Geoderma 328 (2018) 79–90

Contents lists available at ScienceDirect

Geoderma

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

Sugarcane yield and soil carbon response to straw removal in south-central Brazil

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ARTICLE INFO

Handling Editor: Junhong Bai

Keywords:
Straw management
Bioenergy production
Soil organic matter
Soil quality
Laser-Induced Fluorescence Spectroscopy
Sustainability

ABSTRACT

Understanding the impacts of straw removal on quantity and quality of soil organic carbon (SOC) is crucial for sustaining or improving soil functions and producing economically viable sugarcane yields. Field experiments were carried out on commercial farms to quantify effects of straw removal on sugarcane yields, SOC stocks and the degree of soil organic matter (SOM) humification under three diverse edaphoclimatic conditions (Quirinópolis-GO, Chapadão do Céu-GO and Quatá-SP) in Brazil, while considering the effects of cover crop on sugarcane yields during two harvest seasons. Three straw removal rates (0, 50, and 100%) were arranged in a randomized block design with four replications within two paired areas, one seeded with *Crotalaria spectabilis* (cover crop–CC) and the other kept under bare fallow (BF) during the sugarcane-replanting period. Sugarcane yields were measured annually using an instrumented truck equipped with load cells, and soil samples were collected to a depth of 40-cm two years after establishing the trials. Straw removal for two years did not significantly influence cane yields in Quatá-SP, but in Chapadão do Céu-GO and Quirinópolis-GO, complete straw removal resulted in cumulative yield losses of up to 28 and 62 Mg ha^{-1} respectively. The inclusion of *Crotalaria spectabilis* within sugarcane cropping cycle increased two-year cumulative yields by 25 and 27 Mg ha^{-1} in Chapadão do Céu-GO and Quirinópolis-GO respectively. SOC response to straw removal was highly site-specific after two years. In fine-textured soils, straw removal rates did not significantly affect SOC stocks in Chapadão do Céu-GO, but in Quirinópolis-GO complete straw removal favored the depletion of SOC stock relative to partial or no straw removal in both soil layers (0–10 and 0–40 cm) of the BF area, while within the CC area SOC depletion was observed in the 0–40 cm layer. For sandy soil (Quatá-SP), complete straw removal decreased SOC stock only in the top 10 cm of the CC area. Laser-Induced Fluorescence Spectroscopy showed high degree of SOM humification in soils with depleted SOC stock, indicating that excessive straw removal was degrading soil quality by reducing the amount of labile C in the SOM. Conclusions drawn from this study indicate that, even on a short-term basis, complete straw removal already began to modify the quantity and quality of SOC, while both moderate or complete removals adversely affected sugarcane yields.

1. Introduction

Innovative soil and crop production practices that influence soil organic carbon (SOC) quantity and quality while contributing to development of renewable resources are being evaluated worldwide to reduce reliance on fossil fuels, enhance energy security, and mitigate greenhouse gas (GHG) emissions (Börjesson, 2009; Goldemberg, 2007). As demand for renewable bioenergy feedstock increases, high-yielding sugarcane (*Saccharum* spp.) has been identified as one of the most promising options (Goldemberg and Guardabassi, 2010; Renouf et al., 2008). Brazil is the world's largest sugarcane producer with a cultivated area in 2016/17 of 9.1 million ha, primarily in the south-central region (CONAB, 2017). During the past 15 years, Brazilian sugarcane production increased 160%, from 257 million ton (Mt) in 2000/01 to about

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https://doi.org/10.1016/j.geoderma.2018.05.003
Received 28 November 2017; Received in revised form 29 March 2018; Accepted 2 May 2018
0016-7061/

667 Mt in 2015/16 (UNICA, 2017). In view of the growing world demand for liquid biofuels, Brazil is likely to increase the domestic ethanol production from the current 30.2 (CONAB, 2017) to 61.6 billion L of ethanol in 2021 (Goldemberg et al., 2014), including second-generation ethanol derived from lignocellulosic materials (e.g., straw and bagasse) as an alternative to achieve desired increases in ethanol production (Pereira et al., 2015).

A fundamental change in sugarcane sector during the past decade has been gradual elimination of pre-harvest burning and therefore a proportional increase in mechanical green harvesting. Currently, about 94% of sugarcane fields in south-central Brazil are being harvested mechanically without burning of straw in what is called green cane system (Bordonal et al., 2018). This results in annual straw-carbon (C) inputs of 6.2 Mg ha^{-1} left on the soil surface (Menandro et al., 2017), in which soil C retention depends on the rate of straw-C that is transformed into soil organic matter (SOM) (Carvalho et al., 2017b). This "straw mulching" provides numerous short- and long-term ecosystem services including less soil temperature fluctuation, reduced soil erosion, improved soil physical, chemical and biological properties, increased sugarcane yield, and soil C sequestration with the consequent mitigation of the global climate change (Carvalho et al., 2017a).

Replenishing and preserving SOC is essential to sustaining crop yield and soil health (Blanco-Canqui and Lal, 2009). Estimated to 1-m depth, world soils store (1500 Pg) 2.4 times as much C as in biota (620 Pg) and 1.9 times as much as in the atmosphere (820 Pg) (Lal, 2004). These pools are so large that management-induced changes in SOC stock can have significance in the GHG balance of bioenergy systems (Cherubini, 2010). As the quantity and quality of SOC stock and its dynamics are crucial to numerous soil functions and ecosystem services (Lal, 2016), identifying management strategies that enhance the accumulation of stable SOM is a high priority.

Laser-Induced Fluorescence Spectroscopy (LIFS) is a rapid, efficient and precise technique for the characterization of SOM (Santos et al., 2015), so that the stabilization of SOM (e.g., advanced humification stage) is usually attributed to preservation of the more recalcitrant organic structures (e.g., lignin and phenolic and resistant aliphatic components) of fresh SOM (Senesi et al., 2016). Knowledge about the magnitude of the humification of SOM is essential to evaluating the quality and productivity of soils, and to determining qualitative and quantitative changes by management practices (Tivet et al., 2013). This information is especially critical for soils of the tropics which are strongly vulnerable to SOM losses by several mechanisms (Milori et al., 2006; Senesi et al., 2016).

The growing demand for bioenergy necessities identification of innovative approaches to straw management in the Brazilian sugarcane fields. While in-field residue mulching may benefit the long-term soil quality and biomass production (Aquino et al., 2017; Blanco-Canqui and Lal, 2009; Lal, 2009), sugarcane straw also represents a valuable asset for 2G ethanol production and bioelectricity cogeneration, creating new opportunities for the Brazilian sugarcane industry and helping solve residues management challenges affecting ratoon crops. Thus, field experiments, to evaluate the effects of straw removal under contrasting edaphoclimatic conditions, are critical to assessing the role of crop residues in sustaining soil functions and crop yields while mitigating climate change and supporting several other ecosystem services (Blanco-Canqui and Lal, 2009; Lalljee, 2013; Liska et al., 2014).

While not yet widely used in sugarcane, cover crop with legumes has also innumerous agronomic advantages; such as better control of pests, diseases and weeds; improvements in soil physical, chemical and biological attributes; and significant increases in sugarcane stalk yields (Ambrosano et al., 2011; Fernandes et al., 2012; Park et al., 2010). There is a lack of specifically designed experiments to evaluate the effects of straw removal rates on sugarcane yields under contrasting cover crops, potential changes in quantity and quality of soil C, and the amount of straw that can be sustainably removed without jeopardizing soil quality and crop yield.

Therefore, a field experiment was designed to test the following hypotheses: (i) complete removal of straw for bioenergy production reduces sugarcane yields as well as soil C stock and its quality, and (ii) adoption of cover crop with *Crotalaria spectabilis* in the sugarcane-replanting period is an important management strategy to enhance sugarcane yield. The objective of this study was to assess the changes in quantity and quality of soil C as well as the response of sugarcane yields to a gradient of straw removal rates under diverse edaphoclimatic conditions in south-central Brazil, while considering the inclusion of a cover crop during the sugarcane-replanting period and the associated effects on sugarcane yields. The focus was also to discuss the impact of sugarcane straw removal for bioenergy production to support decision makers in developing sustainable management strategies for maintaining or enhancing soil C stocks while still improving and sustaining high sugarcane yields.

2. Materials and methods

2.1. Description of the study areas

The experimental sites were strategically chosen to represent diverse growing conditions in São Paulo (SP) and Goiás (GO) states within south-central Brazil. Three field experiments were carried out for scientific purposes within commercial farms in Quirinópolis-GO, Chapadão do Céu-GO and Quatá-SP (Fig. 1). In October 2012, soil samples were collected to a depth of 100 cm for chemical and particle-size analyses. Description of each research site (e.g., geographic coordinates, altitude, precipitation, mean annual temperature, climate type, soil classification and parent material) and of soil chemical and physical attributes are detailed in Table 1.

The field experiments were initiated at each location in October 2012 during the renovation period of a sugarcane area under fifth ratoon cycle of mechanized harvest. After desiccation with glyphosate (6 L ha^{-1}) and applications of lime (2 Mg ha^{-1}) and gypsum (1 Mg ha^{-1}), each study site was divided into two paired areas in December 2012, one seeded with *Crotalaria spectabilis* (with cover crop–CC) using a cereal planter at a rate of 25 kg ha^{-1} of seeds and the other left under bare fallow (BF) condition. In March/April 2013, herbicides (5 L ha^{-1} of glyphosate, 1.2 L ha^{-1} of 2,4-D and 0.5 L ha^{-1} of triomax) were applied to desiccate *Crotalaria spectabilis* at flowering and also suppress growth of weeds in the BF area. At the time of the desiccation, biomass production and nitrogen (N) content for *Crotalaria spectabilis* totaled 8.1 Mg ha^{-1} (192 kg N ha^{-1}) in Quirinópolis-GO, 8.3 Mg ha^{-1} (127 kg N ha^{-1}) in Chapadão do Céu-GO and 6.5 Mg ha^{-1} (169 kg N ha^{-1}) in Quatá-SP. Thereafter, the conventional tillage was performed by subsoiling to a depth of up to 45 cm and planting furrows were opened at 30-cm soil depth after a light harrowing. Fertilizers were applied at base of the planting furrow at a rate of 500 kg ha^{-1} of 08-28-20 in Chapadão do Céu-GO and 500 kg ha^{-1} of 08-25-25 in Quirinópolis-GO and Quatá-SP. Same rates of fertilizers were applied in both paired areas under CC and BF. Sugarcane was planted manually using 15–20 buds per meter of the variety RB966928, which presents adequate sprouting and high tillering and has an early to medium maturation cycle.

2.2. Experimental design and treatments

Three treatments were arranged in a randomized block design with four replications within each paired area (i.e., CC and BF) after the harvesting of plant cane (first annual crop cycle) in June 2014. At that time, the soil was collected for baseline characterization of the sites and the amounts of straw were collected from CC and BF areas for determination of the total biomass inputs by using a quadrant (0.25 m^2) at six random points. All straw (e.g., green tops plus dry leaves) from the assessed areas was weighed, and a sensor was used to quantify the moisture content to account the annual straw input on dry weight basis.