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Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis

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ABSTRACT

Soil organic carbon (SOC) balance is an important component of the terrestrial carbon (C) budget. However, effect of cropland management changes on SOC dynamics has not been recently assessed in the tropics.

Studies were compiled in the tropics where SOC stocks were measured in the topsoil (0–20 or 0–30 cm depth) after the adoption of management practices that are expected to enhance SOC stocks, including tillage reduction, crop rotation, exogenous organic amendments, restitution of crop residues, mineral amendments, and combinations of these practices. Random forest regression was used to identify the determinants of SOC accumulation rates (ΔSOC) depending on the climate, soil characteristics and changes in management practices.

214 cases were identified in 48 studies in 13 different countries. The average ΔSOC was 0.41 ± 0.03 Mg C ha^{-1} yr^{-1} (significantly greater than zero), for an average experiment duration of 13.6 ± 0.6 years. Although a large part of the variability remained unexplained due to methodological bias in the studies or a lack of relevant predictors. The strongest predictors of ΔSOC were C inputs, duration of the experiments, and the management practices, whereas neither soil characteristics (soil type, clay content, and initial SOC stock) nor climate variables (mean annual temperature and rainfall, aridity index) affected ΔSOC. The SOC accumulation rates increased linearly with C inputs, and the conversion rate of C inputs to SOC was 8.2 ± 0.8%. Given the competing uses of organic matter on many tropical farms, the benefits of using changes in management practices for climate change mitigation might be overrated. As ΔSOC decreased with the duration of the experiments, ΔSOC would probably be smaller if a period of 20 years were considered, as recommended by the IPCC guidelines. The management practice with the greatest ΔSOC was diversified crop rotation. Cropping systems where diverse practices were combined resulted in higher ΔSOC than individual practices such as reduced tillage and mineral fertilization on their own.

The adoption of improved management practices that increase C inputs is still relevant for meeting the challenges of food security and adaptation to climate change.

1. Introduction

Changes in soil use and management to increase soil organic carbon (SOC) stocks have been identified as a mean of mitigating climate change (Minasny et al., 2017; Paustian et al., 2016; Smith, 2016).Carbon (C) sequestration in the soil is the net carbon dioxide (CO_2) removal from the atmosphere to the soil, where C is stored in soil organic matter (Feller and Bernoux, 2008; Stockmann et al., 2013). Furthermore apart of their role in global carbon balance, soils are also a vital resource for humankind, hosting biodiversity, regulating nutrient cycles, food production, erosion, and fresh water quality (Banwart et al., 2014; Keesstra et al., 2016). There was thus a need to considerer and characterize the land managements that increase SOC stocks.

Large land-use changes, especially deforestation, have taken place in the tropics in recent years (Grace et al., 2014). As conversion of forest to cropland lead to SOC depletion (Deng et al., 2016; Don et al., 2011), there should be a significant potential for SOC accumulation in tropical croplands. Furthermore it may be appropriate to concentrate

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on tropical croplands when seeking to increase SOC stocks, as this also contributes to improving food security and adapting to climate change (Paustian et al., 2016). SOC is particularly important for the fertility of tropical soils, since soil organic matter supplies most of the nutrients such as nitrogen and phosphorous taken up crops that receive little or no mineral amendments. Tropical soils are often highly weathered with a low cation exchange capacity and need the support of organic inputs such as manure or crop residues for the retention of nutrients and water (Bationo et al., 2007; Castellanos-Navarrete et al., 2015; Palm et al., 2001). Increasing SOC stocks in the tropical croplands would therefore help towards meeting the 4 per 1000 initiative targets for climate change mitigation and food security (Minasny et al., 2017).

Changes in SOC stocks are controlled by the balance between C inputs, from plant biomass and anthropogenic organic inputs, and C losses through heterotrophic catabolism (Paul, 2016). Several factors are involved in dynamics of SOC stocks when land management changes, such as climate and soil characteristics, time since the change in practice and the amount of carbon inputs (Dlamini et al., 2016; Don et al., 2011; Laganière et al., 2010; Ogle et al., 2005; Paustian et al., 1997; Virto et al., 2012). SOC stocks can be increased through several land management strategies such as afforestation (Deng and Shangguan, 2017; Laganière et al., 2010), conversion of cropland to grassland (Deng et al., 2016; Don et al., 2011), grassland rehabilitation (Chaplot et al., 2016), restoration of degraded lands (Akpa et al., 2016) but also through cropland management (Minasny et al., 2017; Paustian et al., 1997). The cropland management practices aiming to increase SOC stocks include, for example, crop diversification (Poeplau and Don, 2015), organic or mineral fertilization (Han et al., 2016; Maillard and Angers, 2014), restitution of crop residues (Turmel et al., 2015), agroforestry practices (Cardinael et al., 2017), tillage reduction (Luo et al., 2010), and combinations of these practices, e.g. for conservation agriculture (Powlson et al., 2016). Despite the worldwide growing interest in SOC accumulation, there is no recent synthesis of changes in SOC stocks in tropical croplands. Tropical croplands support various agricultural practices. A focus on the impact of their management on the potential of soil carbon accumulation is thus needed.

An overview of the changes in SOC stocks in response to changes in agricultural practices in the tropics is required to answer simple practical questions. What is the soil C accumulation potential and what are the most appropriate management practices to fulfil this potential? The objectives of the current study were: (i) to collect the existing published data sets on agricultural management practices which are expected to increase SOC stocks in tropical croplands; (ii) to evaluate the SOC accumulation rates can be expected in tropical croplands when management practices are changed and (iii) to identify the predictors of SOC accumulation rates.

Published data from field experiments on SOC accumulation after a change in the agricultural practices for tropical croplands were collected and meta-analyzed.

2. Materials and methods

2.1. Data collection

Data were collected by systematic searching of peer-reviewed literature supplemented by searches for relevant grey literature using web search engines (Google Scholar and Web of Science; 1960–2016). Keywords used were “soil organic carbon”; “sequestration”; “tropic”; “carbon stock”; “annual crops”; “croplands”. Only English language search terms were used but articles or PhD dissertations in French and Portuguese were also considered. The data search was restricted to studies covering areas between the tropics or having a tropical climate according to the IPCC climate classification based on elevation; mean annual temperature and rainfall (IPCC, 2010, 2006).

Paired-plot studies that met the following criteria were selected: (i) field studies where soils were cultivated with annual crops following a given management practice established for at least three years; (ii) SOC stocks were directly reported with means and standard deviations (or standard errors and sample sizes) or where the SOC stocks could be calculated from the measured soil bulk density and organic carbon concentrations; iii) the preferred soil depth was the upper 0–30 cm as the default value recommended in 2006 IPCC guidelines (IPCC, 2006) although studies considering the upper 0–20 cm were also included to enlarge the dataset. Studies that only investigated the top 10 or 15 cm of soil profiles to assess SOC stocks were not considered as inadequate for accounting purpose (IPCC, 2006) Some studies were rejected from the dataset, when we lacked of information: absence of replication, absence of measured bulk density data, absence of a reference situation, absence of information regarding soils characteristics, absence of specific time span data, or unclear design. Studies with unrealistic SOC stocks changes, i.e. larger than 5 Mg SOC ha^{-1} yr^{-1}, were also rejected (two paired-plot comparisons). The studies selected used either diachronic or synchronic approaches. For a diachronic approach, SOC stocks are measured on the same plot before the establishment of a management practice and at the end of the experiment. For a synchronic approach, soil samples are taken from plots under improved management systems at a known time after a change from an initial reference state and, at the same time, from adjacent soils maintained in this initial reference state and considered as controls.

The variables collected included location, mean annual rainfall, mean annual temperature, soil type and clay content, management practice, duration of the experiment, and the carbon inputs applied to the soil per year when available (Supplementary material S1). When the mean annual temperature was not provided by the authors, the WorldClim value for the site location (Hijmans et al., 2005) was used. The aridity index provided by Trabucco and Zomer (2009) calculated as the ratio between the mean annual rainfall (MAR) and the mean annual evapotranspiration (MAE) were used. For approximately half the cases (102 out of 214) there were direct estimates of annual C inputs to the soil for the improved cropping systems (expressed as Mg C ha^{-1} yr^{-1}), or the information required to calculate them, i.e. quantities and C concentrations of the dry matter applied to soil.

The soil type reported in the studies to a WRB reference soil group (IUSS Working Group WRB, 2015) based on the information given in the article was assigned for each case. Four groups of soil were defined according to the clustering proposed by the Soil Atlas of Africa (Jones et al., 2013). Group I comprised relatively homogeneous sandy or young soils with limited or poor profile development: 26 Arenosols and 59 Cambisols. Group II comprised soils with a clay-rich or argic subsoil horizon with a low base status, low activity clay (1 Acrisol), high base status, high activity clay (10 Luvisols) or high base status, low activity clay (4 Lixisols). Group III comprised soils where iron and/or aluminum chemistry plays a major role in their formation: 77 Ferralsols and 10 Nitisols. Group IV comprised soils where their properties are strongly affected by water: 22 Vertisols and 5 Gleysols. The improved management practices found in the dataset were classified according to additional features compared to the control plots or initial states: ROT for crop rotation, e.g. introduction of legumes, cover crops or annual grasses, MIN for mineral fertilization, TILL for no or reduced tillage, and ORG for organic C inputs further be categorized as EOM for soil amendment with exogenous organic matter such as manure or compost and RES for the restitution of crop residues. Management practices with applications of both mineral and organic inputs were recorded as MIN + ORG. Many combinations of these practices were found, e.g. conservation agriculture practices that combined TILL + ROT + RES practices. There was a generic classification TILL+ for tillage reduction associated with other practices.

Agroforestry practices were not evaluated since too few studies of tree-based or shrub-based intercropping with annual crops (such as alley cropping) that met the selection criteria were found.