Applied Soil Ecology 85 (2015) 86–93

Contents lists available at ScienceDirect

Applied Soil Ecology

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

Biosolids amendment dramatically increases sequestration of crop residue-carbon in agricultural soils in western Illinois

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ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form 29 August 2014
Accepted 1 September 2014
Available online 2 October 2014

Keywords:
Carbon sink
Microbial metabolic quotient
Microbial stress
Midwest

ABSTRACT

In agricultural soils, a large portion of C in crop residues (i.e., non-harvested plant parts left in the field) is annually lost to atmosphere due to the low C use metabolism of soil microorganisms adapting to the environmental stress (moisture stress and substrate C and N imbalance). In this study, we tested the hypothesis that amending soil with biosolids (treated sewage sludge with high stable organic matter and low C:N ratio) can improve the C metabolism of microorganisms in agricultural soils through alleviation of microbial stress, leading to increased sequestration of crop residue-C in agricultural soils. Biosolids were applied at a mean annual rate of 4.2 kg m^{-2} (dry weight) to eight agricultural fields (biosolids-amended) for 13 years (1972–1984) in western Illinois. Four agricultural fields (unamended) received chemical fertilizer as control. We measured the sequestration rate of crop residue-C in the soils over the span of 34 years (1972–2006) using a ^{13}C technique. We found dramatically greater sequestration rate of crop residue-C in biosolids-amended soil (32.5 ± 1.7% of total crop residue-C) versus unamended soil (11.8 ± 1.6%). Soil microbial metabolic quotient was significantly lower in biosolids-amended than in unamended fields, indicating that biosolid-amendment reduced soil microbial stress and improved microbial C metabolism. The study concludes use of a soil amendment with high stable C and low C:N is a valid approach to transform agricultural soils from current C-neutral status to a C sink. Biosolids represent a good choice of such soil amendments.

1. Introduction

Of the 2 Pg of crop residue-C generated annually worldwide in agricultural soils (Lal 2005), only 10–20% (Kimble et al., 2002) is sequestered in soil as organic matter. This low sequestration rate not only lessens the replenishment of lost soil organic carbon (SOC) but also limits the capacity of agricultural soils for offsetting global CO_2 emission. Sequestration of crop residue-C in soil requires microbial decomposition and stabilization of transformed organic matter in soil. When crop residues are left in soil, about 70% C is consumed by microorganisms annually (Buyanovsky and Wagner, 1987), and that C is then partitioned as maintenance respiration CO_2-C, microbial biomass-C (cell growth), and metabolite-C (Collins et al., 1997). Although association of undecomposed crop residues and microbial products with clay minerals and soil particles influences transformation of crop residue-C into SOC (Paustian et al., 2000; Six et al., 2002), microbial growth efficiency in utilizing the C source affects C sequestration in soils (Schimel, 2013; Wieder et al., 2013). Manipulation of the soil microbial community in agricultural soils that alters the respiration/growth balance in favor of microbial growth could increase the sequestration rate of crop residue-C in agricultural soils. Yet there are no reports of such a manipulation to improve sequestration of crop residue-C in agricultural soils.

One possible reason for lower sequestration of crop residue-C in agricultural soils than in native soils (Buyanovsky et al., 1987) is deterioration of the agricultural soil environment for microorganisms. Conversion of native to agricultural systems leads to loss of dense vegetation that normally protects the soil from intense fluctuations in moisture (Tian et al., 1997), and reduction in the input of substrates with balanced C:N ratio to soil microorganisms. To tackle moisture stress in agricultural soils, microorganisms allocate more resources to produce osmolytes, which reduce their internal water potential to avoid dehydrating (Harris,

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http://dx.doi.org/10.1016/j.apsoil.2014.09.001
0929-1393/

1981; Schimel et al., 2007). When soil is rewetted, microorganisms have to dispose osmolytes to avoid cell burst (Kieft et al., 1987). Production and disposal of protective molecules against soil moistures stress in agricultural soils causes more crop residue-C to be partitioned to maintenance respiration CO_2-C (Buyanovsky et al., 1987). Because N is transferred to grain, most of crop residues (e.g., wheat straw, corn stover) are depleted in N, and often have a very high C:N ratio (e.g., 50). The C:N ratio in soil microbial biomass is low (8.6 ± 0.3) (Cleveland and Liptzin, 2007) and does not change dramatically with type of substrates (Kallenbach and Grandy, 2011). Even though additional C from the substrate is needed for the maintenance respiration CO_2-C as microorganisms consume the substrate, the optimum substrate C:N ratio for microorganisms involved in residue decomposition is still about 20 (Mooshammer et al., 2014). In utilizing crop residues of high C:N ratios in agricultural soils, microorganisms must “throw out” some C to the atmosphere as extra respiration to maintain low and stable C:N ratio in their biomass. This can reduce the C utilization efficiency in agricultural soils.

In acclimating to environmentally stressed conditions in agricultural soils, microorganisms tend to physiologically change from growth to survival with relatively high respiration and low growth, though there may be a response from community composition (Schimel et al., 2007). Such microbial acclimation can generally cause more crop residue-C in agricultural soils to be partitioned to CO_2 and less to microbial biomass. Thus, low microbial C metabolism (low biomass and high respiration) in agricultural soils could be the predominant reason for the low soil CO_2 sequestration. We hypothesize a soil amendment, which can effectively increase soil water holding capacity (WHC) and decrease substrate C:N ratio, can improve microbial C metabolism in agricultural soils, leading to increased sequestration of crop residue-C.

Organic amendments (e.g., animal manure, green manure, farmyard manure, compost) used in the past (Kallenbach and Grandy, 2011) might have contributed in relieving agricultural soil’s microbial moisture stress through improving soil water holding and/or decreasing the substrate C:N ratio. However, most of the soil amendments tested before could have one or another limitation in relieving microbial stress in agricultural soils. Organic amendments with low C:N (e.g., green manure) can disappear fast in soils because low C:N is often associated with high proportion of easily decomposable C. Organic amendments like compost have some stable C, but still do not have a very long residence time in soil for a persistent effect. Mean residence time of biosolids in soil is estimated at 20 years (Tian et al., 2009) due to the high proportion of stable C. Organic matter in biosolids is mainly derived from microbially dominated-activated sludge, and this causes low C:N ratio of biosolids. Simmons (2003) reported that biosolids have twice as high WHC as soils.

Our objectives were therefore to determine the rate of sequestration of crop residue-C in soil after biosolids amendment, and look into the correlation between crop residue-C sequestration and alleviation of environmental stress to soil microorganisms in agricultural soils. We used a ^{13}C technique, which can separate the C sources, to determine the crop residue-C in soil. We extended the microbial metabolic quotient concept to assess the alleviation of microbial stress and restoration of microbial physiology in agricultural soils by biosolids amendment.

2. Materials and methods

2.1. Site description and treatments

The study was conducted at Fulton County in western Illinois, a typical temperate zone climate with annual mean air temperature of 10.4 °C and annual precipitation of 1013 mm. We conducted the study in 12 agricultural fields in one watershed: four fields as unamended group and eight fields as biosolids-amended group. The soil for the study was predominantly Alfisol (Clarksdale soil series: Fine smectitic, mesic Udollic Endoaqualf) with a small proportion as Entisol (Orthents soil series: Coarse-silty, mixed, superactive, nonacid, mesic Aquic Udifluvent) and Mollisol (Ipava soil series: Fine, smectitic, mesic Aquic Argiudoll) (USDA-NRCS, 1997). Field size averaged 17 ha for unamended group and 19 ha for biosolids-amended group. The initial soils of the two field groups had the same mean soil pH (6.8). Soil texture in both field groups was silt loam (USDA-NRCS, 1997). Prior to the study, mean concentration of SOC was nearly the same in the two field groups: 1.06% for the unamended field group and 1.10% for the biosolids-amended field group. In principle, two groups of fields were managed in the same manner over the study period. Discing as tillage was used for seedbed preparation in all fields. Fields were cropped in rotation with corn (C4 crop), wheat and soybean (C3 crops), and occasionally rye (C3) as a cover crop. Crop residues were retained in the field. Although fields did not have the same crops every year, all fields were predominantly cropped in annual corn/soybean rotation pattern over the study period. Rye was planted in a few years when application of biosolids was not early enough to allow planting of corn/soybean. Rye biomass was incorporated into soil before cropping in subsequent years.

From 1972 to 1984, biosolids-amended fields received lagoon-aged liquid biosolids with mean annual rate of $4.2\,\mathrm{kg\,m^{-2}}$ (dry weight), while unamended fields were treated conventionally with chemical fertilizer at agronomic rate: 300 for N, 100 for P, and 100 for K in $\mathrm{kg\,ha^{-1}\,yr^{-1}}$. The majority of liquid biosolids application (1975–1984) was performed through directing biosolids slurry to between the disc blades by a liquid fertilizer manifold and surface-incorporated by discing. A small portion of liquid biosolids application (1972–1974) was done by spraying biosolids slurry to the fields by a traveling sprinkler and without incorporation. From 1985–2005, both biosolids-amended and unamended fields were treated conventionally with chemical fertilizer at agronomic rate: 300 for N, 100 for P, and 100 for K in $\mathrm{kg\,ha^{-1}\,yr^{-1}}$, and no organic matter applied.

Biosolids were produced in Chicago by anaerobically digesting wastewater treatment sludge for at least 15 days at 35 °C to meet minimum criteria as biosolids. Anaerobically digested sludge was shipped to the site and stored in a holding basin from several months to years before being applied to fields. On a dry matter basis, volatile solids (approximate organic matter), total N and C:N ratio in liquid biosolids averaged 44%, 4.9%, and 5.2, respectively (Tian et al., 2009). The analysis of heavy metals in biosolids used in the fields can be found in Tian et al. (2006). Lagooning at the study site contributed to stabilization of organic matter in biosolids, which mainly occurred during the 0.5 year of storage (Lukicheva et al., 2012).

2.2. Soil sampling and analysis

Soil samples were collected at two depths (0–15 and 15–30 cm) in 2006, and one depth (0–15 cm) in 1972. In sampling, each field was divided into two halves, and about 20–40 cores (depending on field size) were taken to make one composite sample in each half. Sampling cores were distributed randomly to the entire sampling area. Soil bulk density was measured in 2005 using a 7.6 cm (diam.) stainless steel ring.

Soil samples were air-dried and then ground to pass a 2-mm sieve. Soil samples for organic C determination were further ground to <0.063 mm size. Soil pH was measured in a 1:1 water: soil mixture (Thomas, 1996). Concentration of SOC was measured using dry combustion (Nelson and Sommers, 1996).

The ^{13}C isotope was determined by a PDZ Europa ANCA-GSL elemental analyzer interfaced with a PDZ Europa 20–20 isotope-