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High carbon storage in a previously degraded subtropical soil under no-tillage with legume cover crops

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ABSTRACT

The effect of no-tillage (NT) on soil organic carbon (SOC) storage may help Brazil meet its 37% greenhouse gas emissions reduction target by 2025. When combined with legume cover crops, NT could result in even greater SOC storage than NT alone. The objective of this study was to evaluate the SOC storage potential of NT and the contribution of legume cover crops and nitrogen (N) fertilization to this potential in both the surface and subsurface soil layers of a previously degraded subtropical Acrisol of Southern Brazil. Using a split-plot design, the long-term field experiment compared the effect of NT and conventional tillage (CT), with or without legume cover crops, and with or without mineral N fertilization. Thirty years of contrasting management systems resulted in large differences (up to 35 Mg ha^{-1}) in SOC stocks in the whole soil profile (0–100 cm). The combination that provided the greatest increase in SOC was NT combined with two legume cover crops and N fertilization (1.15 Mg ha^{-1} $year^{-1}$ compared to CT, with no N fertilization or legume cover crop). Legume cover crops were twice as efficient in storing SOC as N fertilization, with 1 kg of residue input being converted to 0.15 kg of SOC. Overall, the variation in SOC stocks was explained largely by plant carbon input (R^2 = 80%) which varied with N fertilization and cropping system. About half of the SOC storage that occurred in this 30-year-old NT system was attributable to the increase in SOC stocks in the subsurface layer (30–100 cm), which was confirmed by the contribution of C_3 cover crop residues using carbon isotope signature (from 14.8 to ~17.5‰ in the 75–100 cm layer). Thus, the legume cover crop made a strong contribution to the potential of SOC storage in NT, and high rates of C storage occurred over a longer period in subsurface soil layers than previously believed.

1. Introduction

The Paris climate agreement is aimed at holding global warming to below 2 °C by 2050 and to pursue efforts to limit it to 1.5 °C (Rogelj et al., 2016). Brazil made a voluntary commitment to reduce greenhouse gas (GHG) emissions by 37% by 2025 and established a climate plan, which encompasses a low carbon agriculture plan which includes NT farming as one of five thrusts for mitigation of GHG emissions (Brazil Ministry of Environment, 2015).

In the last century, Brazilian agriculture has revolved around conventional tillage practices that have led to severe soil degradation problems including water erosion and the loss of soil quality (Mielniczuk et al., 2003). In this context, the no-tillage (NT) system emerged as a basis for conservation and sustainable agriculture (Paustian et al., 1997; Bayer et al., 2000; Lal et al., 2007), with strong impact on chemical, physical and biological soil quality (Mielniczuk et al., 2003). Studies conducted in tropical and subtropical environments (Bayer et al., 2006) have highlighted mean annual SOC storage rates ranging from 0.35 to 0.48 Mg $ha^{-1}yr^{-1}$ when conventional tillage systems are converted into NT systems.

The effect of NT on SOC storage is also dependent on the amount and diversity of the crops grown (Diekow et al., 2005; Martins et al., 2012; Raphael et al., 2016). Legume cover crops play an essential role in SOC storage under NT, either through the biomass inputs (shoot and root) associated with these plant species or through the symbiotically fixed N which becomes available and increases the grain and biomass

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production of cash crops grown in succession (Amado et al., 2006). The higher quality (N content and soluble fractions) of the biomass of legume cover crops, whether cultivated alone or intercropped with other species, may improve the efficiency of the microorganisms to accumulate C in the soil (Cotrufo et al., 2013). However, there is no consensus on the effect of nitrogen fertilization on soil SOC stocks because, in spite of the positive effect it has on plant biomass addition and consequent C input (Mack et al., 2004, Kirchmann et al., 2013), inorganic N can also cause accelerated mineralization (Khan et al., 2007) although this conclusion is not universally accepted (e.g., Powlson et al., 2010).

Soil depth should be considered carefully in evaluating SOC storage under NT. In temperate soils of North America and Europe, the gain of SOC in surface layer under NT may be compensated by gains in subsurface layers under CT (Angers et al., 1997; Baker et al., 2007; Blanco-Canqui et al., 2011; Dimassi et al., 2014). By contrast, some studies carried out in tropical and subtropical soils in Brazil have shown that sampling of the surface soil can lead to underestimation of the potential of SOC storage under NT (Boddey et al., 2010; Alburquerque et al., 2015). In those studies, sampling of the 0–100 cm layer resulted in SOC storage rates that were 59% (Boddey et al., 2010) and 100% (Alburquerque et al., 2015) higher than for soil sampling done at a depth of 0–30 cm. The storage of C in subsurface layers under NT may be significant in Brazilian tropical and subtropical soils, especially in the case of cropping and rotation systems that incorporate legume cover crops (Boddey et al., 2010). The high volume of rainfall may favor the percolation of organic compounds and contribute to the potential for SOC storage in subsurface layers of tropical soils under conservation management systems (Hobley and Wilson, 2016). In addition, free-draining soils (Miranda et al., 2016) with Bt horizons (Torres-Sallan et al., 2018) and functional groups on the surface of iron and aluminum oxides that interact strongly and stabilize organic matter (Lawrence et al., 2015) point to considerable potential for SOC storage in subsurface layers.

We hypothesized that over the long term, legume cover crops would make a strong contribution to the potential of SOC storage under NT, and that C storage could occur at high rates in subsurface layers of subtropical soils. Our objective was thus to evaluate the potential that NT offers for SOC storage as well as the contribution of legume cover crops and N fertilization to this potential in both surface and subsurface layers of a previously degraded subtropical Acrisol.

2. Materials and methods

2.1. Description of the experiment

The study was conducted in a long-term experiment (30 years) at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul in the municipality of Eldorado do Sul–RS (30º06 ′ S, 51º40 ′ W, elevation 96 m). The climate is subtropical (Cfa according to the Köppen classification), with a mean temperature of 19.4 °C and annual rainfall of 1440 mm. The soil was classified as a sandy clay loam granite-derived Acrisol (FAO, 2002), with a loamy clay texture in the surface layer. The clay content in the soil profile increases from 217 g kg^{-1} in the 0–5 cm layer to 394 g kg^{-1} in the 20–30 cm layer, reaching 511 g kg^{-1} in the 75–100 cm layer. The main minerals in the clay fraction are kaolinite (720 g kg^{-1}) and iron oxides (109 g kg^{-1}) (Bayer et al., 2001).

Prior to this experiment, the field was a natural grassland (mainly *Paspalum* spp. and *Andropogon* spp.), which was converted to cropland in 1969 and cultivated for 16 years by using conventional tillage practices based on plowing and disking twice a year for winter and summer annual crops with straw removal. When the experiment was started in 1985, the soil showed serious physical degradation and water erosion (Bayer et al., 2000).

The experiment included two soil tillage systems (CT and NT) arranged in main plots of 15 × 20 m. Each tillage system was composed of three cropping systems in subplots of 5 × 20 m: black oats (*Avena strigosa* Schreb)/maize (*Zea mays* L.) (O/M), vetch (*Vicia sativa* L.)/maize (V/M) and oats + vetch/maize + cowpea (*Vigna unguiculata* (L.) Wald) (OV/MC). These combined tillages and cropping systems were managed with two levels of fertilization, 0 and 180 kg ha^{-1} of N-urea (0 N and 180 N), applied in strips in the maize crop only, consisting the sub-subplots (5 × 10 m). The experimental design consisted of randomized blocks with split-split plots and three replicates.

Winter crops, managed as cover crops, were established in April–May of each year using direct drilling in both CT and NT treatments. Oats, when grown alone, were seeded at a rate of 80 kg ha^{-1}. When oats were grown with vetch, oats were seeded at 30 kg ha^{-1}, and vetch at 50 kg ha^{-1}. For vetch cultivated alone, 80 kg ha^{-1} was used. In the OV/MC system, cowpea was sown 15–20 days after the maize, between the lines of this crop which were 40 cm apart.

The CT plots were ploughed to a furrow-depth of 17 cm once a year in spring before maize sowing by using a three-disk plough and harrowed twice to a depth of 10 cm by using a disk harrow resulting in the incorporation of the crop residues in this layer. At the same time, glyphosate-based herbicide (Roundup, Monsanto) was applied in the NT plots at a 1.4 kg ha^{-1} rate relative to the final glyphosate concentration, and 2–3 days later the winter cover crops were managed with a knife-roller and aboveground residues left on the soil surface. In NT, soil disturbance occurred only in the sowing line and the residues of the cover crop were left on the soil surface.

Maize was planted in September–October, with between-row spacing of 90 cm and a sowing rate designed to obtain 50–70 thousand plants per hectare. The fertilizer rate applied in maize was 21.5 and 41.5 kg ha^{-1} of P and K (50 and 50 kg ha^{-1} of P_2O_5 and K_2O), respectively.

The mean annual C input (aboveground and root, with roots being assumed to account for 30% of the aboveground portion) was calculated from cover crop data and the dry-matter maize yields compiled by Zanatta et al. (2007) for the period 1985–2006, which were subsequently updated to 2014 (Fig. 1). The annual aboveground maize dry matter yield was estimated from grain yield, and aboveground C input calculated by assuming dry matter in maize and the cover crops to contain 40% C. The values of CT and NT were averaged due to similar C input in both tillage systems.

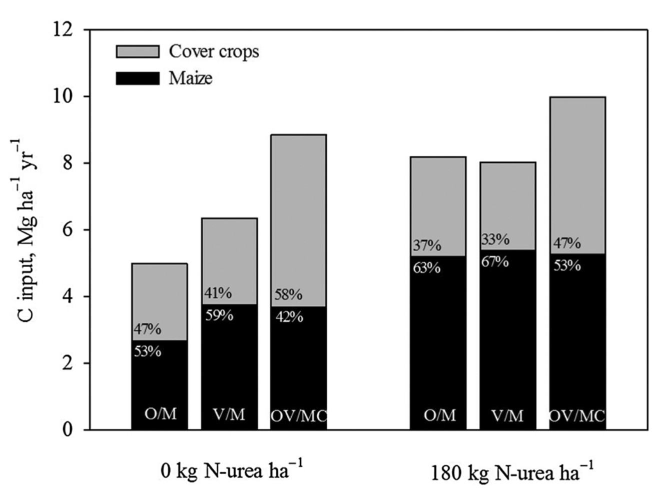

Fig. 1. Mean annual C inputs for oat/maize (O/M), vetch/maize (V/M) and oat + vetch/maize + cowpea (OV/MC) cropping systems subjected to two N-urea rates (0 N = 0 kg ha^{-1} and 180 N = 180 kg ha^{-1}). Values are average of two tillage systems (no-tillage and conventional tillage).