Geoderma 271 (2016) 202–215

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Total soil organic carbon and carbon sequestration potential in Nigeria

Stephen I.C. Akpa [a,c,*], Inakwu O.A. Odeh [a], Thomas F.A. Bishop [a], Alfred E. Hartemink [b], Ishaku Y. Amapu [c]

[a] Department of Environmental Science, Faculty of Agriculture and Environment, The University of Sydney, Biomedical Building C81, 1 Central Avenue, Eveleigh, NSW 2015, Australia
[b] Department of Soil Science, University of Wisconsin-Madison, FD Hole Soils Lab, 1525 Observatory Drive, Madison 53706, USA
[c] Department of Soil Science, Faculty of Agriculture/Institute for Agricultural Research, Ahmadu Bello University, Zaria, Kaduna State, Nigeria

ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form 17 February 2016
Accepted 19 February 2016
Available online 4 March 2016

Keywords:
Digital soil mapping
Legacy data
Soil organic carbon
Random Forest
Cubist
Nigeria

ABSTRACT

This study aimed to quantify SOC stocks and potential C sequestration for Nigeria using legacy soil data. Mass preserving splines were fitted to legacy SOC and bulk density (BD) pedon data based on GlobalSoilmap soil depths. SOC concentrations (g kg^{-1}) were predicted using Random Forest model (RFM), Cubist and Boosted regression tree (BRT). Thereafter, the soil carbon density (Mg C ha^{-1}) was calculated from the SOC concentration and BD (Mg m^{-3}). The information was combined with land use/land cover (LULC) map and agro-ecological zone (AEZ) digital maps to estimate SOC sequestration. The mean SOC concentration ranged between 4.2 and 23.7 g kg^{-1} in the top 30 cm and between 2.6 and 9.2 g kg^{-1} at the lower soil depth. Total SOC stock in the top 1 m was 6.5 Pg with an average density of 71.60 Mg C ha^{-1}. Almost half of the SOC stock was found in the 0–30 cm layer. SOC stocks decreased from the southwest to the northeast of Nigeria, and increased from Sahel to Humid forest agro-ecological zones. Restoration of the various land use types has the potential to sequester about 0.2 to 30.8 Mg C ha^{-1} depending on the AEZ. The Derived Guinea Savannah presents a potential hotspot for targeted carbon sequestration projects in Nigeria. Knowledge of SOC stock and sequestration is vital for framing appropriate management regimes to increase soil carbon stocks, for C accounting and environmental monitoring purposes.

1. Introduction

There is a growing concern over the contribution of agricultural sector to the increasing global warming (IPCC, 2011). This concern has heightened demand for information on spatial patterns of soil organic carbon (SOC) stocks in relation to agricultural land uses and land use/cover (LULC) change. LULC change and the management of agro-ecosystems have the potential to release considerable amount of SOC stored in the soil through tillage, cropping systems, irrigation, fertilization and other agricultural operations (Bruce et al., 1999; Lal, 2005). The soil carbon pool constitutes about two-third of the total terrestrial carbon pool, which is three times the amount of atmospheric carbon (Smith, 2012). Thus it is important to decipher the spatial distribution of soil carbon stock to identify where anthropogenic factors are contributing significantly to carbon-dioxide (CO_2) emissions into the atmosphere.

SOC is sensitive to changes in land use (Poeplau and Don, 2013) and a change from natural or semi-natural LULC to agricultural ecosystems often leads to significant changes in SOC content (Post and Kwon, 2000; Guo and Gifford, 2002; Wilson et al., 2008). According to Powers et al. (2011) the conversion of forests to shifting cultivation or permanent crops can reduce SOC stocks by an average of almost 20% over a period of time. Other studies have estimated the loss of SOC after cultivation of virgin land to be between 20% and 50% (Post and Kwon, 2000; Guo and Gifford, 2002; Murty et al., 2002; Gregorich et al., 2005). Overall, long-term agricultural land use change could decrease soil C content by 48% in the top 10 cm (Don et al., 2011; Poeplau et al., 2011) with a concomitant increase in atmospheric C.

In contrast to land clearing, land management can preserve the SOC pool or even lead to increased C sequestration and thus reduced atmospheric CO_2 concentration (Jenny, 1980; Post et al., 1998; Metting et al., 1999). Additionally, increased carbon storage could be achieved through afforestation where low biomass LULC types such as grasslands or croplands are converted to forests and plantations (Roshetko et al., 2007; Nave et al., 2013). Besides sequestration of C in the soil through C input, afforestation causes increased stabilization of old C as fine fractions protected by micro-aggregates (Del Galdo et al., 2003; Mulugeta et al., 2005; Bekele et al., 2006). Other studies have demonstrated that the conversion of forest to well-managed pastures can enhance SOC storage compared to SOC storage under native forest (Powers et al., 2011). Increased SOC storage following the conversion of cropland to grassland has also been reported (Su et al., 2009; Fang et al., 2012; Poeplau and Don, 2013).

The capacity of soils to store more C following restoration of various land uses to their pristine ecosystem, depends on several factors such as vegetation (Jobbágy and Jackson, 2000), climatic conditions (Dixon

* Corresponding author at: Department of Environmental Science, Faculty of Agriculture and Environment, The University of Sydney, Biomedical Building C81, 1 Central Avenue, Eveleigh, NSW 2015, Australia.
E-mail addresses: stephen.akpa@sydney.edu.au, sicakpa@gmail.com (S.I.C. Akpa).

http://dx.doi.org/10.1016/j.geoderma.2016.02.021
0016-7061/

et al., 1994), soil texture (Six et al., 2002) and topography (Rosenbloom et al., 2006). Climatic elements affect SOC storage through alteration of decomposition rate of SOC as well as changes in the quantity and quality of C cycled through the ecosystem. Vegetation often determines the vertical distribution of SOC through root biomass differences with depth (Jobbágy and Jackson, 2000; Dorji et al., 2014). In addition to climate and vegetation, soil properties, such as texture, play important role in C storage through their stabilizing effects on SOC (Jobbágy and Jackson, 2000). Also, topography affects SOC stock through its influence on soil moisture regime as well as redistribution of soil particles (Gulledge and Schimel, 2000).

Although several studies have shown that LULC changes affect SOC content and sequestration potential of soils (Post and Kwon, 2000; Albaladejo et al., 2013), the magnitude and dynamics of these changes in different ecosystems have not been extensively studied. In Nigeria, for example, natural ecosystems have been degraded following deforestation, overgrazing, nutrient mining, soil erosion, and loss of biodiversity (UNEP, 2007). These degraded lands have great potential to sequester C in the soils (Follett et al., 2001). In addition, most soils in Nigeria are highly weathered with low activity clays (FMANR, 1990) that have small mineral surfaces to allow physical protection and stabilization of SOC. Such soils are more susceptible to perturbations associated with LULC changes, leading to SOC decline. Several studies on the influence of land use on SOC storage have been reported for various ecosystems in Nigeria (Raji and Ogunwole, 2006; Anikwe, 2010; Obalum et al., 2012). These studies are localized based on small datasets and no information on SOC storage up to 1 m soil depth has been covered. This presents uncertainties in the understanding of the impacts of LULC change on the C cycle and the sustainability of agricultural systems (Meersmans et al., 2009; Wiesmeier et al., 2012). This study therefore aims to (i) estimate the total SOC stock and (ii) determine the potential carbon sequestration of soils under different land use types across agro-ecological zones of Nigeria.

2. Materials and methods

2.1. Study area

Nigeria, with a total area of about 923,768 km^2, extends across a broad geographical area characterized by a large climatic range with two major biomes: the tropical humid forest in the south, and the savannah in the north (Keay, 1959). The savannah comprises Southern Guinea, Northern Guinea, Sudan, and Sahel zones respectively (Adegbehin and Igboanugo, 1990). An addition to the two vegetation types is the derived savannah which is a transition zone between the rainforest and savannah caused by significant loss of forest by clearance. These climatic variations, combined with the soil, constitute the agro-ecological zones (AEZs) shown in Table 1 (IITA, 1992). The environmental and anthropogenic factors across these AEZs give rise to a somewhat north-south gradient in LULC across Nigeria (see Fig. 1). LULC ranges from sparse vegetation and grassland in the fringes of the northern region, through croplands/savannas/shrublands mosaics in the middle belt region to croplands/shrublands/forests mosaics in the coastal southern region. The LULC distribution includes croplands (31%), Savannas (36%), grasslands (18%), forests (11%), shrublands (1%) and others (3%).

Farming systems in Nigeria are heterogeneous depending on the agro-ecological and socio-economic environments. This is exacerbated by the variability in farmers' land holdings and farm management (Giller et al., 2011). Farming systems range from shifting cultivation and perennial tree cropping in the humid forest AEZ to crop–livestock farming in the savannah (Dixon et al., 2001). Smallholder farming systems are variable with farm size ranging from 0.2 to less than 2 ha.

2.2. Data sources and processing

2.2.1. Soil data

The major SOC and BD profile data used in this study were taken from the ISRIC compilation of Africa Soil Profiles Database obtained from soil survey reports and field research conducted in Nigeria (Leenaars, 2012; Odeh et al., 2012). The procedures for the determination of these properties are described by Leenaars (2012). Bulk of the SOC data were measured by the wet oxidation/digestion using either Walkley Black (WB) method or the modified WB method of Nelson and Sommers (1996), while a few were measured using the dry combustion method. However, data obtained from these two methods were harmonized to the dry combustion method (Leenaars, 2012). The BD data were determined using the core sampling method. The SOC concentrations were originally reported in percentage mass unit but were converted to g kg^{-1} following the GlobalSoilMap specifications (Arrouays et al., 2014). We calculated mass-preserving splines (Bishop et al., 1999) to convert the soil profile data to standard depth intervals (0–5, 5–15, 15–30, 30–60, 60–100, 100–200 cm) in accordance with the GlobalSoilMap specifications (Arrouays et al., 2014). Overall, SOC data from 711 soil profiles and BD data from 222 profiles of the ISRIC African soil database were used in this study after data preprocessing. The distribution of SOC profile data across the various AEZs in Nigeria is shown in Fig. 2.

2.2.2. Predictor variables

In this study, 23 predictor variables were used in the SCORPAN model (McBratney et al., 2003) as the predictors of SOC and BD- both of which are fundamental to SOC stock estimation (see Table 2). The predictors include SRTM 90 m digital elevation model (DEM) (USGS, 2006) from which other predictors, such as slope gradient, aspect, profile and plan curvatures, flow accumulation, topographic wetness index (TWI), stream power index (SPI), were derived following Reuter and Nelson (2009). Related predictors used include landform classifications based on algorithms by Iwahashi (Iwahashi and Pike, 2007) and Hammond (Dikau et al., 1991), physiographic regions map derived from DEM (Akpa et al., 2014). MODIS enhanced vegetation index (EVI) and Normalized difference Vegetation Index (NDVI) maps (https://lpdaac.usgs.gov), and bands 1, 2, 3, 4 and 7 of Landsat 7-ETM+ coverage obtained from Landsat GeoCover ETM+ 2000 edition (MDA-Federal,

Table 1
Description of the major agro-ecological zones (AEZ) in Nigeria.

AEZ based on IITA's definition	Annual rainfall (mm)	Annual temperature (°C)	Days of growing period	Pristine vegetation	Dominant FAO soil group
Humid Forest	2000–3000	25–27	270–360	Forest	Ferralsols, Acrisols
Derived Guinea Savannah	1500–2000	26–28	211–270	Forest	Ferralsols, Luvisols, Arenosols, Nitosols
Southern Guinea Savannah	1200–1500	26–29	181–210	Savanna	Luvisol, Ferralsols, Acrisols, Lithosols
Northern Guinea Savannah	900–1200	27–29	151–180	Savanna	Luvisols, Vertisols, Lithosols,Ferralsols
Sudan Savannah	500–900	25–30	91–150	Savanna	Lixisols, Luvisols, Regosols
Sahel Savannah	250–500	21–32	≤90	Grassland	Aridisols, Regosols
Mid-High Altitude	1100–1500	20–23	160–200	Savanna	Luvisols, Lithosols, Ferralsols

Adapted and modified from Sowunmi and Akintola (2010) and Jagtap (1995).
Abbreviation: IITA; International Institute of Tropical Agriculture, FAO; Food and Agriculture organization.