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Soil microbial diversity and activity linked to crop yield and quality in a dryland organic wheat production system

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ABSTRACT

One of the primary goals of organic agriculture is increasing soil quality through the enhancement of soil biological diversity and activity. Greater soil microbial activity and diversity increase soil organic matter turnover and contribute to soil fertility, one of the main challenges associated with organic management. The objectives of this study were to 1) compare soil microbial abundance and activity between organic and conventional cropping systems, and 2) explore connections between soil microbial community indicators and crop productivity in organic and conventional winter wheat (*Triticum aestivum*)/spring wheat/winter pea (*Pisum sativum*) rotations. Soil and plant tissue was sampled following six years of organic and conventional management, and soil was analyzed for microbial abundance and activity. Fungal and bacterial abundance, soil enzyme activity, and soil organic carbon (C) were greater in the organic system than in the conventional system, and all four measures were positively correlated. Community-level physiological profiling (CLPP) indicated that C substrate utilization was greater in the organic than in the conventional system, though bacterial T-RFLP data did not demonstrate different community structure between systems, suggesting that management type affected bacterial community function, but not structure. Fungal T-RFLP results indicated that fungal community structure was different between the organic and conventional systems. Hay yield and tissue nitrogen (N) were greater in the organic system, and were positively correlated with fungal and bacterial abundance, but grain yield and protein were greater in the conventional system. The results of this study indicate that management type (organic vs. conventional) has implications for microbial abundance and microbial community function, and that differences in soil microbial abundance and activity likely impact crop yields and N uptake.

1. Introduction

A central tenet of the organic agriculture philosophy revolves around improving soil quality through building soil organic matter (SOM), enhancing biodiversity, and increasing soil biological activity (Lotter, 2003). Greater soil microbial diversity has been considered an indicator of greater overall ecosystem diversity and function, and is considered a sign of a "healthy" organic soil. Organic agriculture emphasizes the use of animal and green manures and composts to enhance soil fertility, as these materials have been shown to increase SOM (Fliessbach et al., 2007; Haynes and Naidu, 1998; Ros et al., 2006). The precise character of fertility amendments used in organic versus conventional agriculture exert a large effect on soil microbial populations, in the same way that the amount and type of organic matter inputs strongly affect soil microbial status (Shannon et al., 2002).

As SOM accumulates, ecosystem productivity can often become limited by the mineralization rate of soil humic materials (Parfitt et al., 2005), which is determined by the amount and activity of extracellular enzymes produced by soil microorganisms that break down complex organic molecules (Allison and Vitousek, 2005; Sinsabaugh, 1994). Extracellular enzyme production depends on bacterial and fungal biomass, physiological state, and species composition of the community, as well as a variety of environmental factors (Allison et al., 2007). Organic producers have reported that they struggle to maintain adequate soil inorganic N to achieve levels of production equal to those of conventional systems (Tautges and Goldberger, 2015; Walz, 2004). However,

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several studies report finding similar or greater total N levels in organic versus conventional soils (Gosling and Shepherd, 2005; Marinari et al., 2006; Marriott and Wander, 2006).

While total soil N may be greater in organic than conventional soils, N is usually the most limiting nutrient for crops in organic systems because much of the N is tied up in organic matter (Badgley et al., 2007; Seufert et al., 2012). Greater partitioning of N to the organic fraction may be favorable for soil health; however, a high organic to inorganic N ratio in soils often results in insufficient levels of available N for crop plants and consequently low grain yields. Mader et al. (2002) found that the soluble fraction of N was lower in organic than in conventional soils, but that extracellular enzyme activity and microbial diversity was greater in organic soils. Further, they observed more complete decay of particulate organic matter and greater microbial biomass in organic systems, indicating greater turnover of SOM but not necessarily a surplus of soluble forms of nutrients. Instead, N released through mineralization is likely being immobilized via assimilation into microbial biomass (Burger and Jackson, 2003; Willson et al., 2001). For example, yield benefits are observed in grain crops when legumes are added into the crop rotation to increase soil N with additional N fertilizer. Additional soil available N observed following the legume crop has been attributed to turnover of microbial biomass N, rather than the release of N from the legume tissues or roots (Bremer and van Kessel, 1992; Peoples et al., 2009). Some studies have found that, over time, organic systems that return large amounts of organic matter to the soil accumulate enough SOM that mineralization of SOM results in sufficient quantities of inorganic N that can support high-yielding grain crops (Mason and Spaner, 2006). For example, Zentner et al. (2004) found in years 5 through 12 of a long-term study that an organic spring wheat-legume green manure rotation achieved yields similar to that of a conventional spring wheat-fallow rotation. They also observed a significant increase over time in grain protein and N mineralization, indirectly indicating that microbial mineralization of accrued SOM can reach levels sufficient to support high-yielding organic crops. Therefore, soil microbial diversity and activity is of great interest in evaluating the outcomes of organic management practices on soil fertility, especially as compared to conventional management.

Perhaps not surprisingly, important biological indicators of soil health, including microbial biomass (Birkhofer et al., 2008; Fliessbach et al., 2007; Tu et al., 2006), microbial abundance (Shannon et al., 2002), enzyme activity (Marinari et al., 2006; Tu et al., 2006), microbial diversity (Mader et al., 2002; Shannon et al., 2002), and C substrate utilization (Ros et al., 2006) have all been found to be greater in organically-managed soils than in conventionally-managed soils. Fungal biomass has also been consistently found to be greater in organic systems, compared to conventional systems (Birkhofer et al., 2008; Gunapala and Scow, 1998; Shannon et al., 2002; Yeates et al., 1997). While some studies have reported bacterial abundance to be higher in organically-managed soils (Mulder et al., 2003; Van Diepeningen et al., 2006), others have found bacterial abundance to be less sensitive to management practices than fungal abundance (Yeates et al., 1997). Activity and diversity of soil microbes is, at least in part, a function of the availability, variety, and recalcitrance of C substrates and, as organic systems generally receive greater organic matter inputs than conventional systems (Burger and Jackson, 2003; Tu et al., 2006; Yeates et al., 1997), soils under organic management generally have a higher C content than those under conventional management. Greater soil C content does not necessarily imply greater microbial utilization of C, however. Birkhofer et al. (2008) found that soil C in a conventional system was more labile and therefore more easily accessible to microbes than in an organic system.

While many studies have reported differences in soil microbial biomass and diversity between organically- and conventionally-managed soils, few have examined correlations directly between these indicators. Those that have did not observe soil microbial indicators over a long-term time frame, following the conversion from conventional to organic agriculture. Long-term studies are needed to determine whether microbial soil health indicators can be linked to improved crop yield and quality outcomes. If greater soil microbial diversity and activity increase crop yield and quality, growers may be incentivized to cultivate a more diverse and functional soil microbial community, which would eventually also promote ecosystem health. This study aims to establish the link between soil microbial community health measures and enhanced crop yield and quality by 1) comparing soil microbial abundance and activity between organically- and conventionally-managed winter wheat (*Triticum aestivum*)/spring wheat/winter pea (*Pisum sativum*) rotations, and 2) exploring connections between soil microbial community indicators and crop productivity. The identification of these connections could substantiate the claim that greater soil health in turn contributes to greater agro-ecosystem function, and better crop quality and productivity.

2. Materials and methods

2.1. Site description and treatment design

Research was conducted at a site near Pullman, WA (46°45′N; -117°4′W) in the Palouse region of eastern Washington. The field was situated on a west-facing slope with the soil type Palouse silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls). Average annual precipitation for the area is 509 mm with the majority falling between November and March (Gallagher et al., 2010). The field site had been transitioned to certified organic management during an organic transitional crop rotation study conducted from 2003 to 2007 (see Gallagher et al., 2010 and Borrelli et al., 2012 for field history), after which time the field was maintained under continuous organic certification for the six-year study (2009–2014). At the initiation of the study period, in 2008, a conventional block was also established for comparison.

Identical organic and conventional crop rotations were designed in the study to enable direct comparisons between organic and conventional management, which differed in fertilizer and herbicide inputs. Plots were arranged in a randomized complete block design with 5 replicates of each treatment system and rotation within a block. The organic system was a certified organic three-year winter wheat/spring wheat/winter pea (hayed) rotation, similar to conventional rotations commonly grown in the region. Poultry manure (5% total N, with a C:N ratio of 6) was applied to the winter and spring wheat crops at the time of planting at a rate of 4400 kg ha^{-1} (220 kg N ha^{-1}), assuming a seasonal mineralization rate of 75–80% (165–176 kg N ha^{-1}). The conventional system is the conventional mimic of the organic system, and rotates winter wheat/spring wheat/winter peas (hayed). All grain crops in the conventional system received 56 kg ha^{-1} starter fertilizer at planting, and 112 kg ha^{-1} urea after planting, to match the estimated N mineralized in one cropping season within the organic system. Herbicides were used to control weeds in the conventional system. Glyphosate was applied each year prior to planting, pyrasulfotole, bromoxynil, and pinoxaden were applied post-emergence in spring wheat, and metribuzin was applied post-emergence in winter pea. A cultivator was used to prepare the seedbed for planting in both systems. All tillage operations in both systems were performed at depths of 10 cm or less to conserve soil, and no inversion tillage was utilized at any point throughout the duration of the study.