performed more poorly than the surface models in Figure 4.