Soil organic matter and texture affect responses to dry/wet cycles: Effects on carbon dioxide and nitrous oxide emissions

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ABSTRACT

Soil organic matter (SOM) content and texture are important factors affecting carbon (C) and nitrogen (N) mineralisation under constant soil moisture but their effects on organic matter mineralisation and associated biogenic gas (carbon dioxide (CO_2) and nitrous oxide (N_2O)) production during dry/wet cycles is poorly understood. A laboratory incubation study was conducted to quantify CO_2 and N_2O production during sequential dry/wet cycles and under constant soil moisture conditions along a gradient of SOM contents in two soil types representing different texture classes (silt loam vs. clay loam). Three soil moisture treatments were established: wet (WW; field capacity), moderately dry (MD; 120% of soil moisture content (SMC) at wilting point (WP)) and very dry (VD; 80% of SMC at WP). To each of the two 'dry' treatments two different dry/wet treatments were applied where the soils were either maintained continuously dry (MD & VD) or subjected to three sequential 20-day long dry/wet cycles (MDW & VDW) during the treatment phase of the experiment. At field capacity soil moisture content, the rate of C mineralisation increased with increases in SOC content and the increase per unit of C was twice as high in silt loam (0.30 mg CO_2-C g^{-1} SOC d^{-1}) as in clay loam (0.13 mg CO_2-C g^{-1} SOC d^{-1}) soils. N_2O-N emissions also increased with increasing in SOC content. However, in contrast to C mineralisation, the effect was four-fold greater for clay loam (1.38 μg N_2O-N g^{-1} SOC d^{-1}) than silt loam (0.32 μg N_2O-N g^{-1} SOC d^{-1}) soils. Following rewetting, the VDW and MDW soils produced a short-term C mineralisation flush that was, on average, 30% and 15% greater, respectively, than in WW soils. However, the flush of C mineralisation was not sufficient to compensate for the reduction in mineralisation during the drying phase of each cycle, resulting in a lower total C mineralisation from MDW and VDW soils, on average, compared with WW soils over the three sequential dry/wet cycles. The C mineralisation flush also remained a relatively constant proportion of the total C mineralised from both silt loam (23%) and clay loam soils (22%), irrespective of their SOC content. In contrast, the short-term flush of N_2O that followed rewetting of dry soil accounted for 62% and 68% of the total N_2O emissions from silt loam and clay loam soils, respectively. On average, the total N_2O emissions from dry/wet treatments imposed on silt loam and clay loam soils were 33% and 270% greater, respectively, than from the WW treatments, though the effect varied greatly and depended on SOC content. Overall, N_2O emissions were highest where we had a combination of fine texture, an adequate supply of available C (i.e. high SOM content), and a water-filled pore space (WFPS) > 0.60 cm cm^{-3} at field capacity. Prediction of C mineralisation over dry/wet cycles using mineralisation data from soils at constant moisture content is possible, but knowledge of the stress history for the soil would be required to improve accuracy. The prediction of N_2O-N emissions during dry/wet cycles using emission data from soils at constant moisture was very inaccurate, due to the inherent spatial variability of N_2O emissions.

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1. Introduction

Soils are subject to temporal variations in temperature and moisture that can cause changes to soil physical and chemical properties. Soil dry/wet cycles result from natural variations in soil moisture driven by environmental and biophysical processes such as precipitation, evapo-transpiration, and drainage. Management factors such as irrigation, tillage and land cover (i.e. vegetation type) can moderate or accentuate the amplitude of these natural cycles (Oliveira et al., 2005). Understanding how dry/wet cycles affect carbon (C) and nitrogen (N) transformations is important in

predicting soil organic matter (SOM) dynamics, determining the effects of climate change on greenhouse gas emissions (principally carbon dioxide (CO_2) and nitrous oxide (N_2O)) from soils and estimating the supply of plant available nutrients, especially nitrogen (Wu and Brookes, 2005).

Wetting dry soil typically results in a flush of C and N mineralisation (Birch, 1958; Kieft et al., 1987; Orchard and Cook, 1983; Soulides and Allison, 1961), with elevated rates of CO_2 production persisting for up to 2 weeks following wetting (Beare et al., 2009; Fierer and Schimel, 2002; Franzluebbers et al., 2000). However, the extent of the mineralisation response to wetting of dry soils varies greatly between studies (Beare et al., 2009; Butterly et al., 2010; Fierer and Schimel, 2002; Mikha et al., 2005). It is generally accepted that C and N mineralisation tends to increase with increases in SOM content in soils held at constant soil moisture (Butterly et al., 2010; Hassink, 1995; Wang et al., 2003). Although the effects of continuously wet conditions are well described, relatively little is known of how SOM content affects the mineralisation response to dry/wet cycles and the associated production of biogenic greenhouse gases (e.g. CO_2 and N_2O). SOM content may be an important factor in this response owing to its potential role in substrate supply and effects on soil moisture release characteristics. Those studies that have investigated relationships between SOM content and the mineralisation responses to wetting dry soil have tended to focus on the short-term (3–4 days) flush of CO_2 that follows wetting (Butterly et al., 2010; Franzluebbers et al., 2000). To our knowledge, no previous studies have attempted to explicitly quantify the contributions of SOM content to CO_2 and N_2O emissions that occur over sequential dry/wet cycles.

Soil texture may also be an important factor affecting the mineralisation response to dry/wet cycles due to its role in the stabilisation of SOM (Gregorich et al., 1991; Hassink, 1992; McInerney and Bolger, 2000; Wang et al., 2003) and effects on pore size distribution that also affect the moisture release characteristics of soils (Thomsen et al., 1999). As with SOM content, most of the previous research has focussed on the effects of texture (especially clay content) on the short-term flush of CO_2 that follows the rewetting of dry soil (Cable et al., 2008; Sugihara et al., 2010), but few studies have described their effects on CO_2 and N_2O emissions over sequential dry/wet cycles.

As discussed above, the focus of much of the previous research has tended to be on short-term (days) C mineralisation following soil rewetting, less is known about the longer term implications of repeated dry/wet cycles on C and N dynamics (Borken et al., 2003; Van Gestel et al., 1991), including CO_2 and N_2O emissions. Previous research has shown that moisture stress history can affect the size of the CO_2 flush following rewetting of dry soil, which tends to decline with repeated dry/wet cycles (Butterly et al., 2009; Fierer and Schimel, 2002; Mikha et al., 2005; Xiang et al., 2008). If, after the short-term flush of CO_2 and N_2O, soil processes return to their pre-stress state then it is relatively unimportant to include dry/wet dynamics into soil process models due to their relatively short duration and limited magnitude in annual C and N transformations. If, however, a dry/wet event changes the equilibrium of soil C and N transformations (relative to the unstressed soil), or if the recovery to pre-stress basal rates is slow, then incorporating dry/wet events into C and N models becomes more important, and probably more difficult. Furthermore, if the frequency of dry/wet events controls soil processes, then the variability in rainfall over a given period, not just average rainfall, would need to be incorporated into models of soil C and N dynamics (Fierer and Schimel, 2002). A key question in this discussion is: can we adequately predict the emissions of CO_2 and N_2O that occurs over repeated wet/dry cycles from emission data obtained from soils held at constant water contents?

The objectives of this study were to: (1) determine how soil texture and organic matter content affect the production of CO_2 and N_2O from soils at constant moisture contents and over a series of dry/wet cycles of different amplitudes, and (2) determine whether the CO_2 and N_2O produced under different, but constant moisture conditions can be used to satisfactorily predict the total emissions that occur during repeated dry/wet cycles.

2. Materials and methods

2.1. Soils

Two soil types commonly found on the Canterbury Plains of New Zealand were selected for study: Lismore silt loam (NZ classification: Typic orthic brown soil, FAO classification: Dystric Camibsol), and Temuka clay loam (NZ classification: Melanic orthic gley soil, FAO classification: Mollic Gleysol). Plant & Food Research's Soil and Land Management database was used to identify sites on these soil types with differing soil organic matter (SOM) contents (measured as soil organic C (SOC)). For each soil type a total of six sites were selected for sampling to establish an SOM gradient. Soil organic C concentrations ranged from 22 to 49 mg C g^{-1} in the Lismore silt loam soil, and 20–41 mg C g^{-1} in the Temuka clay loam soil (Table 1). The sampling sites were all located on the flat-lands of the Canterbury Plains and all of the sites for each soil type were within a 20 km radius. The TEM 1 soil was later excluded from the study as it was found to be not representative of the soil type.

2.2. Sample collection and preparation

Soil samples were collected from the A horizon at six locations within each site, taking care to avoid wheel tracks, stock camps, fence lines and other such artefacts. At each location a soil sample (15 × 15 cm square, 7.5 cm in depth) was collected with a spade and placed in a crush resistant container for transport to the laboratory.

In the laboratory, samples were passed through a 4 mm sieve to remove coarse plant residues (including roots) and stones. The samples from the six locations were then combined and mixed to form a single homogeneous sample for each site. This composite soil sample was then air-dried at 25 °C and stored at room temperature until the beginning of the experiment.

Basic physical and chemical properties of the individual soils are shown in Table 1. The percentage of sand, silt, and clay was determined using the pipette method (Gee and Or, 2002), with sand defined as particles >53 μm, silt between 2 and 53 μm and clay as <2 μm. Total carbon (C) and nitrogen (N) content was measured on a LECO CNS-2000 analyser. The soil moisture content (SMC) of the soils at field capacity (FC, −0.01 MPa) and wilting point

Table 1
Some chemical and physical properties of the soils used.

Soil ID	Current land use	C	N	C:N	Sand	Silt	Clay	pH	Min N
		Mg g^{-1}		Ratio	%				(μg g^{-1})
LIS 1	Pasture	49	4.4	11.1	25	59	16	5.4	136
LIS 2	Pasture	47	4.1	11.5	21	63	16	5.1	167
LIS 3	Pasture	44	4.0	11.0	27	56	17	5.9	77
LIS 4	Cropping	29	2.6	11.1	22	62	16	5.5	34
LIS 5	Cropping	26	2.4	10.8	21	64	15	5.7	42
LIS 6	Cropping	22	2.2	10.0	22	60	18	5.4	45
TEM 2	Cropping	41	3.8	10.8	11	60	29	5.1	28
TEM 3	Cropping	37	3.1	11.9	9	69	22	5.1	14
TEM 4	Cropping	31	2.7	11.5	21	52	27	6.1	52
TEM 5	Cropping	32	2.8	11.4	20	55	25	5.5	40
TEM 6	Cropping	20	1.9	10.5	23	58	19	5.3	37

LIS = Lismore silt loam soil; TEM = Temuka clay loam soil.