Applied Soil Ecology 119 (2017) 294–306

Contents lists available at ScienceDirect

Applied Soil Ecology

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

Short-term dynamics of greenhouse gas emissions and cultivable bacterial populations in response to induced and natural disturbances in organically and conventionally managed soils

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ARTICLE INFO

Keywords:
Carbon dioxide
Methane
Nitrous oxide
Harmonics analysis
Oscillations
Soil health

ABSTRACT

Organically managed (ORG) soil is often considered healthier than conventionally managed (CONV) soil, with greater resistance and resilience to disturbances, as evidenced by reduced oscillations in bacterial populations and activities. Greenhouse gas (GHG) fluxes are mediated by bacterial processes, but variations in GHG emissions have not been related to bacterial oscillations in soil. Two environmentally controlled and two field experiments were set up to compare oscillations in bacterial colony-forming-units (CFUs) and GHG (nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4)) fluxes after disturbances in ORG and CONV soils. Soil amendment with grass-clover (GC) or cattle manure (CM) resulted in peaks in N_2O and CO_2 emission, followed by CFUs. CH_4 temporarily increased in GC- but decreased in CM-amended soil. Ratios of CFUs and GHGs in amended over nonamended soils oscillated during three weeks, mostly with lower frequencies and amplitudes in ORG soils. Fluctuations were more irregular in field soils, but significant oscillations were detected after irrigation or intensive rain in summer. Cross correlations between variables showed several significant sequences of microbial processes under controlled conditions but not in the field. Average GHG emissions were higher from ORG soil than CONV soil under these conditions, indicating that these have to be taken into consideration when estimating soil health.

1. Introduction

Emission of the greenhouse gases (GHG) carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) has demanded a lot of attention in recent decades, in connection with observed and predicted global climate change. All three gases contribute to global warming, but the potential effects of N_2O and CH_4 are considered to be 300 and 36 times as high as that of CO_2 over a period of 100 years (https://www.epa.gov/ghgemissions/). Agriculture is responsible for 9% of GHG emissions in the USA and 24% worldwide, mostly as a result of soil and plant nutrition management (https://www.epa.gov/ghgemissions/). The emissions vary with the type of farming system and production practices (Knudsen et al., 2014). Many authors found that emissions per unit area were lower at organic (ORG) than at conventional (CONV) arable and horticultural farms (Benoit et al., 2015; Foteinis and Chatzisymeon, 2016; Knudsen et al., 2014; Meier et al., 2015; Skinner et al., 2014; Trimpler et al., 2016; Tuomisto et al., 2012; Zhang et al., 2016), while others observed the reverse (Bos et al., 2014; McGee, 2015; Nagano et al., 2012). GHG emissions per unit product are generally considered higher for organic products (Bos et al., 2014; Foteinis and Chatzisymeon, 2016; Knudsen et al., 2014; Meier et al., 2015; Skinner et al., 2014; Tuomisto et al., 2012), but not per unit protein (Benoit et al., 2015).

These two farming systems differ significantly in soil management, resulting in enhanced soil carbon (Hiddink et al., 2005; van Diepeningen et al., 2006), higher microbial densities (van Bruggen

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http://dx.doi.org/10.1016/j.apsoil.2017.07.011
Received 18 April 2017; Received in revised form 5 July 2017; Accepted 7 July 2017
Available online 16 August 2017

Table 1
Characteristics of soils collected from organically managed fields at the Droevendaal experimental farm and surrounding conventionally managed fields of Wageningen University, used for pot experiments in 2007 and field experiments in 2006.

Soil characteristics	Spring, 2007		Summer, 2007	
	Organic soil	Conventional soil	Organic soil	Conventional soil
Sand content (%)	92.78 ± 1.31[a]	93.24 ± 1.00	89.30 ± 0.06	91.17 ± 0.54
Silt content (%)	4.77 ± 0.19	4.51 ± 0.23	7.00 ± 0.62	6.13 ± 0.17
Clay content (%)	2.45 ± 0.27	2.25 ± 0.18	3.70 ± 0.09	2.70 ± 0.20
pH ($CaCl_2$)	5.59 ± 0.03	5.55 ± 0.04	5.37 ± 0.01	5.51 ± 0.05
Organic matter content (%)	2.85 ± 0.01	2.25 ± 0.02	3.03 ± 0.01	1.91 ± 0.01
Total N content (mg kg^{-1})	1039 ± 26	806 ± 30	1115 ± 41	662 ± 19
Soil characteristics	**Spring, 2006**		**Summer, 2006**	
	Organic soil	Conventional soil	Organic soil	Conventional soil
Sand content (%)	75.40 ± 1.06	77.50 ± 1.21	78.20 ± 1.53	80.90 ± 2.79
Silt content (%)	17.43 ± 0.39	14.56 ± 0.70	15.59 ± 0.20	12.95 ± 0.32
Clay content (%)	7.17 ± 0.12	7.94 ± 0.45	6.21 ± 0.33	6.15 ± 0.20
pH ($CaCl_2$)	4.92 ± 0.02	6.49 ± 0.03	4.91 ± 0.05	5.15 ± 0.02
Organic matter content (%)	2.64 ± 0.02	2.40 ± 0.02	2.65 ± 0.03	2.21 ± 0.02
Total N content (mg kg^{-1})	534 ± 17	484 ± 21	1481 ± 57	1070 ± 29

[a] The values are means ± standard deviations (n = 3).

et al., 2006) and diversity (Girvan et al., 2004; van Diepeningen et al., 2006), and consequently improved soil health in ORG compared to CONV systems (Hiddink et al., 2005; Liu et al., 2007; Melero et al., 2006; Senechkin et al., 2014; van Bruggen and Finckh, 2016; van Bruggen et al., 2006, 2016; van Bruggen and Semenov, 1999, 2000, 2015; van Diepeningen et al., 2006). Healthy soils are characterized by greater resilience and resistance of microbial communities to disturbances, evidenced by dampened oscillations in relative microbial populations, and enhanced internal nutrient cycling (van Bruggen and Semenov, 2000; van Bruggen et al., 2006, 2015b).

It has been well documented that cultivable and total bacteria respond quickly to the input of organic nutrients followed by wave-like oscillations of soil bacterial populations over time (Zelenev et al., 2005, 2006) and in space (Semenov et al., 1999; van Bruggen et al., 2000; Zelenev et al., 2000). These oscillations had periods of about 3–5 days, and were attributed to growth and death cycles in response to carbon availability, but could also be related to alternations in micro-scale aerobic and anaerobic conditions (van Bruggen et al., 2006).

Soil microbes play an important role in nutrient cycling and organic matter decomposition, which are closely linked with emission and consumption of important greenhouse gases including CO_2, N_2O and CH_4 (Oertel et al., 2016). Carbon dioxide, nitrous oxide and ammonium are released as a result of the decomposition of organic compounds by microorganisms (Ball et al., 1999; Maljanen et al., 2002). Ammonium is nitrified leading to some loss of nitrous oxide during nitrification (Maljanen et al., 2002), and nitrate can be denitrified under anaerobic conditions, resulting in additional emission of nitrous oxide and nitrogen gas (Ball et al., 1999). Methane is produced by methanogenic bacteria and oxidized by methanotrophic bacteria in soil (Le Mer and Roger, 2001). Under anaerobic conditions, methanogenesis exceeds methanotrophy resulting in methane emission (Dutaur and Verchot, 2007; Oertel et al., 2016).

The alternations in carbon and oxygen availability and microbial populations is likely accompanied by oscillations in GHG emissions (Semenov et al., 2013; Zelenev et al., 2005, 2006). Diurnal oscillations in CO_2, N_2O, and CH_4 emissions from ORG soils were observed that were related to diel temperature oscillations (Maljanen et al., 2002; Oorts et al., 2007; Savage et al., 2014; Schütz et al., 1990). After major rainfall events, the peaks in CO_2 and N_2O emissions increased and the periods seemed to be longer compared to fluctuations in the absence of rainfall (Oorts et al., 2007; Savage et al., 2014; not noted by Maljanen et al., 2002). Priemé and Christensen (2001) described initial peaks followed by fluctuations in N_2O and CO_2 emissions from ORG soil cores after drying and wetting or freezing and thawing. The periods seemed to be 2–3 days, although oscillations were not analysed. CH_4 emissions were low and without fluctuations (Priemé and Christensen, 2001). Similarly, CO_2 emission per unit biomass peaked one day after tillage and fluctuated with periods of 2–3 days thereafter (Calderón et al., 2000). The extent of the fluctuations in CO_2 emission depended on the tillage system (Omonode et al., 2007; Oorts et al., 2007; Teixeira et al., 2013), although the period remained 3–4 days (Teixeira et al., 2013). Oscillations after a disturbance can best be characterized by harmonics analysis when daily measurements are made (Semenov et al., 2013; Zelenev et al., 2005). Weekly measurements can also show peaks in CO_2 emissions after tillage (Li et al., 2012; Omonode et al., 2007; Ruan and Robertson, 2013), but not necessarily the pursuant oscillations.

Considering that oscillations in microbial populations after a disturbance relative to those without disturbance are expected to be dampened in a relatively healthy soil like an ORG versus a CONV soil (van Bruggen and Semenov, 2000, 2015; van Bruggen et al., 2015a, 2015b), one might expect that oscillations in GHG emissions would be reduced as well. However, this has not been investigated extensively (Semenov et al., 2013). Therefore, our research was aimed at understanding the short-term dynamics of GHG emissions in relation to the daily changes of bacterial populations after induced or natural disturbances in ORG versus CONV soils. Specific objectives were: (1) to investigate how GHG emissions respond to controlled or natural soil disturbances in the short-term; (2) to determine the relations between GHG emissions, bacterial populations, and soil chemical characteristics, and (3) to compare the daily changes of GHG emissions, soil microbial populations, and chemical properties between two differently managed soils.

2. Materials and methods

2.1. Controlled experiments

Two pot experiments were carried out at Wageningen University in spring (23 May–12 June) and summer (2–22 August) of 2007, and each with two pairs of sandy soils (ORG and CONV) as published previously (Table 1). Soil samples were collected from the organic experimental farm the Droevendaal and adjacent conventional experimental fields of Wageningen University. The Droevendaal farm was converted to organic in 2002 and certified in 2004. Two series of PVC pots (diameter