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Spatial variability of soil carbon stock in the Urucu river basin, Central Amazon-Brazil

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HIGHLIGHTS

- The SOC stocks across 30 and 100 cm depth were 3.28 and 7.32 kg C m^{-2}, respectively.
- SOC stocks were 34 and 16%, respectively, lower than those observed in other studies.
- Regions with waterlogging soils presented the lowest SOC stock.
- Heterotopic cokriging, using CTI, improved the accuracy of SOC stock maps.

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ABSTRACT

The Amazon Forest plays a major role in C sequestration and release. However, few regional estimates of soil organic carbon (SOC) stock in this ecoregion exist. One of the barriers to improve SOC estimates is the lack of recent soil data at high spatial resolution, which hampers the application of new methods for mapping SOC stock. The aims of this work were: (i) to quantify SOC stock under undisturbed vegetation for the 0–30 and the 0–100 cm under Amazon Forest; (ii) to correlate the SOC stock with soil mapping units and relief attributes and (iii) to evaluate three geostatistical techniques to generate maps of SOC stock (ordinary, isotopic and heterotopic cokriging). The study site is located in the Central region of Amazon State, Brazil. The soil survey covered the study site that has an area of 80 km^2 and resulted in a 1:10,000 soil map. It consisted of 315 field observations (96 complete soil profiles and 219 boreholes). SOC stock was calculated by summing C stocks by horizon, determined as a product of BD, SOC and the horizon thickness. For each one of the 315 soil observations, relief attributes were derived from a topographic map to understand SOC dynamics. The SOC stocks across 30 and 100 cm soil depth were 3.28 and 7.32 kg C m^{-2}, respectively, which is, 34 and 16%, lower than other studies. The SOC stock is higher in soils developed in relief forms exhibiting well-drained soils, which are covered by Upland Dense Tropical Rainforest. Only SOC stock in the upper 100 cm exhibited spatial dependence allowing the generation of spatial variability maps based on spatial (co)-regionalization. The CTI was inversely correlated with SOC stock and was the only auxiliary variable feasible to be used in cokriging interpolation. The heterotopic cokriging presented the best performance for mapping SOC stock.

1. Introduction

Models of carbon cycle require accurate estimations of the carbon storage in different reservoirs. Regarding the soil compartment, global C pools are difficult to estimate because of the limited knowledge about specific properties of soil types (Sombroek et al., 1993; Batjes, 1996), the considerable spatial variability of soil C even within the same soil mapping unit (Cerri et al., 2000), and the different effects of factors controlling soil organic C dynamics (Pastor and Post, 1986; Parton et al., 1987). Thus, regional studies are necessary to refine large-scale estimations obtained by aggregation of regional estimates (Bernoux et al., 2002).

Estimates of SOC stocks for the Brazilian Amazon are presented in Table 1. Cerri et al. (2000), using pedotransfer functions, estimated 41 Pg C stocked in the top 1 m in the Brazilian Amazon, which represents about half of all soil carbon stocked in Brazil, emphasizing the importance of the Amazon Forest in carbon storage. The potential total soil C stock of the Brazilian Amazon under native vegetation, estimated by Bernoux et al. (2003) and Batjes (2005) was 22.7 and 23.9–24.2 Pg C in the 0–30 cm layer, respectively. For the Brazilian Amazon (about 500 Mha), Batjes and Dijkshoorn (1999) observed that organic C

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Table 1
An overview of the papers published about SOC stock in the Amazon region (5,217,423 km^2).

Source	SOC (Pg)		N	Methodology
	0–30 cm	0–100 cm		
De Moraes et al. (1995)	21	47	1162	1:5 M soil map linked to national profile data — mean SOC content per soil unit. Missing bulk density (BD) data replaced with the mean measured BD of the corresponding soil group. Source of dates: EMBRAPA (1981); RADAMBRASIL (1973–1983).
Batjes and Dijkshoorn (1999)	25	46.5	1828	1:5 M SOTER for Latin America — mean SOC content per FAO soil unit. Estimates of missing BD data. Source of dates: SOTER-LAC
Cerri et al. (2000)	23.4	41		1:5 M soil map linked to national soil profile dataset — medians for SOC content per soil type. Missing BD data from linear regression.
Bernoux et al. (2002)	22.7	–	3969	Soil-Vegetation Associations (SVA), using national soil data (1:5 M); Calculation of representative C stock values for each SVA category producing a map of their distribution, and extraction of part of the Brazilian Amazon portion from the stock produced for the whole of Brazil. Source of dates: (EMBRAPA, 1981; RADAMBRASIL, 1973–1983; IBGE, 1988).
Batjes (2005)	23.9–24.2	42.3–43.8	584	Updated 1:5 M SOTER database for Brazil (Batjes et al., 2004) and simulation of phenoforms (Batjes, 2005).
Fidalgo et al. (2007)	23,9–24,2	–	363	IPCC/UNEP/OECD/OEA (IPCC, 1997). Soil-vegetation association (1:5 M). Source of dates: IBGE (2004).
This study	–	–	96	Data were obtained from a detailed soil survey (1:10,000). SOC stock for each soil profile was calculated by summing C stocks by horizon, determined as a product of BD, SOC and the horizon thickness. In each one of the 315 soil observations, relief attributes were derived from a topographic map. Maps of SOC stock were derivate using geostatistical techniques.

stock was 25 Pg C (0–30 cm) and 46.5 Pg C (0–100 cm), similar to the values reported by de Moraes et al. (1995).

Despite the quality and the importance of these SOC stock estimations for the amazon region, it is important to highlight some common aspects of these results presented in Table 1, such as: a) directly or indirectly, the data source used by different authors has the same origin (RADAMBRASIL), which was generated a long time ago (from 1973–1984); b) the maps used by different authors were published at a coarse scale and the data available for SOC calculations were very sparse along the Amazon region (~0.7–3.5 soil profiles for each 10,000 km^2 — Table 1); c) the Legal Amazon region is a huge territory covering an area of 5,217,423 km^2 (59% of the total Brazilian territory), encompassing different ecosystems. The latter implies that a model based on low-density data information, probably fails to predict SOC stock for the entire Amazon Region; d) the estimates of SOC stocks have been made through soil mapping or soil-vegetation units linked to representative soil profile data; e) in general, authors do not clearly reveal the mechanistic relation between the SOC stock, relief and vegetation. Some decisions during the mapping process are not completely explained, and consequently, maps become hardly reproducible.

The aspects presented above demonstrate the necessity to generate new data at a higher spatial resolution, as well as to apply appropriate methods for mapping SOC stock. A broad range of statistical methods has been applied towards digital soil mapping of SOC stock. Most commonly, multiple and linear regressions have been used for spatial quantifications of carbon stock (Moore et al., 1993; Powers and Schlesinger, 2002; Thompson et al., 2006). Based on the variability structure, geostatistics can be used to estimate the spatial distribution of carbon stock through kriging with or without external drift or cokriging (Simbahan et al., 2006). Some authors have applied regression kriging to predict SOC stock or soil organic matter (Bhatti et al., 1991; Hengl et al., 2004).

Considering the demand for reliable and reproducible maps of SOC stock based on data that were collected at a high spatial resolution in the Amazon region, we conducted a study in an area located in the Central part of the Amazon State. The aims of this work were: (i) to quantify SOC stock under undisturbed vegetation for the 0–30 cm and 0–100 cm reference layers in the Amazon Forest; (ii) to correlate the SOC stock with soil mapping units and relief attributes; (iii) to evaluate three geostatistical techniques to generate spatial variability maps of SOC stock (ordinary kriging, isotopic cokriging and heterotopic cokriging). We hypothesized that relief is the dominating process responsible for soil and vegetation variability along the study site. As a soil attribute, SOC stock is a consequence of these relationship and consequently some relief attributes can be used to adequately estimate spatial variability of SOC stock using cokriging.

2. Methods

2.1. Study area

The study site is located in the central region of the Amazon State, nearby the Urucu River, in the municipality of Coari, Brazil (Fig. 1). The study site belongs to Içá Formation, and encompasses an area of 80 km^2 in the Amazon Forest. The region, about 640 km from Manaus (State capital), can be accessed only by boat or airplane. The climate is equatorial (Af — Köppen climate classification) where the temperature of the coldest month is higher than 20 °C, with no pronounced dry period and a mean annual precipitation of 2500 mm.

According to RADAMBRASIL (1978), the soils of the study site were formed from sediments of Içá Formation. The sediments of Içá Formation cover an area of 563.264 km^2 (36% of the Amazon State) and were deposited in the Tertiary–Quaternary Period. The Içá Formation consists of fine to medium sandstone and siltstone, locally with clay conglomerates and yellow-red colors (Galvão et al., 2012). The Holocene alluvium of the Quaternary Period deposits is related to the current Amazonian drainage networks.

2.2. Soil database

Between the years of 2008 and 2009, a soil survey was conducted in the Oil Province of the Urucu River, called Geologo Pedro de Moura. The work resulted in the generation of a soil map, which covers an area of 80 km^2 (Fig. 1), along with its respective report (Villela, 2013). Throughout the soil survey, 315 field observations were performed, consisting of 96 soil profiles and 219 soil boreholes (Fig. 2). Due to the limitations imposed by native vegetation, the 315 field observations were restricted to the vicinity of access roads. The soils were classified as suggested by the Brazilian Soil Classification System (Embrapa, 1999). The soil-mapping units of the study site, as well as the number of profiles and area of occurrence are shown in Table 2.

All the data used for SOC stock calculation were obtained from the report of the soil survey. In each horizon of the 96 soil profiles, the following soil attributes were determined: soil organic carbon (SOC), soil bulk density (BD), sand, silt and clay content. SOC was measured by wet combustion, according to the methodology proposed by Walkley and Black (1932). BD was measured using undisturbed soil core samples (Kopeck rings: 4.2 cm height and 4.0 cm diameter). Soil particle