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Spatial structures of soil organic carbon in tropical forests—A case study of Southeastern Tanzania

Joni Rossi [a,*], Annelies Govaerts [b,1], Bruno De Vos [e,2], Bruno Verbist [a,3], André Vervoort [b,4], Jean Poesen [c,5], Bart Muys [d,6], Jozef Deckers [a,7]

[a] Division Soil and Water Management, Department of Earth and Environmental Sciences, Celestijnenlaan 200e-bus 2411, 3001 Leuven, Belgium
[b] Natural Resources Section, Department of Civil Engineering, Kasteelpark Arenberg 40-bus 2448, 3001 Leuven, Belgium
[c] Physical and Regional Geography Research Group, Department of Earth and Environmental Sciences, Celestijnenlaan 200e-bus 2409, 3001 Leuven, Belgium
[d] Division Forest, Nature and Landscape Research, Department of Earth and Environmental Sciences, Celestijnenlaan 200e-bus 2411, 3001 Leuven, Belgium
[e] Research Institute for Nature and Forest, Gaverstraat 4, 9500 Geraardsbergen, Belgium

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ABSTRACT

Southeastern Tanzania serves as a typical example of soil degradation and soil organic carbon (SOC) losses on the African continent. Although sequestration of SOC through aforestation or reforestation proved favorable, these measures are restricted by the ability to produce rapid, cost-effective and precise sampling schemes. The aim of this study is to contribute to a better knowledge of the spatial distribution of soil C in tropical natural and plantation forest. This paper presents sampling strategies for estimating mean SOC values as well as for SOC mapping, based on different methods for SOC determination and on different precision levels. To do so we conducted a carbon variability study in five common forest types of Southeastern Tanzania (coastal dry forest, Miombo woodland, teak plantation, pine plantation and cashew plantation) using conventional statistical methods, as well as geostatistics. In the 5 forest types of this study, SOC stocks in the upper 5 cm ranges between 5 (in the cashew plantation) and 13 (in the coastal forest) t ha^{-1}. The optimal sampling distance for measuring mean SOC stocks varies between 36 m (in the patchy miombo woodland) and 422 m (in the homogenized cashew plantation). Sample sizes fluctuate between 6 and 72 (1 t ha^{-1} precision) for respectively cashew plantation and coastal forest. A rectangular grid with a sample interval of 25 m can be used for SOC mapping with a point kriging estimation error of 3.0 t ha^{-1} in the coastal forest, 2.6 t ha^{-1} in miombo woodland, 2.2 t ha^{-1} in the teak plantation and 1.1 t ha^{-1} in the cashew plantation. Since the pine plantation has no spatial structure; samples can be arranged randomly and its best soil map has an average C content attributed over the whole field. Refining the sampling strategy with a new spatial variability study in other forest types can be based on a regular grid with sampling distances of half the range identified in this study. This paper proves that the optimal sampling scheme varies strongly as a result of the different spatial behavior of SOC in forests and depends on the required precision and research question. Only when the right strategy is followed, high standards of precision can be met without economic loss or risk of statistical misinterpretation.

1. Introduction

Soil organic carbon (SOC) is well known to maintain several functions. On the one hand, being the major component of soil organic matter (SOM), it is a determinant of soil physical and chemical properties, an important proxy for soil biological activity and a measure of soil productivity (Batjes and Sombroek, 1997; Reeves, 1997). Land use management that will enhance soil carbon (C) levels is therefore important for farmers and land use planners (Walker and Desanker, 2004), particularly in semiarid and sub-humid Africa where severe soil degradation and desertification are related to perpetual food crises and overall impoverishment (Vågen et al., 2005). On the other hand C sequestration in the soil is an important climate change mitigation measure. The global SOC stock is about 1500 Gt (Houghton,

* Corresponding author. Fax: +32 16 329760.
E-mail addresses: Joni.Rossi@ees.kuleuven.be (J. Rossi), Annelies.Govaerts@bwk.kuleuven.be (A. Govaerts), Bruno.Devos@inbo.be (B. De Vos), Bruno.Verbist@ees.kuleuven.be (B. Verbist), Andre.Vervoort@bwk.kuleuven.be (A. Vervoort), Jean.Poesen@ees.kuleuven.be (J. Poesen), Bart.Muys@ees.kuleuven.be (B. Muys), Seppe.Deckers@ees.kuleuven.be (J. Deckers).
[1] Fax: +32 16 321988.
[2] Fax: +32 54 436160.
[3] Fax: +32 16 329760.
[4] Fax: +32 16 321988.
[5] Fax: +32 16 322980.
[6] Fax: +32 16 329760.
[7] Fax: +32 16 329760.

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1995; Batjes, 1996), which is about three times the amount of organic C in the vegetation and twice the amount of C in the atmosphere (Batjes and Sombroek, 1997; IPCC, 2000). Globally forest soils are estimated to hold about 40% of all belowground C (Dixon et al., 1994; Huntington, 1995) and tropical soils 26% (Batjes, 1996). Soil C stocks generally decrease with 25% following deforestation and cultivation of previously forested areas (Houghton et al., 1987). After reforestation, SOC increases over the long run and reaches a steady state after about 30 years (Vågen et al., 2005), which shows that forest restoration may act as an important global C sink (Huntington, 1995).

Southeastern Tanzania serves as a typical example of soil degradation and SOC losses through land use change, deforestation and increased land pressure on the African continent (Bhatia, 1990; Anonymous, 1994; Huwe et al., 1994; Tenga, 2006). Aforestation/reforestation activities which could counter these problems are supported by local institutions (Topper and Kasuga, 2003) and can be funded by the Clean Development Mechanism (CDM) of the Kyoto Protocol. However, the Protocol limits reporting of C sequestration activities to those that are both "measurable and verifiable". Even if allowed as part of an accounting system, credit for C sequestration activities could be withdrawn if high standards of measurement cannot be met (UNFCCC, 2007). The feasibility and sustainability of C credit schemes will depend on appropriate measuring and monitoring schemes which are rapid, feasible and cost-effective.

Reliable measurements of SOC content are hard to get and labor-intensive due to the substantial spatial variability. Soil carbon stocks are influenced by climate, vegetation, soil physical characteristics and historical land use (up to more than 30 years before present) all of which vary spatially (Conant and Paustian, 2002; Conant et al., 2003). This is especially the case in forest soils, as a result of the heterogeneous nature of vegetation, microclimate and soil physical properties (Saetre, 1999). The IPCC (2000) states that adopted sampling techniques should be used that take into account spatial variability. A good knowledge of the soil C stock and its spatial variation leads to a sampling strategy that is balanced between reliability and cost-effectiveness, in agreement with the error that is allowed for the purpose of the study.

Factors to take into account are sample size and sample density in relation to the spatial scale of the variation. Sampling intervals can be optimized for soil mapping and for calculating average values, by application of classical and geostatistical theories (Van Meirvenne, 1991). Several studies described SOC spatial variability using geostatistics in agricultural soils (Liu et al., 2006) or grasslands (Schloeder et al., 2001; Cerri et al., 2004). Similar studies on forest soils only focused on temperate regions (Kirwan et al., 2005; Bengston et al., 2007). In tropical forest soils geostatistic analyses were merely used to determine spatial dependence scales (Wang et al., 2002; Oake-Anti and Ogoe, 2006), but these results were not used to develop sampling strategies.

The aim of this study is to contribute to a better knowledge of the spatial distribution of soil C in tropical natural and plantation forest. Specific objectives are to identify the most cost-effective sampling technique for measuring SOC in different forests in Southeastern Tanzania. This article presents a practical method for optimizing the sampling strategy for SOC. It provides a tool for reliable and cost-effective estimation of average C stocks and creation of C maps based on a chosen forest type and predefined precision.

A sampling strategy is proposed for 5 forest types. This design can be directly used in similar forests in the area; or it can be used as a guideline to set up new sampling schemes in different forests in a different environment.

2. Study area

2.1. Area description

The research was conducted in the Mtwara and Lindi districts situated respectively in the Mtwara and Lindi regions of Southeastern Tanzania (Fig. 1). Two plateaus dominate the region. The larger Makonde Plateau is situated between 38°00′ and 40°30′E and 10°05′

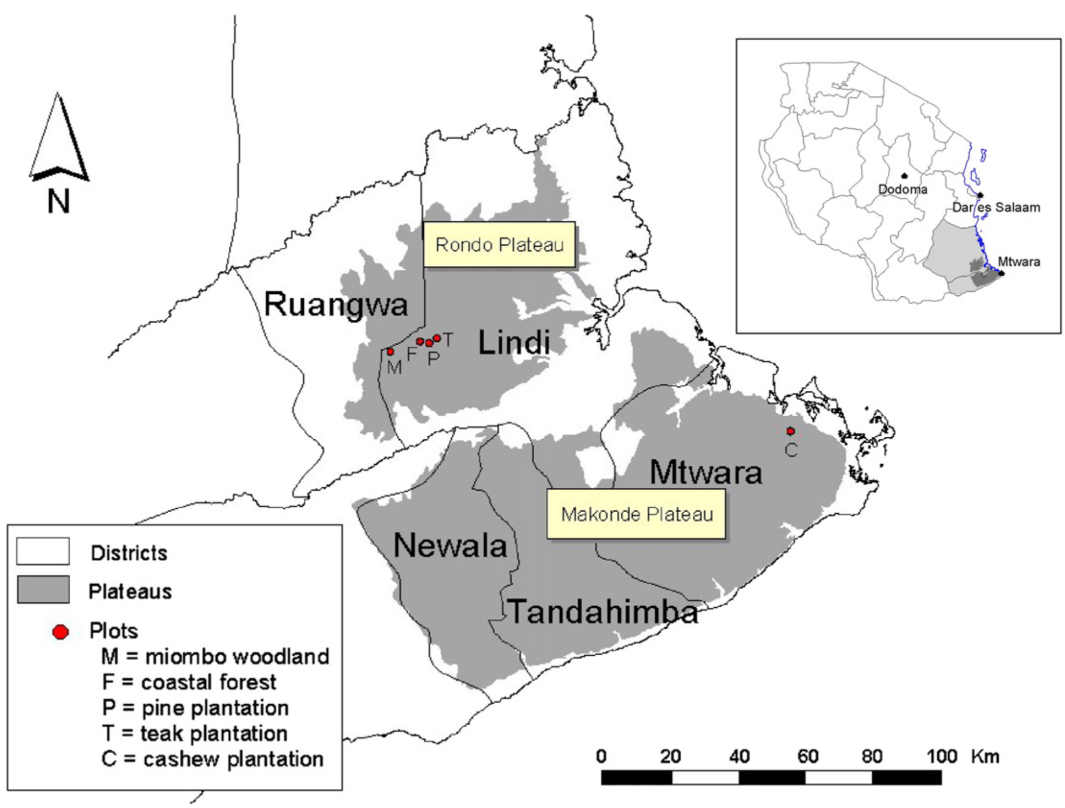

Fig. 1. Location of the Mtwara and Lindi regions in Southeastern Tanzania. The research plots are situated in the Mtwara and Lindi districts on the Makonde and Rondo plateaus.