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Incorporating organic matter alters soil greenhouse gas emissions and increases grain yield in a semi-arid climate

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ABSTRACT

Increasing soil organic matter (OM) is promoted as a strategy for improving the resilience of coarse-textured cropping soils in semi-arid climates. While increasing soil OM can benefit crop productivity, it can also enhance nitrous oxide (N_2O) emissions in temperate climates. Our objective was to investigate if increasing soil OM affected soil greenhouse gas (GHG) fluxes and grain production in a semi-arid region in south-western Australia. We firstly measured N_2O and methane (CH_4) fluxes from a free-draining sandy soil with contrasting soil OM content for 2.5 years using automated soil chambers. The randomized block design included two OM additions (no OM, plus OM) by two nitrogen (N) fertilizer rates (0, 0N; 100 kg N ha^{-1} yr^{-1}, +N) by three replicate plots. Organic matter (chaff) had been applied to the plus OM treatments every three years since 2003, with 80 t OM ha^{-1} applied in total. Secondly, we investigated the interaction between soil OM content and N fertilizer addition on grain yield for two growing seasons. The randomized split-plot design included two OM treatments by five N fertilizer rates (0, 25, 50, 75 and 100 kg N ha^{-1}), by three replicates. Increasing soil OM increased grain yields and soil mineral N, but also enhanced soil N_2O emissions. Nitrous oxide emissions were low by international standards (<0.12% of the N fertilizer applied), with total N_2O emissions after two years ranked: plus OM (+N; 427 g N_2O-N ha^{-1}) > plus OM (0N; 194 g N_2O-N ha^{-1}) > no OM (+N; 41 g N_2O-N ha^{-1}) = no OM (0N; 14 g N_2O-N ha^{-1}). Increasing soil OM also decreased CH_4 uptake by 30%. Management practices that increase soil OM in sandy-textured rainfed, cropping soils in semi-arid regions should be encouraged as they can improve grain yield without substantial increases in soil N_2O or CH_4 emissions.

1. Introduction

Increasing soil organic matter (OM) has multiple benefits for agricultural soils in semi-arid climates. It has the potential to improve the resilience of coarse-textured cropping soils to drying climates by increasing water infiltration, water-holding capacity and nutrient retention capacity (Hoyle et al., 2011), in turn benefiting grain yield (Chen et al., 2013; Lehtinen et al., 2014; Liu et al., 2014). Increasing soil OM is also a strategy for sequestering carbon dioxide (CO_2) to mitigate anthropogenic greenhouse gas (GHG) emissions. Agricultural management practices such as the conversion from conventional to no-till or reduced tillage, residue retention and addition, and crop rotations all have the potential to increase soil OM (Smith et al., 2000; Luo et al., 2010; Liu et al., 2014). It is estimated that widespread adoption of these recommended practices would increase soil OM in croplands by 0.4–0.8 Pg C per year globally (Lal, 2004). However, while these agricultural practices may benefit soil carbon (C) sequestration, their contribution to mitigating global climate warming may be offset by GHG emissions (Six et al., 2004; Liu et al., 2014).

Increasing soil OM can enhance nitrous oxide (N_2O) emissions, a potent GHG, by increasing the availability of nitrogen (N) and C to soil microorganisms (Stehfest and Bouwman, 2006). Crop residues are subject to N mineralization, and in turn nitrification and denitrification; microbial processes that lead to N_2O production (Butterbach-Bahl et al., 2013). For example, nitrifying microbes convert soil ammonium (NH_4^+) to nitrate (NO_3^-) under aerobic conditions, which may result in N_2O as a by-product of the N transformation. Likewise, anaerobic denitrifiers sequentially reduce N oxides (e.g. NO_3^-) to nitric oxide, N_2O and finally N_2; with N_2O emissions resulting from an incomplete conversion. Soil methane (CH_4) uptake could also be inhibited should increasing

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soil OM result in increased soil N concentrations (Le Mer and Roger, 2001). While soil C sequestration would be expected to reach a maximum threshold (Ingram and Fernandes, 2001), the effects on soil GHGs emissions could continue if soil OM concentrations were maintained. Understanding the interaction between increasing soil OM and GHG emissions is critical when assessing the effectiveness of land management practices to abate GHG emissions from the agricultural land sector. However, such studies do not appear to have been conducted in rainfed cropping systems in semi-arid regions.

Increasing soil OM can also increase crop production and has the potential to lower crop fertilizer requirements. International meta-analyses have demonstrated the incorporation of straw and crop residues into soil benefits crop yield with time by improving plant nutrient availability [N, phosphorous (P) and potassium (K)] and soil physical conditions (Chen et al., 2013; Lehtinen et al., 2014; Liu et al., 2014). Realising the benefits of increased soil OM on plant nutrient availability would benefit farmers in semi-arid regions, as fertilizer applications can be a significant expense for grain production. Furthermore, better matching N fertilizer inputs to crop demand not only increases farming profitability, but also decreases the risk of soil N_2O emissions (Millar et al., 2010). Understanding how increasing soil OM influences N fertilizer requirements in semi-arid regions would optimise N fertilizer use, and potentially minimise N_2O emissions, from grain production.

Approximately 17 million ha of semi-arid land in south-western Australia is cropped to cereals, oilseeds and grain legumes on an annual basis, contributing 40% to Australia's annual grain production [Australian Bureau of Agricultural and Resource Economics (ABARE); http://www.agriculture.gov.au/abares; accessed: 16 March 2016]. Mineral N fertilizer is used throughout the region to a varying extent (0–100 kg N ha^{-1} yr^{-1}), with many soils reaching less than 60% of their modelled attainable C storage capacity under a range of cropping systems (Hoyle et al., 2013). The effect of increasing soil OM on GHG emissions and N fertilizer requirements is poorly understood for rainfed cropping soils in semi-arid regions. Instead our knowledge is mainly derived from studies in temperate climates (Stehfest and Bouwman, 2006; Chen et al., 2013; Lehtinen et al., 2014; Liu et al., 2014). Consequently the overall objective of this study was to investigate if increasing soil OM affects soil GHG emissions and grain production in a semi-arid region in south-western Australia. Firstly, we investigated if increasing soil OM altered soil GHG emissions by continuously measuring sub-daily N_2O and CH_4 fluxes from a cropping soil for 2.5 years. Based on the above observations in temperate climates we hypothesized that increasing soil OM would increase soil N_2O emissions and decrease soil CH_4 oxidation. Secondly, we investigated if increasing soil OM altered grain yield and N fertilizer requirements. We hypothesized that increasing soil OM would increase grain yield and lower the amount of N fertilizer required for crop production.

2. Material and methods

2.1. Soil and site

We investigated the effect of increasing soil OM on GHG emissions and grain yield at Buntine (30.01 S, 116.34 E; elevation of 315 m) in south-western Western Australia, 296 km north-east of Perth. The site was established in 2003 using a randomized block design, where each of the three replicate blocks contained a variety of treatments aimed at altering soil OM concentrations; the two treatments of interest to this study were chaff addition (plus OM) and no chaff (no OM) addition. Each replicate treatment plot was large (800 m^2), and divided into sections for use in the present study (see below for details). While applying chaff is not an economic land management practice in the region, it was a means of rapidly increasing soil OM for experimental purposes. Organic matter (chaff) had been applied (20 t OM ha^{-1} per application) to the plus OM treatments every three years since 2003; all treatments were tilled annually each autumn (fall) prior to, and during, the present study. The most recent application of OM was applied and incorporated approximately three months (15 March 2012) prior to commencing the present study, with a total of 80 t ha^{-1} applied to the plus OM treatments since the study site was established. No further OM was applied for the remainder of the study. Consequently the soil organic carbon (SOC) in the surface 100 mm averaged 16 g C kg^{-1} (standard error, 1.2 g C kg^{-1}) in the plus OM treatment versus 10 g C kg^{-1} (standard error, 0.4 g C kg^{-1}) in the no OM treatment during the course of the present study.

The study site was located in a semi-arid region of Western Australia. The nearby town of Dalwallinu has an annual rainfall of 291 mm, a mean daily maximum temperature of 26.3 °C and a mean daily minimum temperature of 11.7 °C (calculated using data collected from 1997 to 2015; Commonwealth Bureau of Meteorology, http://www.bom.gov.au/climate/averages/tables/cw_008297_All.shtml; accessed 18 March 2016). The soil at the experimental site consisted of a free-draining sand (Basic Regolithic Yellow-Orthic Tenosol; Isbell, 2002) and was located on flat to gently undulating land (Table 1).

The land-use history (and grain yield where applicable, averaged across treatments) of the site for the five years prior to commencing this study was: 2007, wheat (*Triticum aestivum*, no yield due to poor growth); 2008, wheat (3.02 t ha^{-1}); 2009, lupin (*Lupinus angustifolius*; no yield); 2010, wheat (2.15 t ha^{-1}); 2011, wheat (3.83 t ha^{-1}). The site was exclusively cropped, and not grazed by farm animals following its establishment in 2003.

2.2. Experimental design and approach

The study included two field-based experiments conducted at the same research site, but using separate areas within each treatment plot for each experiment.

2.2.1. Assessing the effect of increasing soil OM on GHG fluxes

In Experiment 1, the effect of increasing soil OM on GHG fluxes was investigated for 2.5 years (7 June 2012 – 5 December 2014)

Table 1
Selected soil properties (0–100 mm) of plots used to measure the effect of organic matter (OM) addition on greenhouse gas emissions at Buntine, south-western Australia.

Soil property	Plus OM	No OM	$LSD_{0.05}$
Nitrogen (%)[a]	1.05 (0.2)	0.62 (0.03)	0.27
pH (0.01 M $CaCl_2$)[b]	6.20 (0.1)	6.31 (0.1)	0.33
pH (H_2O)[b]	6.84 (0.1)	6.93 (0.1)	0.39
Electrical conductivity (μS cm^{-1})[c]	216 (25)	136 (6.8)	58
Cation exchange capacity (cmol (+) kg^{-1})[d]	4.19 (0.3)	2.28 (0.1)	0.79
Silt (%)[e]	3.2 (0.3)	2.2 (0.2)	0.86
Clay (%)[e]	6.4 (0.2)	4.9 (0.2)	0.59
Sand (%)[e]	90.4 (0.1)	92.9 (0.2)	0.56
Field capacity (g H_2O cm^{-3})[f]	0.39 (1.0)	0.33 (1.7)	0.05

Values are means (and standard errors) of at least six replicates.
[a] Total nitrogen content determined by dry combustion of air-dry, finely ground soils using a CNS analyzer.
[b] Soil pH measured in 0.01 M $CaCl_2$ or water or using a glass electrode and a 1:5 soil to extract ratio.
[c] Electrical conductivity measured in water using a probe and a 1:5 soil to extract ratio.
[d] Cation exchange capacity (CEC) (soil <2 mm) measured using a silver thiourea exchange method (Rayment and Higginson, 1992).
[e] Particle size analysis determined using the method described by McKenzie et al. (2002).
[f] Field capacity determined using ceramic suction plates (McKenzie et al., 2002).