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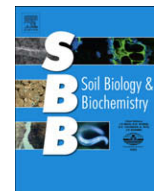

Compaction effects on CO_2 and N_2O production during drying and rewetting of soil

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ABSTRACT

The effects of compaction on soil porosity and soil water relations are likely to influence substrate availability and microbial activity under fluctuating soil moisture conditions. We conducted a short laboratory incubation to investigate the effects of soil compaction on substrate availability and biogenic gas (CO_2 and N_2O) production during the drying and rewetting of a fine-loamy soil. Prior to initiating the drying and wetting treatments, CO_2 production (−10 kPa soil water content) from uncompacted soil was 2.3 times that of compacted soil and corresponded with higher concentrations of microbial biomass C (MBC) and dissolved organic C (DOC). In contrast, N_2O production was 67 times higher in compacted than uncompacted soil at field capacity. Soil aeration rather than substrate availability (e.g. NO_3^- and DOC) appeared to be the most important factor affecting N_2O production during this phase. The drying of compacted soil resulted in an initial increase in CO_2 production and a nearly two-fold higher average rate of C mineralization at maximum dryness (owing to a higher water-filled pore space [WFPS]) compared to uncompacted soil. During the drying phase, N_2O production was markedly reduced (by 93–96%) in both soils, though total N_2O production remained slightly higher in compacted than uncompacted soil. The increase in CO_2 production during the first 24 h following rewetting of dry soil was about 2.5 times higher in uncompacted soil and corresponded with a much greater release of DOC than in compacted soil. MBC appeared to be the source of the DOC released from uncompacted soil but not from compacted soil. The production of N_2O during the first 24 h following rewetting of dry soil was nearly 20 times higher in compacted than uncompacted soil. Our results suggest that N_2O production from compacted soil was primarily the result of denitrification, which was limited by substrates (especially NO_3^-) made available during drying and rewetting and occurred rapidly after the onset of anoxic conditions during the rewetting phase. In contrast, N_2O production from uncompacted soil appeared to be primarily the product of nitrification that was largely associated with an accumulation of NO_3^- following rewetting of dry soil. Irrespective of compaction, the response to drying and rewetting was greater for N_2O production than for CO_2 production.

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1. Introduction

Soil biological activity is primarily governed by the size and composition of the soil microbial community, the availability of substrates and nutrients, and the below-ground environmental conditions (Swift et al., 1979; Beare et al., 1995). Any change in soil structure which alters these conditions is therefore likely to affect the biological processes that lead to C and N transformations and the production of biogenic gases (e.g. CO_2, N_2O). Soil compaction is a common form of soil structure degradation in eastern Canada, particularly in eastern Ontario where the climate is humid and the soils generally have a heavy texture and are poorly drained (Lapin et al., 2004). Compaction of soil reduces total soil porosity and shifts the pore size distribution toward smaller pores. These changes in porosity can reduce the mineralization of C and N (Hassink, 1992; Breland and Hansen, 1996) by physically protecting organic matter from microbial attack (van Veen and Kuikman, 1990) and rendering microorganisms less accessible to predation by nematodes and protozoa (Elliott and Coleman, 1988; Hassink et al., 1993). However, other studies have reported no effect (De Neve and Hofman, 2000) or increased mineralization of N in compacted soil (Rasiah and Kay, 1998). Several previous studies have shown that soil denitrification and the resulting N_2O production are strongly affected by the soil physical environment including the extent of water-filled pores and

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associated effects on air permeability and gas diffusivity (Groffman and Tiedje, 1988; Davidson, 1992; Ball et al., 2008) that may increase the frequency of anaerobic microsites in soil. These factors have been used to explain higher N_2O emissions from poorly aerated no-tillage soils (Rochette, 2008) and from soils compacted by livestock treading (Thomas et al., 2004) and wheel traffic (Ruser et al., 2006).

Surface soils in most terrestrial ecosystems undergo periods of drying followed by rapid rewetting during precipitation or irrigation events. Increased rates of C and N mineralization can occur for up to several days following the wetting of dry soil (Birch, 1958; Bloem et al., 1992; van Gestel et al., 1993; Franzluebbers et al., 2000; Fierer and Schimel, 2002). The flush of CO_2 that follows rewetting has been attributed to the mineralization of organic matter exposed after the physical breakdown of soil aggregates (Beare et al., 1994; Appel, 1998; Denef et al., 2001) and/or release and subsequent mineralization of microbial C (Halverson et al., 2000; Fierer and Schimel, 2003; Mikha et al., 2005). The release of microbial C results from cell lysis and/or the release of intercellular solutes (Kieft et al., 1987; Halverson et al., 2000) when microbes undergo osmotic shock following a rapid increase in soil water potential during rewetting (Harris, 1981). While wet/dry cycles have also been shown to increase dissolved organic C (DOC) concentrations (Lundquist et al., 1999), DOC is not generally considered to be an important source of the carbon mineralized following rewetting of dry soil (Fierer and Schimel, 2003).

Although the effects of drying and rewetting on C mineralization and microbial biomass have been well studied, we know of only one study that has examined how differences in soil physical conditions (e.g. compaction) affect substrate availability and the production of biogenic gases during drying and rewetting of soil. Ruser et al. (2006) reported that CO_2 production from a fine-loamy soil fertilized with nitrate was not strongly effected by soil moisture except for heavily compacted soil at >90% water-filled porosity where respiration was markedly reduced. The increased production of N_2O from compacted soil was primarily the result of increased water-filled pore space (WFPS). The highest rates of CO_2 and N_2O production from all compaction treatments were measured following rewetting of dry soil.

The effects of soil compaction on soil porosity and soil water relations are likely to influence the amount and source of mineralizable C and N and the production of CO_2 and N_2O during wetting and drying of soils. Our objective in this study was to determine how compaction affects the supply of microbial substrates and the production CO_2 and N_2O during the drying and rewetting of a fine-loamy soil.

2. Materials and methods

2.1. Trial site and soil

Soil samples were collected from a field compaction trial located on the Central Experimental Farm of the Eastern Cereal and Oil Seed Research Centre, Ottawa, ON, Canada (45°22′N, 75°43′W). The compaction trial was established in 2002 to investigate the effects of tractor wheel traffic and fertilizer rates (0, 75, 150 kg N ha^{-1} applied in the spring) on soil physical properties, N availability and greenhouse gas emissions over several years. The compaction treatments were established through multiple passes with a tractor during wet conditions after fertilization but prior to sowing a maize (*Zea mays* L., Pioneer variety 38 W36) crop in each of two consecutive years (2002–2003). The preceding crop was red clover (*Trifolium pratense* L.). The soil at this site is a Brandon loam (fine loamy, mixed, mesic Typic Endoaquoll; an Orthic Humic Gleysol, in the Canadian classification). The top 15 cm of soil was composed of 33% clay, 31% silt and 36% sand, and contained 2.45% organic C and 0.19% N with a pH of 7.4 (0.01 M $CaCl_2$).

2.2. Sample collection and preparation

Twenty-five intact cores were collected in September 2004 (after crop senescence) from each of the compacted and uncompacted (control) treatments for use in a laboratory incubation experiment. All samples were taken from the 75 kg N ha^{-1} fertilizer treatment. To collect the intact soil cores, the top 10 mm of soil at each sample location was first removed with a hand trowel to create a relatively flat surface. This surface was then picked with the pointed end of a knife to remove any smeared surface and to expose the pore structure. Cylindrical Büchner funnel tops (58 mm inner diam.; 30 mm deep; Fisher Scientific) were placed upside down on the prepared soil surface, a solid PVC cylinder fitted to the base and pressed to a depth of 30 mm to collect an intact soil core. A wood block and mallet were required to position the cores to the full 30 mm depth in the compacted soil. Care was taken to not exceed this depth in either treatment in order to avoid artificially compacting the soil contained in the funnel.

Each core was carefully dug from the soil so as to leave a convex surface on the face of the Büchner funnel core. The cores were labelled, wrapped in plastic bags and placed on a foam pad for transport to the laboratory. There they were prepared for the incubation experiments by carefully shaving the soil from the top of the cores with a sharp knife to a depth of ≈7 mm from the top edge of each core. The actual depth to the soil surface was measured at 10 positions on the surface of each core and the results used to calculate soil bulk density. The soil water content (oven dried, 105 °C) used in the bulk density calculations was measured (5 replicates per treatment) on composite soil samples collected from each treatment at the same time as the intact cores. The intact cores were stored field moist at 5 °C prior to their use in the incubation experiments. The water-filled pore space (WFPS) was calculated as:

$$\mathrm{WFPS}(\mathrm{cm^3\ cm^{-3}}) = \text{core water volume}(\mathrm{cm^3}) / \text{total core porosity}(\mathrm{cm^3}),$$

where total porosity was calculated from the soil core bulk density, assuming a particle density of 2.65 g cm^{-3}.

A further set of five soil cores (100 mm diam., 0–50 mm) were collected from each compaction treatment for use in determining their water content at −10 kPa. For this determination the cores were first wetted to saturation on a tension table and the water column gradually lowered to 100 cm. After allowing the cores to equilibrate at this tension for 10 days, the cores were removed and their gravimetric water content determined by oven drying (105 °C).

2.3. Soil incubations

The intact cores were incubated at room temperature (22 °C) for a total of 18 days inside 1.5 l canning jars fitted with lids containing rubber gas sampling septa. The incubation experiment was conducted in three phases: a pre-incubation phase (5 days), a drying phase (3 days) and a rewetting phase (10 days).

2.3.1. Pre-incubation phase

At the start of the pre-incubation phase, all 25 intact cores from each treatment were adjusted gravimetrically to their water content at field capacity (equivalent to −10 kPa). This adjustment was relatively small, as the initial water content of the compacted and uncompacted cores was at or very close to field capacity at the time of collection. The intact cores were then sealed inside the

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