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Total and permanganate-oxidizable organic carbon in the corn rooting zone of US Coastal Plain soils as affected by forage radish cover crops and N fertilizer

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ABSTRACT

Forage radish (*Raphanus sativus L. var. longipinnatus*) is a relatively new winter cover crop becoming widely grown in humid temperate North America. Little is known about how the use of this fall/winter cover crop may influence carbon sequestration and distribution in the soil profile in corn silage production system. The objectives of this study were to determine quantities and distribution in the soil profile of total organic carbon (TOC) and permanganate oxidizable carbon (POXC) as affected by forage radish cover crops and to examine the relationship between TOC and POXC in the profile. While there was no significant difference in TOC between radish (RAD) and no cover crop (NC) treatments for each depth interval at each site, the TOC in RAD (10.3 g C/kg) was higher compared with NC (9.3 g C/kg) in surface soil depth (0–30 cm) when analyzed across all site years. Forage radish impacts on POXC were observed not only for surface horizons (0–15 cm), but also for deep horizons (90–105 cm). Banded nitrogen fertilizer affected the soil C:N ratio deep in the soil profile at both sites (at 90–105 cm in RAD and at 60–75 cm in NC). Where N fertilizer was applied, soil POXC in 0–30 cm was significantly greater following radish (535.7 mg POXC/kg) than following no cover crop (418.2 mg POXC/kg). Additionally, strong positive linear relationships between POXC and TOC were observed ($P < 0.05$), with a much steeper regression slope (higher POXC/TOC ratio) in the 60–105 cm layer (POXC/TOC ratio = 0.22) was much steeper than for the surface soil (0–30 cm) with POXC/TOC ratio = 0.05. We speculate that the higher POXC levels may have resulted from increased rooting and exudation by both corn and radish where nitrogen fertilizer was placed. Using forage radish cover crops show potential for mitigating against soil C depletion.

1. Introduction

Soil organic matter (SOM) is a key factor of soil quality since it influences nutrient holding and cycling, soil structure, erosion resistance, and soil biological processes (Weil and Magdoff, 2004; Lucas and Weil, 2012). Levels of SOM are most often estimated by measuring total organic carbon (SOC). Because SOC is such a large pool of C and mainly comprised of relatively stable material protected from decomposition, the effects of contrasting soil management practices may take many years to become apparent in SOC measurements (Weil et al., 2003). It remains difficult to measure small quantitative changes in SOC pools caused by variations in soil management practices over short time scales of a few years, despite the fact that these changes may impose significant effects on soil properties and associated microbial processes (Weil et al., 2003). Alternatively, labile soil organic carbon (LOC) is a relatively small fraction of TOC that has a short half life in soils and responds quickly to changes in soil management and fertilization practices (Weil and Magdoff, 2004). The LOC fraction is an important component that determines soil quality because of its involvement in soil aggregate stabilization (Tisdall and Oades, 1982) and its direct link to soil carbon (C) and nitrogen (N) mineralization (Gunapala and Scow, 1998).

Recently Culman et al. (2012), in a meta-analysis of 12 studies, presented evidence that the LOC reactive with a dilute (0.02 M) potassium permanganate solution (Weil et al., 2003) is a microbial

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processed pool of labile soil C that often exhibits greater sensitivity to changes in management or environmental variation than other commonly measured parameters such as particulate organic carbon (POC), microbial biomass carbon (MBC) or total TOC. They recommended that this fraction be termed permanganate oxidizable carbon (POXC). Several recent studies have reported that POXC was one of the most sensitive and reliable indicators for evaluating the short- and long-term impacts of soil management practices on soil quality (Awale et al., 2013; Chen et al., 2009; DuPont et al., 2010; Melero et al., 2009; Morrow et al., 2016; Plaza-Bonilla et al., 2014; Spargo et al., 2011; Veum et al., 2014). Studies found that POXC quantified by a modified potassium permanganate method (Weil et al., 2003) is sensitive to the changes in SOC content induced by organic amendments (Miles and Brown, 2011), cover crop treatments (Jokela et al., 2009), and high-residue cropping systems (Miles and Brown, 2011). Lucas and Weil (2012) reported that POXC determination is useful for identifying soils where improved SOC management is likely to increase grain productivity and further contribute to soil quality interpretations for producers. Measurement of the POXC content of a soil is also a very simple, inexpensive and non-hazardous method for estimating the LOC fraction (Culman et al., 2012; Morrow et al., 2016; Lucas and Weil, 2012).

Forage radish (*Raphanussativus* L.) is a unique fall/winter cover crop that is relatively new but becoming rapidly adopted in temperate, humid North America. Forage radish performs a number of unique and desirable functions, including alleviating soil compaction through effective bio-drilling (Chen and Weil, 2010), and efficient capture of N from deep soil layers. The N capture function prevents excess N from leaching into natural waters (Kristensen and Thorup-Kristensen, 2004; Dean and Weil, 2009). The radish has also been reported to increase soil test phosphorous (White and Weil, 2011) and very effectively suppress early spring weeds (Lawley et al., 2011).

Given two months of favorable growing conditions in fall (600+ growing degree days), radish cover crops typically produce 3–8 metric tons/ha of dry matter (approximately 20–30% of which is in the fleshy, partially above ground root). Because of its rapid growth in fall, a forage radish cover crop can add significant quantities of organic carbon to the soil (Mutegi et al., 2011, 2013; Dean and Weil, 2009). It is important to keep in mind however that forage radish biomass is highly decomposable so the carbon added to the soil system after radish cover crops has a rapid turnover rate (Kremen and Weil, 2006). More sensitive measures of SOC (e.g., POXC) may be able to detect changes in SOC resulting from radish cover cropping but we could find no published studies to date investigating radish effects on labile soil organic carbon. Moreover, the vast majority of studies measuring cover crop and management effects on SOC have investigated only the upper 10–30 cm of soil, but the few studies that have looked deeper point to the importance of carbon changes in the deep subsoil layers (Baker et al., 2007; Jandl et al., 2014).

This study investigates corn silage production with and without the use of forage radish as a fall/winter cover crop planted immediately after corn is harvested for silage. Within each cover crop treatment (radish or no cover), low and high fertilizer application was also compared. The variables measured included above ground plant C and dry matter production and the distribution of TOC, C:N ratio and POXC in the upper 105 cm of the soil profile. Thus, the objectives of this study were (1) to evaluate the effect of forage radish on soil organic carbon distribution in profile, (2) to determine effects of radish cover cropping on POXC in the soil profile, (3) to measure the effect of band-applied V5 stage corn side-dress nitrogen solution on the soil TOC and POXC in the soil profile, and (4) to determine the relationship between the soil organic carbon and permanganate oxidizable carbon at different soil depths.

2. Materials and methods

2.1. Field site description and experimental design

The study was conducted on two fields of the USDA Dairy Farm (39°01′N, 76°89′ W) at Beltsville Agriculture Research Center, Beltsville, Maryland. A completely randomized split-plot design experiment with four replicates was conducted in field BARC1-18 from May 2011 through August 2012 and in field BARC1-21 from May 2012 through August 2013.

The dominant soils types at BARC1-18 are Christiana soils (Fine, kaolinitic, mesic Aquic Hapludults) with silt loam A horizons and clay loam Bt and C horizons. The BARC1-21 site is approximately 1 km away from BARC1-18, the soil is a complex of Russett soil (Fine-loamy, mixed, semi-active, mesic Aquic Hapludults) with silt loam A horizons mainly in Blocks 3 and 4 and Christiana soils mainly in Blocks 1 and 2. The general soil properties of the Ap horizon (0–20 cm) and the management histories (for the study period and the previous 3 years) of two fields are presented in Tables 1 and 2, respectively. Fig. 1 shows the monthly mean air temperature and cumulative rainfall values for the sites during the study period.

During this study, no-till management was used in all fields. Sites BARC1-18 and 1-21 were divided into four blocks in May 2011 and 2012 respectively. Each block contained two main plots each randomly assigned one of two winter cover crop treatments: forage radish cover crop and no cover crop (crop residue and winter weeds only) (Fig. 2). The block dimension was 9.5 m × 110 m. The main plot size was 4.6 m × 110 m. In mid-June preceding the cover crop planting, 112 kg N ha^{-1}as urea ammonium nitrate (UAN) solution was side-dressed in every other corn row middle in bands of liquid fertilizer applied 150 cm apart such that each row of corn had access to nearby N on one side or the other, but not both sides. This allowed us to track this fertilizer N by differential growth and N uptake over the side-dress bands by cover crop plants drilled in rows just 15 cm apart. The N side-dressed and non-sidedressed strips were considered to be sub-plots characterized as high N (side-dressed row) and low N (non- side-dressed row) (Fig. 2). The sub plot size was 0.75 m × 110 m. In order to determine the effects of different N fertilizer rates on silage corn yield and examine whether corn silage, with or without a radish cover crop, benefits from side-dressed nitrogen fertilizer on these periodically manured soils, four N fertilization rates (no nitrogen, N0; 56 kg ha^{-1}, N1; 112 kg ha^{-1}, N2; and 168 kg ha^{-1}, N3) were applied in June 2012 (BARC1-18) and 2013 (BARC1-21). These N rates were factorially combined with previous fall cover crop treatment as sub-subplots in a split-split plot design with four replications giving a total of 32 sub plots of 20 m length and 4.6 m width each.

Table 1
Soil characteristics of the tested soils in 0–20 cm depth.

Site	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	Organic Carbon (g kg^{-1})	pH	Mehlich 3 P (mg kg^{-1})	Available K (mg kg^{-1})
BARC1-18	138	597	265	11.4	6.8	58	147
BARC1-21	152	620	228	15.2	6.3	73	105