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Research Paper

Greenhouse gas emissions from intensively managed peat soils in an arable production system

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ABSTRACT

Organic-rich, eutrophic peat soils (Histosols) represent a major store of carbon (C) within the terrestrial biosphere. However, these soils are also highly susceptible to damage, particularly when used for intensive agricultural production. Sustainable management of such soils is contingent upon improved understanding of the impact of their management on the environment. In this context, we report the first annual budget of greenhouse gas emissions from temperate peat soils under intensive horticultural production. Fluxes of CO_2, N_2O and CH_4 were measured using static chambers on three farms along an organic matter loss gradient (~20%, ~35%, and ~70% soil organic matter (SOM) content respectively), under a number of commercially important crops in similar rotations. Cumulative annual fluxes of CO_2 in fallow and cropped soils were large and ranged from 13.0 ± 2.4 to 30.9 ± 2.5 t CO_2-e ha^{-1} y^{-1}, showing a general increase with SOM, and on cropped compared to bare soils. Annual emissions of N_2O varied from 5.0 ± 0.7 to 13.9 ± 1.9 t CO_2-e ha^{-1} y^{-1}, and CH_4 from -0.02 ± 0.08 to 0.04 ± 0.02 t CO_2-e ha^{-1} y^{-1}; neither showed a significant relationship with either SOM content or cropping. Distinct seasonal patterns of CO_2 and N_2O fluxes were observed, corresponding to significant correlations between emissions and soil and air temperature, soil moisture content, water table depth, and soil nitrate on some soil types. No discernible seasonal pattern in CH_4 fluxes was observed, and very few significant correlations with soil environmental variables were found. Compared to emissions estimates suggested in IPCC inventory guidelines for cultivated peat soils, the observed emissions in this study were relatively high, and net annual fluxes of CO_2 and CH_4 are equivalent to a loss of soil depth of 0.33–0.75 cm y^{-1}. We conclude that arable farming is promoting extreme mineralization of the soil's organic carbon reserves and that a change in land use or management regime is needed to protect and preserve this natural capital.

1. Introduction

Peat soils (Histosols) represent a major store of carbon (C) within the terrestrial biosphere (Limpens et al., 2008). While most studies of C loss have focused on non-agricultural peat soils, current evidence suggests that intensively cultivated lowland peats may also represent hotspots for greenhouse gas (GHG) emissions and related soil organic C (SOC) losses (Cannell et al., 1999; Dawson et al., 2010; Smith et al., 2007). Work on these arable peat systems has mainly focussed on quantifying CO_2 emission and changes in SOC storage, largely neglecting emissions of CH_4 and N_2O, and complete GHG budgets for organic soils under continuous arable management are extremely scarce (Evans et al., 2011; IPCC, 2014; Worrall et al., 2011). As GHG Emission Factors (EF) for arable mineral soils, or peat under managed grassland, are not likely to reflect emissions from these arable peats (due to differences in management regime and soil properties, for example), there is an urgent need to develop accurate and robust EFs for these agroecosystems. This is reinforced by their economic importance in terms of food security in many countries (Parish et al., 2008).

Improving emissions estimates facilitates accurate inventorying at the national level, a legal requirement for emissions reduction target compliance in many countries, and an important step in identifying mitigation priorities (IPCC, 2006). Mitigating agricultural emissions could contribute substantially to overall reduction targets. For example, in 2013, agriculture was estimated to be the second-largest sector contributor to emissions in Europe

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(9.9% CO_2-e of total EU_{28} emissions), with direct agricultural soil emissions of N_2O accounting for approximately 40% of this figure (EEA, 2015). Agricultural peat emissions at the national level are currently calculated using a default EF averaged over all temperate zones, with little recognition of regional differences in climate, peat soil characteristics and agricultural management practices when compared to the temperate-zone average. Consequently, soil N_2O EFs in particular have been identified as a priority for refinement, dominating overall sources of uncertainty in EU GHG estimates since 1990 (EEA, 2015; Leip, 2010).

The sustainability of cropping on peat soils is an important consideration for long-term food security, with soil loss rates in drained and intensively cropped regions indicating that these practices are detrimental to the conservation of soil C stocks. Rates of soil loss from temperate lowland peats have been reported at 0.2–7.0 cm y^{-1} (Richardson and Smith, 1977; Ewing and Vepraskas, 2006), with a recent estimate from UK East Anglian arable fens of 1.10–1.48 cm y^{-1} between 1982 and 2004 (Dawson et al., 2010). Emissions of CO_2 may constitute between 35% and 100% of peat subsidence C losses (Leifeld et al., 2011), but the literature remains unclear regarding the proportion of total SOC loss that can be attributed to other routes (principally, wind and water erosion, leaching, and crop adherence). Quantifying GHG emissions from arable peats under different management regimes can therefore contribute to estimates of future soil losses, and enable prioritisation of soil loss mitigation measures via the different routes of loss.

Factors influencing emissions from agricultural soils are numerous and interact in often complex ways; they include soil (e.g. moisture, temperature, porosity, substrate availability), climate (rainfall, temperature), and vegetation (yield, water uptake), which in turn are driven by human activities such as farm operations (Li, 2007). Often, a change in a single variable may simultaneously increase the emission of one GHG and result in the reduction of another (Smith et al., 2008). Whilst individual studies have been conducted and models created that identify the relative importance of these factors in driving agricultural soil emissions (e.g. Giltrap et al., 2010), quantification of emissions drivers requires further attention with regard to intensively managed agricultural peat soils.

The primary aim of this study was to quantify and compare emissions of CO_2, CH_4 and N_2O from soils of comparatively high organic matter content (~20% SOM, ~35% SOM, and ~70% SOM respectively, to 1 m depth), under a number of commercially important horticultural/arable crops. We also aimed to determine which soil and crop factors most strongly influenced GHG fluxes from these soils.

2. Methods and materials

2.1. Study sites

The study area was located in East Anglia, UK, and comprised drained lowland fen typified by flat topography (0–1% slope) with long-term (1980–2013) mean annual rainfall of 621 mm, mean annual temperature of 10.2 °C (winter mean 4.4 °C, summer mean 16.4 °C), and mean annual sunshine of 1280 h (UK Met Office, 2014). All sites have been under long-term horticultural/arable production in rotation since c. 1940, growing primarily vegetables (e.g. celery, leeks, lettuces, potatoes, red beet) and wheat. Details of management practices implemented during the monitoring period are provided in the Supplementary material (Supplementary Tables S.1–S.3).

Three farms (sites) were identified for monitoring on the basis of their contrasting soil organic matter content to 1 m depth: (1) Site 1 comprised the low SOC farm site (SOC_{LOW}) where the soils had a SOM content of ~20%; (2) Site 2 comprised the medium SOC farm site (SOC_{MED}) where the soils had a SOM content of ~35%; (3) Site 3 comprised the high-SOC farm site (SOC_{HIGH}) where the soils had a SOM content of ~70%. Experimental monitoring sites were selected from each farm using farm records to identify fields with typical commercial cropping rotations. Crops selected for study included: celery (*Apium graveolens* L.), red beet (*Beta vulgaris* L., grown in tandem with a cover crop of barley, *Hordeum vulgare* L.), lettuce (*Lactuca sativa* L.), radish (*Raphanus sativus* L.), and potato (*Solanum tuberosum* L.). Six fields (three at the SOC_{MED} farm site, and three at the SOC_{HIGH} farm site) were sampled monthly from April 2011 until June 2012, with a seventh field at the SOC_{LOW} farm site added in June 2011.

One experimental sampling block (6 × 30 m) was randomly positioned within each field (Fig. S.1). Blocks were located at least 10 m from field margins and areas of heavy vehicle trafficking were avoided. Each sampling block contained five randomised pairs of cropped (C) and bare (B) fallow plots 6 × 6 m in size with the long axis of the block running parallel to the crop planting line. Inclusion of both cropped and bare plots enabled estimation of autotrophic vs. heterotrophic respiration (after Koerber et al., 2010). During the growing season the bare plots were covered with black geo-textile ground cover to suppress weed growth. Each 6 × 6 m plot enclosed a 1 m buffer around its inner boundary to reduce edge effects of adjacent plots and field areas, leaving a 4 × 4 m monitoring area containing one randomly positioned GHG monitoring collar.

2.2. Seasonal greenhouse gas fluxes

Monthly greenhouse gas measurements were undertaken at all sites. Closed, non-vented static chambers were used to monitor soil emissions of N_2O and CH_4. Cylindrical black polyethylene collars (internal dimensions d = 26.3 cm, h = 19.8 cm; PBSL, Colchester, UK) were inserted 12 cm into the soil and left in situ unless removed to allow tillage operations to take place. All vegetation was removed from within and surrounding the collar at installation at least 24 h before each sampling event. The static chambers fitting onto the collars consisted of white opaque polypropylene closed cylinders (internal dimensions d_1 = 22.0 cm, d_2 = 25.0 cm, h = 26.3 cm; CJK Packaging, Derbyshire, UK), with a rubber septum sampling port 7 cm from the top of the chamber, and an internal battery powered 25 mm 12 V fan (typical flow rate = 54 l min^{-1}; CPC Ltd., Leeds, UK). Chambers were inserted 4.5 cm into the top lip of the soil collar so that the flexible seal around the chamber rim formed an air-tight seal with the collar, giving a final enclosed headspace volume of 19.8 dm^3 (Fig. S.2). All chambers were vented for >5 min prior to collar attachment and GHG sampling.

The chamber headspace was sampled four times at approximately 10 min intervals, with the first gas sample taken immediately after chamber enclosure. Glass sample vials (20 ml) fitted with butyl rubber septa (QUMA Electronik & Analytik GmbH, Wuppertal, Germany) were manually evacuated (60 ml) prior to sampling. Gas samples were removed from the headspace of the static chambers using a 30 ml syringe and a 21G, 5 cm needle. On insertion of the needle into the septum, the syringe was flushed twice then the sample taken and injected into the vial.

Gas samples were stored at room temperature in the dark until analysis. Sample analysis was within six weeks of collection using a gas chromatograph (Varian 450-GC, Bruker UK Ltd., Coventry, UK), equipped with a flame ionisation detector (FID, operated at 120–125 °C) and electron capture detector (ECD, operated at 300 °C), and attached to a QUMA QHSS®-40 Headspace Sampler (QUMA Electronik & Analytik GmbH, Wuppertal, Germany), which injected 2 ml of sample into the GC. Gas standards with certified concentrations to within 2–10% of their specification (STG Ltd.,