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Use of laboratory incubation techniques to estimate greenhouse gas footprints from conventional and no-tillage organic agroecosystems

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A B S T R A C T

Organic agroecological systems “produce goods using methods that preserve the environment” but can be a substantial source of greenhouse gases (GHG) if not managed properly. The objective of this experiment was to monitor nitrogen (N) and carbon (C) transformations in soils resulting from N additions, water filled pore space (WFPS) and prior tillage management during a simulated freeze-thaw. Incubated soils were taken from two USDA certified organic five-year small grain rotations with mixed legume cover crops that varied only in tillage, conventional (CT) vs. no-tillage (NT) for 3 yr prior to sampling. Soils incubated for 149 d were left unamended or amended with ^{15}N labelled urea or sugar beet residue and maintained at 40, 60 and 80% WFPS. Non-metric multidimensional scaling (NMS) verified that soils amended with beet vs urea clustered separately in ordination space. A two way PerMANOVA analysis confirmed a significant interaction between WFPS and N amendment ($p = 0.0002$). Prior tillage management, N treatment and WFPS had a significant effect on GHG emission from soils. At 40% WFPS, soil previously in NT amended with beet residues emitted more nitrous oxide (N_2O) and carbon dioxide (CO_2) relative to soil previously in CT. At 60% WFPS, soil previously in CT amended with beet residues emitted greater N_2O and less CO_2 relative to soil previously in NT. Our research indicates that climate, carbon stocks and duration of prior tillage management determined the potential of no-till to reduce GHG emissions during a simulated freeze-thaw. Growers should note that as much as 4.51% of nitrates (NO_3^-) in residues can be lost as N_2O at an average soil temperature of 10 °C.

1. Introduction

The agriculture sector contributes up to 10–12% of the total global anthropogenic greenhouse (GHG) production. Therefore, reductions in GHG emissions have the potential to reduce radiative forcing by 1.15–3.3 Pg C equivalents per yr (Cole et al., 1997). Tillage is one of the major agronomic activities that influences CO_2 emissions and regulates soil organic carbon (SOC) stocks by preventing or reducing soil erosion (Petersen et al., 2011), enhancing accrual and sequestration of C (Gollany et al., 2012; West and Post, 2002), mitigating GHG emissions (Kong et al., 2009) and enhancing biological activity (Helgason et al., 2010). However, augmenting stocks of C and N in soil also affects N_2O emissions. Several NT cropping systems (>90% residue remaining on the soil surface) that are not organic certified have been found to emit less CO_2 but more N_2O relative to moldboard plow systems (Powlson et al., 2012) with less than 10% residues on the soil surface (Shelton et al., 1995). In no-till systems receiving synthetic N fertilizer applications such as urea, gains in soil C (i.e. reduced CO_2 emissions) resulting from NT may be countervailed by greater N_2O production (Stockle et al., 2012; Skinner et al., 2014).

This increase in N_2O emissions under NT may in part be the result of tillage effects on physico-chemical and hydro-thermal conditions in soils that often create anaerobic microsites with

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increased microbial activity. Such conditions lead to greater competition for oxygen (O_2) and stimulate denitrification (Mangalassery et al., 2014). Emissions of N_2O are of concern because the gas is a potent GHG with 298 times the global warming potential (GWP) as CO_2 based on a 100-yr time frame (IPCC, 2007). Although NT systems have the potential to mitigate CO_2, their potential to contribute greater N_2O emissions requires further examination, as does calculation of an overall GHG budget (N_2O and CO_2) for a given tillage system (Beaulieu et al., 2011).

Organic management practices may improve soil health by increasing pools of soil N and C, relative to other agroecosystems. Carbon and N often cycle differently in organic relative to conventional farming systems under NT management as organic certification disallows use of synthetic fertilizers and encourages reliance upon organic amendments that contain more C than N, "mimicking natural ecosystems" that foster coupling of C and N (e.g. bond in the form of crop residues, cover crops, animal amendments) (Cavigelli et al., 2013; Lyon and Hergert, 2014). In addition, most of the N in organic fertilizers must be converted to inorganic N ($NH_4^+ + NO_3^-$-N) before it is available for plant uptake which often leads to tight nutrient cycling minimizing the potential for N_2O loss.

Some studies have reported that implementing NT in organic systems can augment SOC by 9% after 2 years and by 21% after 6 years (Carr et al., 2013; Gadermaier et al., 2011). Previous studies have reported that organic systems provide ecosystem services by reducing nutrient losses (Cavigelli et al., 2013; Drinkwater et al., 1998) and GHGs resulting in lowered GWPs in organic agroecosystems (Cavigelli et al., 2013). Thus, NT organic agroecosystems may foster agricultural sustainability and provide environmental benefits after an initial transition period of some years (Six et al., 2004). Yet, there is still uncertainty with respect to the potential of NT organic management systems to reduce or minimize N_2O emissions. Additions of organic amendments may provide mineralizable C and N, microbial substrates that can contribute to CO_2 and N_2O emissions if not managed properly (Johnson et al., 2012).

Climate determines temperature and rainfall events which in turn partially determine WFPS and N_2O emissions from soil. Water filled pore space (WFPS) is defined as the weight of moist soil minus that of the oven-dried soil divided by the weight of oven-dried soil (Haney and Haney, 2010). Most of the studies conducted to date focus on N_2O emissions during the growing season when prevailing temperatures are well above 10 °C and are not conducted at varying WFPS. Regions of mid to higher-latitude are characterized by long winters during which soil is frozen and or snow-covered for five to six months of the yr. Application of N fertilizer and return of residues to soil prior to soils freezing is a common practice in cooler regions that receive sufficient precipitation to limit using field equipment in spring. In addition many growers assume that at temperatures below freezing microbial respiration is reduce to insignificant levels (Phillips, 2007). However, prior research has shown that denitrifiers and to a lesser extent bacterial and archaeal nitrifiers that produce N_2O are active at or below 10 °C (Avrahami and Conrad, 2003; Braker et al., 2010; Wertz et al., 2013). In fact, 39–90% of annual N_2O emissions can occur at temperatures below 10 °C after freeze-thaw events release C and N substrates suitable for microbial metabolism (van Bochove et al., 2000; Jayasundara et al., 2007; Németh et al., 2014; Teepe et al., 2004; Wagner-Riddle et al., 2008; Yanai et al., 2011).

There is a knowledge gap with respect to the effects of climate, and duration of tillage and cropping system, on the greenhouse gas footprint or GWP, defined as GHG emissions expressed as CO_2 equivalents (Wiedmann and Minx, 2008) of organic agroecosystems. A recent study conducted by Bhowmik et al. (2016) estimated losses of reactive N including N_2O from long-term organic management systems (12 yr USDA certified organic). They reported that addition of mixed compost and pasture management for 10 yr augmented the slow pool of soil C (turnover in yr, ~40–50% of total soil organic C) reducing the potential of N_2O losses likely due to the temporary immobilization of inorganic N. The study above indicated that freeze-thaw cycles of short duration (4 d) release C and N substrates that can lead to N_2O production when soil moisture is $\geq$ 60% of WFPS and temperatures are at or below 10 °C, a temperature range at which microbial communities are still active, allowing for turnover of C and N. Length and type of organic management practices also affect the amount of reactive N that can be immobilized or lost as N_2O (Scialabba and Müller-Lindenlauf, 2010).

Based on our and others previous research, we aimed to determine whether a recently established (~3 yr) NT organic management system receiving minimal organic inputs consisting of residue biomass of small grains and legume cover crops could reduce GHG (N_2O, CO_2) relative to a comparable CT system. We defined CT as a system where <15% of crop residues remain on the soil surface after planting. The NT system limited soil disturbance to a single-disk opener for placement of seeds in the ground. Recently established NT organic agroecosystems may have the potential to emit significant amounts of N_2O relative to the CT system when excess reactive N is made available from plant residues or fertilizer applications under climatic conditions typical of North Dakota (ND) and colder climates across the globe where, soil temperatures are below 10 °C and soil water contents are at or above field capacity, concurrently. The objective of this study was to determine the effects of previous tillage management (CT/NT), WFPS and a simulated winter freeze-thaw (70 d at −5 °C followed by a thaw of 30 d at 10 °C) on reactive forms of N (NH_4^+-N, NO_3^--N, N_2O, NH_3), gene copies of N cycling microorganisms (*nosZ*, *amoA* of AOA and AOB) and GHG emissions (i.e. global warming potential (N_2O, CO_2) of two (CT and NT)) USDA certified organic 5-yr small grain rotations with mixed legume cover crops using laboratory incubation techniques.

2. Materials and methods

2.1. Site description, soil sampling and storage

The Long Term Organic Tillage Study (LOTS) was managed and certified according to the standards of the United States Department of Agriculture (USDA) National Organic Program (NOP). These standards restrict the use of fertilizers such as urea and require growers to demonstrate the use of approved substances and management practices that protect natural resources and conserve biodiversity (https://www.ams.usda.gov/grades-standards/organic-standards (accessed 17 April 2017)). Approved substances are found on the Organic Materials Review Institutes (OMRI) lists and do not include synthetic fertilizers such urea, a fertilizer commonly used in small grains systems. Our field experiment was established in 2010 on Reeder-Farnuf loams (fine-loamy, mixed, superactive, frigid, typic Argiustolls) at the North Dakota State University Dickinson Research and Extension Center, USA (46°53′ N, 102°49′ W; elevation 760 m). The plots were arranged in a randomized complete block design (RCBD) containing 4 field replicates per treatment (30 m × 9 m). The CT plots were cultivated with a tandem disc to a soil depth of 10 cm in late summer (August to October of each year) and again the following spring (March-early April) prior to seeding in June. No soil disturbance except by a low-disturbance planter at seeding occurred in NT plots. Detailed information with respect to cover crop management, field activities and soil sampling can be found in Table S1.

Soil samples (0–30 cm) were collected from CT and NT plots in