Geoderma 213 (2014) 46–56

Contents lists available at ScienceDirect

Geoderma

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

Soil organic carbon stocks in the Limpopo National Park, Mozambique: Amount, spatial distribution and uncertainty

A.H. Cambule [a,*], D.G. Rossiter [b], J.J. Stoorvogel [c], E.M.A. Smaling [b]

[a] Universidade Eduardo Mondlane, Faculdade de Agronomia e Engenharia Florestal, C.P. 257, Maputo, Mozambique
[b] University of Twente, Faculty of Geoinformation Science and Earth Observation (ITC), P.O. Box 6, 7500 AA Enschede, The Netherlands
[c] Wageningen University, Land Dynamics Group, P.O. Box 47, 6700 AA Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 14 March 2012
Received in revised form 25 June 2013
Accepted 21 July 2013
Available online 26 August 2013

Keywords:
Soil organic carbon stocks
Kriging
Regional trend
Digital soil mapping

ABSTRACT

Many areas in sub-Saharan African are data-poor and poorly accessible. The estimation of soil organic carbon (SOC) stocks in these areas will have to rely on the limited available secondary data coupled with restricted field sampling. We assessed the total SOC stock, its spatial variation and the causes of this variation in Limpopo National Park (LNP), a data-poor and poorly accessible area in southwestern Mozambique. During a field survey, A-horizon thickness was measured and soil samples were taken for the determination of SOC concentrations. SOC concentrations were multiplied by soil bulk density and A-horizon thickness to estimate SOC stocks. Spatial distribution was assessed through: i) a measure-and-multiply approach to assess average SOC stocks by landscape unit, and ii) a soil-landscape model that used soil forming factors to interpolate SOC stocks from observations to a grid covering the area by ordinary (OK) and universal (UK) kriging. Predictions were validated by both independent and leave-one-out cross validations. The total SOC stock of the LNP was obtained by i) calculating an area-weighted average from the means of the landscape units and by ii) summing the cells of the interpolated grid. Uncertainty was evaluated by the mean standard error for the measure-and-multiply approach and by the mean kriging prediction standard deviation for the soil-landscape model approach. The reliability of the estimates of total stocks was assessed by the uncertainty of the input data and its effect on estimates. The mean SOC stock from all sample points is 1.59 kg m^{-2}; landscape unit averages are 1.13–2.46 kg m^{-2}. Covariables explained 45% (soil) and 17% (coordinates) of SOC stock variation. Predictions from spatial models averaged 1.65 kg m^{-2} and are within the ranges reported for similar soils in southern Africa. The validation root mean square error of prediction (RMSEP) was about 30% of the mean predictions for both OK and UK. Uncertainty is high (coefficient of variation of about 40%) due to short-range spatial structure combined with sparse sampling. The range of total SOC stock of the 10,410 km^{-2} study area was estimated at 15,579–17,908 Gg. However, 90% confidence limits of the total stocks estimated are narrower (5–15%) for the measure-and-multiply model and wider (66–70%) for the soil-landscape model. The spatial distribution is rather homogenous, suggesting levels are mainly determined by regional climate.

1. Introduction

Soil organic carbon (SOC) drives natural soil fertility and is a common indicator of livelihoods and ecosystem functions. It has been a focus of attention in the context of both agricultural development and carbon sequestration. Under the various United Nations protocols, there is an increasing need for accurate estimates of SOC stocks at national and sub-national scale to aid policy makers in making land use and management decisions (Milne et al., 2007). Estimates of current SOC stocks and their spatial variation are the starting point for the estimation of the carbon sink capacity and SOC sequestration. The focus of the study determines the type of data required. In the case of climate change, estimates of total SOC stocks are important for mitigation purposes. However, when carbon payments are considered, the spatial distribution of stocks and their respective change become important (Antle et al., 2007).

Techniques for estimating SOC stocks have been grouped into two categories (Mishra et al., 2010; Thompson and Kolka, 2005): (1) the measure-and-multiply approach and (2) the soil-landscape modeling approach. In the measure-and-multiply approach the study area is stratified. Point measurements per stratum are averaged and multiplied by the area of each stratum of maps that stratify (Guo et al., 2006; Tan et al., 2009; Thompson and Kolka, 2005). Soil survey maps and field observations are primary resources to estimate SOC stocks with the measure and multiply approach that has been applied from regional (Amichev and Galbraith, 2004; Batjes, 2008; Tan et al., 2004; Thompson and Kolka, 2005) to global (Batjes et al., 2007) scales. The approach has the advantage of being simple, though it is not exempt of several limitations like potentially high within-stratum SOC variability

* Corresponding author. Tel.: +258 843285400.
E-mail address: armindo.cambule@uem.mz (A.H. Cambule).

0016-7061/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geoderma.2013.07.015

(Mishra et al., 2010; Thompson and Kolka, 2005). The soil landscape modeling approach analyzes the spatial variability of SOC stocks with respect to variations in environmental covariables such as topography, land use or climate (Mishra et al., 2010). A model is built based on the various environmental covariables covering the entire study area plus limited number of field observations of SOC stocks, and is used to make predictions over a grid across the study area (Gessler et al., 2000; Thompson et al., 2001). These are then summed to an area total. Examples of use of this approach are many, e.g., Ungaro et al. (2010) and Ziadat (2005), though many have successfully been applied to small areas (<100 ha) and using of digital elevation models as the covariate, e.g. Florinsky et al. (2002), Bhatti et al. (1991) and Gessler et al. (2000).

The soil-landscape approach may result in a lower estimation error at each prediction location, due to the use of complete spatial coverages of secondary information, i.e., the environmental covariables. The measure-and-multiply approach has the advantage of simplicity, although within-stratum variability (heterogeneous strata) limits precision (Aubry and Debouzie, 2000; Mishra et al., 2010; Thompson and Kolka, 2005). Further, the soil-landscape approach produces a grid map of SOC stocks whereas the measure-and-multiply approach produces a chloropleth map with an average value per stratum. It is not clear a priori which method gives lower estimation errors for total stocks.

In 2001, Mozambique declared an area known as "Coutada 16" (hunting zone) the Limpopo National Park (LNP), which forms part of a trans-frontier park with South Africa and Zimbabwe. The LNP provides ecosystem services and supports the livelihoods of about 20,000 people living within its boundaries. The formation of LNP and the planned relocation of the communities within the park will result in major land use changes, both in terms of vegetation and wildlife (Ministerio do Turismo, 2003). These changes are expected to affect SOC stocks in and around the LNP, including in resettlement areas where SOC stocks are a major contributor to soil fertility. Any change cannot be assessed without a proper baseline, i.e., present-day stocks. Therefore, the aim of this study was to quantify the total SOC stock and its spatial variation in the Limpopo National Park, and the probable causes of any variation. Further, we wanted to compare the various approaches to estimating SOC stocks.

2. Study area

The study area of 10,410 km^{-2} covers most of Limpopo National Park, which is one part of the study area of the "Competing Claims on Natural Resources" project (Giller et al., 2008), centered on the trans-frontier national parks of the Mozambique–Zimbabwe–South Africa border. LNP is located in Mozambique (Fig. 1) between 22° 25′ and 24° 10′ S and 31° 18′ and 32° 38′ E. Altitudes range from about 50 to about 500 m above sea level (Stalmans et al., 2004). It has a warm arid climate (BWh, Köppen classification) with a dry winter and mean annual temperature exceeding 18 °C (Peel et al., 2007). Absolute maximum temperatures (between November and February) increase northwards to above 40 °C. Annual rainfall decrease northwards from above 500 mm in the southeast to about 350 mm at the extreme north (Ministerio do Turismo, 2003; Stalmans et al., 2004).

The dominant lithology is the extensive Quaternary aeolian sand cover along the NNW–SSE spine of the park. Tertiary sedimentary rocks (limestones, sandstone) are found close to the drainage lines where the sand mantle has been exposed. Rhyolite rocks from the Karroo formation are located along the western border while alluvium

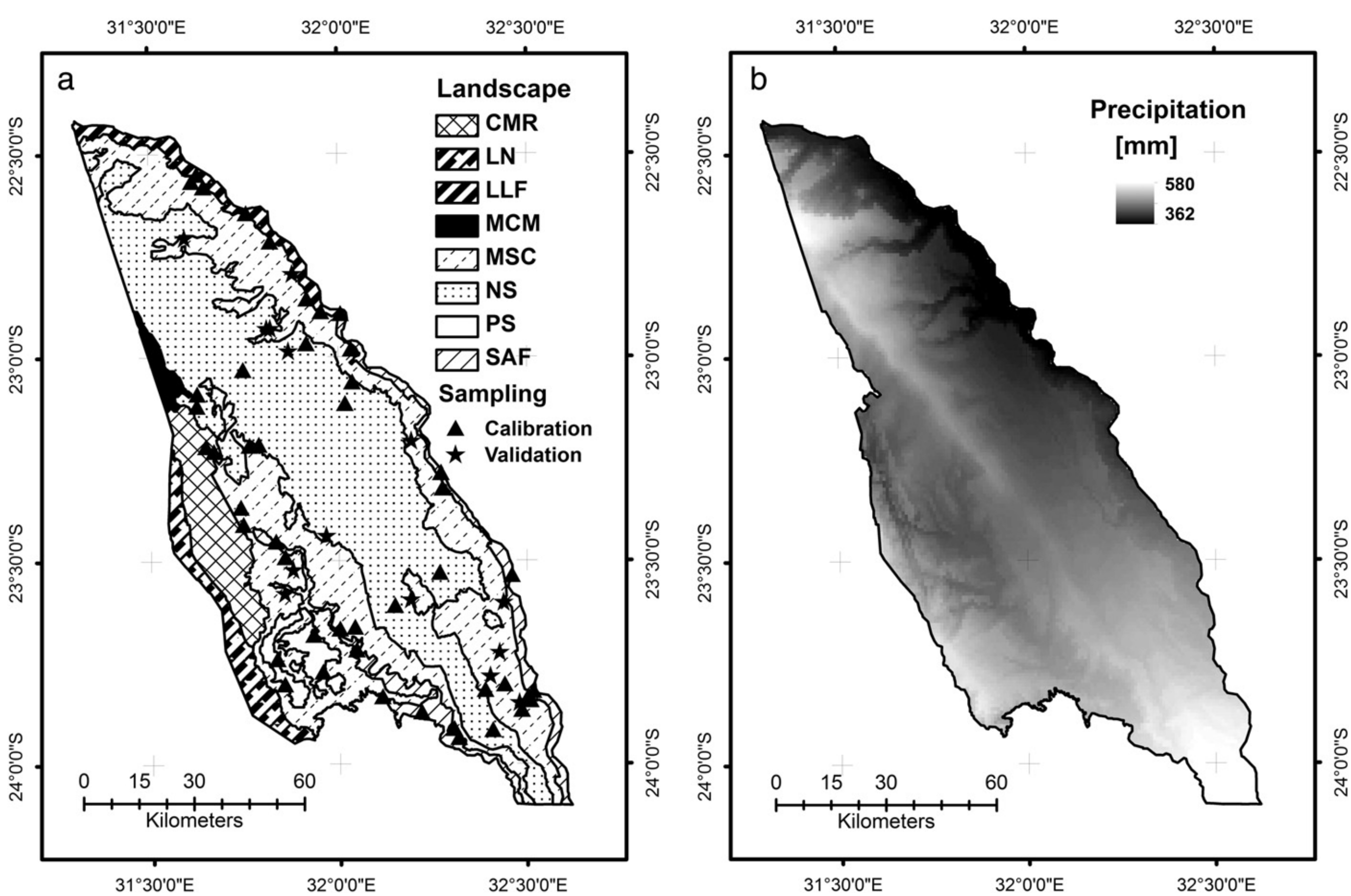

Fig. 1. (a) LNP landscapes and sampling points; (b) annual precipitation. Landscapes after Stalmans et al. (2004); precipitation after Hijmans et al. (2011).