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Forages, cover crops and related shoot and root additions in no-till rotations to C sequestration in a subtropical Ferralsol

Nícolas Zendonadi dos Santos [a], Jeferson Dieckow [a,*], Cimélio Bayer [b], Rudimar Molin [c], Nerilde Favaretto [a], Volnei Pauletti [a], Jonatas Thiago Piva [a]

[a] Departamento de Solos e Engenharia Agrícola, Universidade Federal do Paraná, Rua dos Funcionarios 1540, Bairro Cabral CEP 80035-050, Curitiba/PR, Brazil
[b] Departamento de Solos, Universidade Federal do Rio Grande do Sul, P.O. Box 15100, CEP 91501-970 Porto Alegre/RS, Brazil
[c] Fundação ABC para Assistência e Divulgação Técnica Agropecuária, P.O. Box 1003, CEP 84166-990 Castro/PR, Brazil

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ABSTRACT

To improve C sequestration in no-till soils requires further development of crop rotations with high phytomass-C additions. The objectives of this study were (i) to assess long-term (17 years) contributions of cover crop- or forage-based no-till rotations and their related shoot and root additions to the accumulation of C in bulk and in physical fractions of a subtropical Ferralsol (20-cm depth); and (ii) infer if these rotations promote C sequestration and reach an eventual C saturation level in the soil. A wheat (*Triticum aestivum* L., winter crop)–soybean (*Glycine max* (L.) Merr, summer crop) succession was the baseline system. The soil under alfalfa (*Medicago sativa* L., hay forage) intercropped every three years with maize (*Zea mays* L., summer crop) had the highest C accumulation (0.44 Mg C ha^{-1} year^{-1}). The bi-annual rotation of ryegrass (*Lolium multiflorum* Lam., hay winter forage)–maize–ryegrass–soybean had a soil C sequestration of 0.32 Mg C ha^{-1} year^{-1}. Among the two bi-annual cover crop-based rotations, the vetch (*Vicia villosa* Roth, winter cover crop)–maize–wheat–soybean rotation added 7.58 Mg C ha^{-1} year^{-1} as shoot plus root and sequestered 0.28 Mg C ha^{-1} year^{-1}. The counterpart grass-based rotation of oat (*Avena strigosa* Schreb., winter cover crop)–maize–wheat–soybean sequestered only 0.16 Mg C ha^{-1} year^{-1}, although adding 13% more C (8.56 Mg ha^{-1} year^{-1}). The vetch legume-based rotation, with a relative conversion factor (RCF) of 0.147, was more efficient in converting biomass C into sequestered soil C than oat grass-based rotation (RCF = 0.057). Soil C stocks showed a close relationship (R^2 = 0.72–0.98, $P < 0.10$) with root C addition, a poor relationship with total C addition and no relationship with shoot C addition. This suggests a more effective role of root than shoot additions in C accumulation in this no-till soil. Most of the C accumulation took place in the mineral-associated organic matter (71–95%, in the 0–5 cm layer) compared to the particulate organic matter. The asymptotic relationship between root C addition and C stocks in bulk soil and in mineral-associated fraction supports the idea of C saturation. In conclusion, forages or legume cover crops contribute to C sequestration in no-till tropical Ferrasols, and most of this contribution is from roots and stored in the mineral-associated fraction. This combination of soil and rotations can reach an eventual soil C saturation.

1. Introduction

Farming systems that increase soil C stocks are fundamental to the sustainability of agricultural production systems. Positive results related to soil C increments, and thus to soil chemical, physical and biological quality, and to mitigation of global warming potential by atmospheric CO_2-C removal, have been obtained by adopting no-till farming worldwide (Lal, 2004; Paustian et al., 1997; West and Post, 2002) and in (sub)tropical Brazilian soils (Bayer et al., 2002; Carvalho et al., 2009; Sá et al., 2001; Sisti et al., 2004; Zanatta et al., 2007). This conversion of conventional to no-till farming, however, is far from being the ultimate possible achievement in terms of soil C accumulation in tropics and subtropics. The challenge now is to develop and improve crop rotation schemes with high net primary productivity and phytomass-C additions that maximize the benefits of no-till as a strategy to promote CO_2-C sequestration and soil quality (Vieira et al., 2009).

The simultaneous production of grain crops (mainly soybean and maize [*Zea mays* L.]) and livestock (mainly beef and dairy cattle) within the same farm, either by direct grazing in areas that rotate between pasture and cropland or by mowing and subsequent forage

Abbreviations: TOC, total organic carbon; POM-C, particulate organic matter carbon; min-C, mineral-associated carbon; HI, harvest index; S/R, shoot-to-root ratio.

* Corresponding author. Tel.: +55 41 3350 5608; fax: +55 41 3350 5673.
E-mail address: jefersondieckow@ufpr.br (J. Dieckow).

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supply in stable, is being adopted as an integrated crop-livestock production system in Southern Brazil. The cultivation of forage species for grazing or mowing has shown benefits in terms of soil C accumulation (Cerri et al., 2004; Franzluebbers et al., 2001; Salton, 2005), although soils under hayed management are reported to accumulate less than those under grazed management (Franzluebbers et al., 2001). For integrated crop-livestock in the Brazilian Cerrado region (savannah), Salton (2005) reported soil C accumulation rates of 0.44 Mg ha^{-1} $year^{-1}$ in a 9-year old integrated production system with soybean for two years followed by brachiaria (*Brachiaria decumbens*) pasture for other two years. Franzluebbers and Stuedemann (2008) did not observe evidence of negative influence of integrated crop-livestock system on soil C and N fractions and thus recommended this system as a viable conservation approach for intensifying agricultural land use.

Forages accumulate more C in soils, compared to grain crops, due to a higher root biomass production stimulated by grazing. Souza et al. (2008), in a study conducted in Southern Brazil, showed increases in oat plus ryegrass root biomass production due to grazing, but worldwide results of grazing effects on root biomass are not consistent (Milchunas and Lauenroth, 1993). For cash and cover crops, the role of shoots and roots as sources of soil organic matter has been the subject of several studies (Balesdent and Balabane, 1996; Gale and Cambardella, 2000). Results from these studies suggest that in croplands, root-derived C is the predominant contributor to soil organic C. However, further information with respect to root contribution in no-till management is still necessary. The methodological limitations associated with root quantification is the main reason for few studies on below ground C additions compared to the number of studies on above ground C additions (Balesdent and Balabane, 1996). However, a helpful approach toward understanding roots and shoots contribution to organic matter is considering the harvest index and the shoot-to-root ratio (S/R) of species, so that root biomass can be satisfactorily estimated (Bolinder et al., 2007).

The cultivation of legume cover crops has also been reported to increase soil C stocks in no-till soils of Southern Brazil (Diekow et al., 2005b; Sisti et al., 2004; Vieira et al., 2009). In a long-term (13 years) study conducted in a subtropical Ferralsol of Brazil, Sisti et al. (2004) concluded that the main factor that appears to control C accumulation in no-till soil was the contribution of N_2 fixation by winter legume cover crop (in that case, vetch [*Vicia villosa* Roth]), emphasizing the importance of the inclusion of such species in rotation schemes.

Besides quantifying C accumulation in bulk no-till soil subjected to crop rotations with varying rates of annual C additions, it is also important to quantify how C accumulates in the mineral-associated fraction (silt and clay size fractions). The amount of C accumulated in the mineral-associated fraction (min-C) provides information about the potential of the soil to serve as a C sink. Several studies have reported that min-C, especially that inside microaggregates within macroaggregates, store most of the C accumulated in no-till soils, making it a diagnostic fraction to assess C accumulation in no-till soils (Denef et al., 2007; Six et al., 2000). In contrast, the amount of C in particulate organic matter (POM-C) may serve as an indicator about the efficiency of macroaggregates to physically protect this C (Bayer et al., 2002; Diekow et al., 2005a).

Developing and improving crop rotation schemes with high phytomass-C additions may lead to soil reaching saturation in regard to C sequestration. The concept of C saturation was introduced during the last decade (Six et al., 2002; Stewart et al., 2007) and proposes that soils have an upper limit for C accumulation, in which the steady-state C stock shows little or no increase with respect to further increases in C addition by changes in soil management practices. Traditionally, the models of soil C accumulation are based on a linear relationship between steady-state C stock and annual C addition, the so-called linear first-order model. This model has been recently questioned and replaced by the C saturation asymptotic model (Stewart et al., 2007; Stewart et al., 2008). However, more studies are required to come to consistent conclusions about whether soils can become C-saturated, especially for tropical and subtropical soils where little information is available.

The objectives of this study were (i) to assess the long-term (17 years) contributions of cover crop- or forage-based no-till crop rotations and their related shoot and root additions to the accumulation of organic C in bulk and in particulate and mineral-associated fractions of organic matter of a subtropical Ferralsol; and (ii) make inferences about the capability of these rotations to promote C sequestration and reach an eventual C saturation level in the soil.

2. Material and methods

2.1. Field experiment and soil sampling

The study was based on a long-term field experiment (17 years) conducted in the experimental station of ABC Foundation for Agricultural Assistance and Technical Divulgation, near the town of Ponta Grossa, in the Campos Gerais region of Paraná state, Brazil (25°00′42″S, 50°09′13″W, altitude of 877 m). Soil is classified as a Ferralsol (FAO), or Oxisol (Soil Taxonomy) or Latossolo Vermelho distrófico típico (Brazilian Classification System), with sandy clay to clayey texture in the 0–20 cm layer (450 g kg^{-1} sand, 150 g kg^{-1} silt and 400 g kg^{-1} clay). The parent material is sandstone derived from the Silurian/Devonian Period (MINEROPAR, 2001). Climate is subtropical, classified as Cfb (Köppen), with average monthly temperatures varying from 11 to 12 °C in the coldest month (July) to 21–22 °C in the warmest month (January), and average annual precipitation between 1700 and 1800 mm, well distributed across the year (IAPAR, 1984).

The experimental area was originally under native grassland. In the 1960s (supposition), it was converted to annual cropland for commercial wheat (*Triticum aestivum* L.) and soybean (*Glycine max* (L.) Merr) cropping under conventional tillage and low technology. This management was maintained until the establishment of the current experiment. In the winter season of 1989 the current no-till practice was adopted. Treatments comprise seven crop rotations, distributed in 7.0-m × 10.5-m plots, according to a randomized complete block design, with four replicates. The following six crop rotations were selected:

(i) Wheat (*Triticum aestivum* L.)–soybean (*Glycine max* (L.) Merr) [W–S]. This is an annual crop sequencing that represents the reference or baseline system for the region. Wheat is cropped in winter and soybean in summer, for grain production.
(ii) Oat (*Avena strigosa* Schreb.)–maize (*Zea mays* L.)–wheat–soybean [O–M–W–S]. This is a bi-annual crop rotation with oat as a grass winter cover crop, desiccated with glyphosate herbicide before maize planting on summer. Wheat and soybean cropped in the second year are for grain production. This was a rotation designed for higher phytomass addition compared to W–S, being constituted mainly by grass species of high C:N ratio in shoot biomass.
(iii) Vetch (*Vicia villosa* Roth)–maize–wheat–soybean [V–M–W–S]. This is another bi-annual crop rotation for higher phytomass addition compared to W–S. Different from the previous, this is a legume-based rotation in which vetch is the winter cover crop, also desiccated with glyphosate herbicide before maize planting.
(iv) Vetch–maize–oat–soybean–wheat–soybean [V–M–O–S–W–S]. This is a tri-annual crop rotation with vetch and oat as