Soil Biology & Biochemistry 109 (2017) 188–204

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

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

Cover cropping frequency is the main driver of soil microbial changes during six years of organic vegetable production

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ARTICLE INFO

Article history:
Received 1 October 2016
Received in revised form
19 December 2016
Accepted 17 January 2017
Available online 1 March 2017

Keywords:
Microbial biomass
Organic vegetable production
Cover crops
Yard-waste compost
Soil microbial communities
Soil organic matter
Soil health

ABSTRACT

Soil microbes play a key role in soil health, and understanding the functional role of this living component of soil organic matter is critical to developing sustainable systems in major vegetable production regions like Salinas, California. Soil microbial community size and composition was evaluated after six years of commercial-scale production in five organic vegetable systems in a long-term systems experiment. All systems produced lettuce, and spinach or broccoli annually, and differed in yard-waste compost inputs (none or 15.2 Mg ha^{-1} $year^{-1}$), winter cover crop frequency (annually or every 4th year), and cover crop type (legume-rye, mustard, or rye). The same levels of irrigation, and supplemental fertilizer were applied to all systems. Cumulative organic matter inputs from compost and cover crop shoots over the six years ranged from 7.4 to 136.8 Mg ha^{-1} and caused differences in microbial biomass C (MBC) and N (MBN), and soil organic C (SOC). MBC increased by 40 mg C kg^{-1} soil with compost and infrequent cover cropping, and to levels that were relatively high (200–250 mg C kg^{-1} soil) for a loamy sand soil in systems with annual cover cropping. Changes in SOC between systems were caused primarily by compost while changes in MBC and MBN were more related to cover cropping frequency. Fatty acid methyl ester (FAME) analysis revealed differences in microbial community structure that were consistent with differences between systems in MBC and MBN. Across systems, the ratio of fungal: bacterial FAME indicators decreased over time while indicators of invertebrates, and gram positive bacteria increased. High-throughput sequencing revealed relatively few differences in bacterial phyla between systems, but the increase in cropping intensity across all systems changed the relative abundance of some bacterial phyla (*Bacteroidetes*, *Deinococcus-Thermus*) and genera (*Flavobacterium*, *Nocardioidetes*). Cover crop type and frequency also influenced the abundance of two bacterial genera (*Pseudomonas*, *Agromyces*). These results provide evidence that carbon (C) inputs from frequent cover cropping are the primary driver of changes in the soil food web and soil health in high-input, tillage-intensive organic vegetable production systems.

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1. Introduction

Soil health depends on the soil food web which is a complex community of interacting organisms - bacteria, fungi, protozoa, nematodes, arthropods, and earthworms – that rely on inputs of energy-rich plant residues (Ball, 2006; Thies and Grossman, 2006; Ferris and Tuomisto, 2015). Microbial-mediated decomposition of these residues releases energy and nutrients that enables soil organisms to function and provide essential soil ecosystem services (i.e., nutrient transformation and cycling, soil aggregation). Comparisons of organic and conventional management have provided critical insights of soil food web dynamics and the benefits of organic matter inputs (Drinkwater et al., 1995; Ferris et al., 1996; Bossio et al., 1998; Gunapala and Scow, 1998; van Diepeningen et al., 2006; Briar et al., 2007; Birkhofer et al., 2008; Overstreet et al., 2010; Reganold et al., 2010; Cao et al., 2011; Williams and Hedlund, 2013; Henneron et al., 2015). However, there are many ways to farm organically and conventionally for a given cash crop and also many ways to add organic matter to the soil (i.e., compost, cover crops, cash crop residue) which may have different effects on soil health. The terms 'soil health' and 'soil quality' are often used interchangeably (Romig et al., 1995; Karlen et al., 1997) however, in this paper we chose to use 'soil health' because we consider it a more intuitive concept that is akin in many ways to understanding

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http://dx.doi.org/10.1016/j.soilbio.2017.01.014
0038-0717/Published by Elsevier Ltd.

the concept of human health (Doran and Parkin, 1996).

To develop more sustainable vegetable systems, long-term research is needed on the effects of specific organic matter inputs and management practices on microbial aspects of soil health. This need is particularly important in high intensity, organic systems in regions such as the central coast of California that provide a large proportion of the organic vegetables that are sold throughout the U.S. (Klonsky and Healy, 2013; USDA-ERS, 2013). Unfortunately, in such systems, 'best management practices' like cover cropping can reduce the number of cash crops produced and complicate management (Hartz, 2006; Klonsky and Tourte, 2011; Brennan, 2017). This helps explain troubling reports (Guthman, 2000; Bowles et al., 2014) of infrequent cover cropping in many organic farms in California.

Vegetable farmers in central coast region of California that practice sustainable soil management typically add large amounts of organic matter to the soil (>5 Mg oven-dry material ha^{-1} annually) from yard-waste compost or frequent cover cropping. These C inputs are important in high-value, intensive vegetable systems because common management practices (i.e., intense tillage, multiple crops annually, frequent irrigation, relatively high nitrogen fertilization rates) may exacerbate C losses from the soil. Furthermore, many leafy vegetables (i.e., lettuce, spinach) return relatively little post-harvest residue to the soil (Mitchell, 1999), and such residues decompose rapidly because of their high nitrogen (N) and moisture content.

Compared with cover cropping, applying compost is a convenient and rapid way to add large amounts of C to the soil. An on-farm survey of row and perennial crop systems in California found positive effects from compost on several soil characteristics (i.e., bulk density, water infiltration, SOC, microbial biomass) (Brown and Cotton, 2011). A two year, vegetable experiment in Salinas, California found that organic matter inputs from compost (made from manure, straw, and vegetable waste) and rye cover crop prolonged soil MBC, and the researchers hypothesized that compost provided a 'slow-release' source of nutrients relative to the more labile (i.e., biologically active) C added by cover crops (Jackson et al., 2004). Labile pools of SOC, specifically the living (i.e., microbial biomass) and non-living fractions (i.e., particulate organic matter), are sensitive indicators of soil quality, whereas total SOC is a relatively crude indicator (Haynes, 2005)

To our knowledge there are no previous reports of the longer-term (>5 years) effects of various combinations of yard-waste compost and cover crops on the soil microbial communities in tillage-intensive, organic or conventional vegetable systems in California. Given the economic importance of agriculture in the Central Coast region of California, there has been considerable research focused on controlling soil borne disease organisms (Koike et al., 1996; Subbarao et al., 2007; Bensen et al., 2009; Njoroge et al., 2009; Fennimore et al., 2014; Muramoto et al., 2014), however, few studies (Klose et al., 2006) on how these agricultural practices affect the soil microbial community size or structure.

An ongoing, long-term study known as the Salinas Organic Cropping Systems (SOCS) experiment began in 2003 to evaluate the effects of cover crops and yard-waste compost on various aspects of high-value organic crop production (Brennan and Boyd, 2012). It includes several organic management systems that differed in the quality, quantity, and frequency of organic matter inputs for the same sequence of vegetable crops, and is the longest running systems study in the U.S. focused on high-value, tillage-intensive, cool-season organic crops. The initial evaluation of soil health in this study was based on nematode community analysis during 8 years of vegetable production and found that cover crop frequency (i.e., annually versus every 4 years) had a greater effect on the soil food web than compost additions (Ferris et al., 2012). In the present paper, we extend this work to characterize bacterial and fungal components of the soil food web to further understand soil health changes during the first 6 years of the experiment. The microbial community size was estimated from soil MBC and MBN. We used fatty acid methyl ester (FAME) indicators to evaluate microbial community composition, and high-throughput sequencing to characterize the bacterial diversity and distribution at different taxonomic levels (phyla, genus). Our objective was to determine the impact of winter cover cropping frequency (i.e., annually versus every 4th year), cover crop type (legume-rye, rye, mustard), and yard-waste compost on microbial community size and composition over a 6 year period.

2. Materials and methods

2.1. Site characteristics, climate, management, experimental design

A detailed description of the field site and ongoing experiment is in Brennan and Boyd (2012) and will only be described here briefly. The experiment is located at the USDA-ARS farm in Salinas, California, on the central coast region of the state. Salinas Valley opens to the Pacific Ocean which moderates the climate such that the average air temperature from 2003 to 2009 was 11 °C from October to March when the cover cropping or winter fallows occurred, and 15 °C during the most typical vegetable production period (April to September) (wwwcimis.water.ca.gov, Station #89, South Salinas). The average annual rainfall from 2003 to 2009 was 285 mm and occurred mostly between October and March. The soil is a Chualar loamy sand (fine-loamy, mixed, thermic Typic Argixerol) with 77% sand, 15% silt, and 8% clay. Prior to the experiment, the field was in hay production, and mixed vegetable and sugar beet trials (1990–1996), and from 1997 to 2003 was frequently fallowed with occasional cover crops and vegetables that included minimal inputs of fertilizers or compost. The field has been certified organic by California Certified Organic Farmers since 1999, and to USDA National Organic Program standards since they were implemented in 2002.

The experimental design was a randomized complete block with 8 systems arranged in each of four blocks in an area 49 m wide and 156 m long. Each system plot was 19.5 m long and 12.2 m wide. Only 5 systems with optimal seeding rates for weed suppression (Brennan, unpublished data) of 8 total systems in the study were included in the current paper (Table 1). These 5 systems of interest were the same ones that were used to evaluate soil phosphorous dynamics (Maltais-Landry et al., 2016), whereas in the analysis of the soil nematode community of the experiment (Ferris et al., 2012), all 8 systems were included with the data pooled across optimal and lower seeding rates.

The experiment began in October 2003 with either a winter fallow (Systems 1 and 2) or winter cover crop (System 3, 4, and 5). The cover crops were planted as a solid stand with a grain drill with 15 cm row spacing; the grain drill included cones (Brennan, 2011) that facilitated planting the different types of cover crops at different seeding rates. During the first 6 years, Systems 1 and 2 were fallow during all winters except the 4th winter (2006–2007), when they were cover cropped with the legume-rye mixture. In contrast, System 3, 4, and 5 were cover cropped every winter with the legume-rye mixture, mustard, or rye, respectively (Table 1). These differences between systems resulted in large differences in organic matter inputs from compost and cover crops over the six years (Fig. 1). Each year, the cover crops were incorporated with a soil spader in February or March to prepare the plots for bed formation; the winter fallowed systems were also spaded at this time. Weeds were controlled during the winter fallow by hand weeding or flaming, and shallow tillage with a rototiller as needed to prevent