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Differences in carbon density and soil CH_4/N_2O flux among remnant and agro-ecosystems established since European settlement in the Mornington Peninsula, Australia

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HIGHLIGHTS

- We measured soil CH4 and N2O flux and ecosystem C density along a LUC sequence.
- Forest soil was a CH4 sink but pasture and viticulture soils were CH4 sources.
- Despite soil moisture differences, soil N2O emissions did not differ.
- Forest soil C density was significantly less than the agro-ecosystems.
- Changes in non-CO2 soil processes contribute to the historical GHG impacts of LUC.

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ABSTRACT

National and regional C emissions from historical land use change (LUC) and fossil fuel use are proposed as a basis to ascribe 'burden-sharing' for global emission reduction targets. Changes in non-CO_2 greenhouse gas emissions as a result of LUC have not been considered, but may be considerable. We measured soil–atmosphere exchange of methane (CH_4) and nitrous oxide (N_2O) in remnant forest, pasture and viticulture systems in four seasons, as well as differences in soil C density and the C density of remnant forest vegetation. This approach enabled comparative assessment of likely changes in ecosystem C density and soil non-CO_2 greenhouse gas exchange along a LUC continuum since European settlement. Soil CH_4 uptake was moderate in forest soil (-27 μg C m^{-2} h^{-1}), and significantly different to occasionally large CH_4 emissions from viticulture and pasture soils. Soil N_2O emissions were small and did not significantly differ. Soil C density increased significantly with conversion from forest (5 kg m^{-2}) to pasture (9 kg m^{-2}), and remained high in viticulture. However, there was a net decrease in ecosystem C density with forest conversion to pasture. Concurrently, net soil non-CO_2 emissions (CH_4 and N_2O combined) increased with conversion from forest to pasture. Since European settlement 170 years ago, it was estimated ~8114 Gg CO_2-e has been released from changes in ecosystem C density in the Mornington Peninsula, whereas ~383 Gg CO_2-e may have been released from changes in soil non-CO_2 exchange processes. Principally, a switch from soil CH_4 uptake to soil CH_4 emission after forest clearing to agro-pastoral systems provided this further ~5% contribution to the historical landscape CO_2-e source strength. Conserving and restoring remnant forests and establishing new tree-based systems will enhance landscape C density. Similarly, minimising anaerobic, wet conditions in pasture/viticulture soils will help reduce non-CO_2 greenhouse gas emissions.

1. Introduction

The atmospheric concentration of naturally occurring greenhouse gases (GHG) has increased as a result of anthropogenic activity. Carbon dioxide (CO_2) emissions have increased from the burning of fossil fuels and land-use change (principally deforestation) whilst more potent GHGs, such as nitrous oxide (N_2O) and methane (CH_4), have increased in concentration as a result of land-use change and agricultural and pastoral intensification (Solomon et al., 2007). The importance of soil to the global GHG balance cannot be understated, as soils represent the largest terrestrial carbon sink (Lal, 2004), the largest terrestrial source of CO_2 to the atmosphere (Schlesinger, 1991), the largest source of N_2O to the atmosphere (Dalal et al., 2003;

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Smith and Conen, 2004) and the largest terrestrial sink for CH_4 from the atmosphere (Bousquet et al., 2006). As such, to adequately assess the greenhouse gas impact of any landscape and land-use change (LUC) matrix, a multiple greenhouse gas and C stock approach is most appropriate (Robertson et al., 2000).

Clearing of native forests to a pasture systems invariably leads to 1) instant CO_2 emissions from vegetation burning or decomposition, 2) a rapid decrease in vegetation C stocks, and 3) a gradual, long-term decrease soil C stocks from the subsequent imbalance between plant growth and organic matter C inputs to the soil and mineralization/respiration losses of CO_2 from the soil (Foley et al., 2003). However, if a forest system is replaced by a productive pasture system there can be a post-disturbance recovery in soil C and sometimes even an increase (Guo and Gifford, 2002). Whether such an increase in soil C can offset the loss of vegetation C depends upon the productivity and carbon 'residence time' of that forest, as compared to the agriculture system that replaces it (Gitz and Ciais, 2004).

Any subsequent LUC events (e.g. pasture to cropping, or pasture to urban) often result in a net loss of soil C over time (Guo and Gifford, 2002) unless management intensity and plant productivity are comparable. Theoretically, a change from pasture to intensive horticulture, such as viticulture, should maintain plant productivity and therefore maintain organic matter inputs and soil C stocks. Active management of natural and agricultural systems should strive to conserve existing soil carbon stocks, and where possible, sequester additional soil organic carbon (Lal et al., 2007). Quantifying any change in soil C content requires consideration of soil C concentration, soil density and stone content (McKenzie et al., 2000) and is best assessed through 'equivalent soil mass' rather than fixed soil depth (Ellert et al., 2007).

In addition to changes in vegetation and soil C stocks along a LUC sequence, there can be changes in soil biogeochemistry and non-CO_2 greenhouse production and consumption mechanisms. Soils can be a natural source or sink for CH_4, depending principally upon whether aerobic (oxygen) or anaerobic states dominate (Dalal et al., 2008). Soil methanogenic archea bacteria can produce CH_4 (methanogenesis) under anaerobic conditions, whilst CH_4 can be taken up (oxidised) by soil methanotrophic bacteria (methanotrophy) under aerobic conditions (Conrad, 1996; Dalal et al., 2008). Forest and woodland soils are the largest terrestrial CH_4 sink (Price et al., 2004), whereas pasture soils may be a net sink or a source for CH_4 depending upon soil water content, compaction and nitrogen status (Livesley et al., 2009). Soil moisture and compaction greatly determine soil CH_4 flux as it directly influences gas diffusion of CH_4 substrate to methanotrophic bacteria, or alternatively the diffusion of CH_4 from anaerobic, methanogenic production sites (von Fischer et al., 2009).

Soil N_2O emissions are produced principally by either nitrification or denitrification (Conrad, 1996). Microbial nitrification by ammonia oxidising bacteria transforms ammonium (NH_4^+) to nitrate (NO_3^-) under aerobic conditions, producing N_2O as a by-product. Microbial denitrification transforms nitrate (NO_3^-) to NO_2^-, NO_2, NO, N_2O and N_2 under anaerobic conditions. Forest soils are invariably a small source of N_2O because of tight N cycling, larger soil and litter C:N ratios and drier soil conditions (Attiwill et al., 1996). In contrast, clover-grass pastures can be a major source of N_2O because of the N inputs from N_2-fixation and animal excreta and urea and the warmer, moister soil conditions (Soussana et al., 2007). The behaviour of viticulture soils as a sink or source for CH_4 and N_2O is unknown.

The Mornington Peninsula is a 723 km^2 peninsula extending south-east from Melbourne towards the Bass Strait between Port Phillip Bay and Westernport Bay in Victoria, Australia. The native eucalypt forest and woodland systems have been heavily fragmented by clearing to pasture for cattle and sheep between the 1830's and mid-1900's. In recent decades, some pastures have been converted to cropping or intensive horticulture (viticulture). This landscape matrix is likely to have variable C and nutrient cycling properties and therefore greenhouse gas exchange characteristics, as such four hypotheses were formed:

- Soil CH_4 uptake will be greatest in the forest and least in the pasture and viticulture systems because of differences in soil moisture, compaction and gas diffusion.
- Soil N_2O emissions will be greatest in the pasture and viticulture systems and least in the forest because of differences in soil moisture and inorganic N substrate.
- Soil C density will be least in forests, but similar in pasture and viticulture systems.
- From a LUC sequence, the loss of vegetation C after forest clearing will not be offset by changes in soil C density or soil non-CO_2 GHG exchange.

Soil N_2O and CH_4 flux were measured once in autumn, winter, spring and summer at three properties that provided access to areas of remnant eucalypt forest, cattle grazed clover-grass pasture and viticulture systems. At one property, soil C content was measured in forest, pasture and viticulture systems through a comprehensive spatial survey. By understanding the differences in soil C and GHG exchange within this landscape matrix the impact of LUC events since European settlement can be recognised and better land management practice and policy can be constructed to minimise future GHG emissions and to maximise C stocks.

2. Materials and methods

The Mornington Peninsula extends south from metropolitan Melbourne towards the Bass Strait between Port Phillip Bay and Westernport Bay (Fig. 1). The Peninsula is relatively flat in the northern section but becomes increasing undulating in the central and southern sections, reaching 300 m above sea level at the highest point. Mean annual rainfall is 897 mm (1982–2010; Devils Bend reservoir), with mild mean annual maximum (19.0 °C) and minimum (9.7 °C) temperatures (Fig. 2). 2009 rainfall was below-average at 675 mm, however, April, July, September and November were above-average.

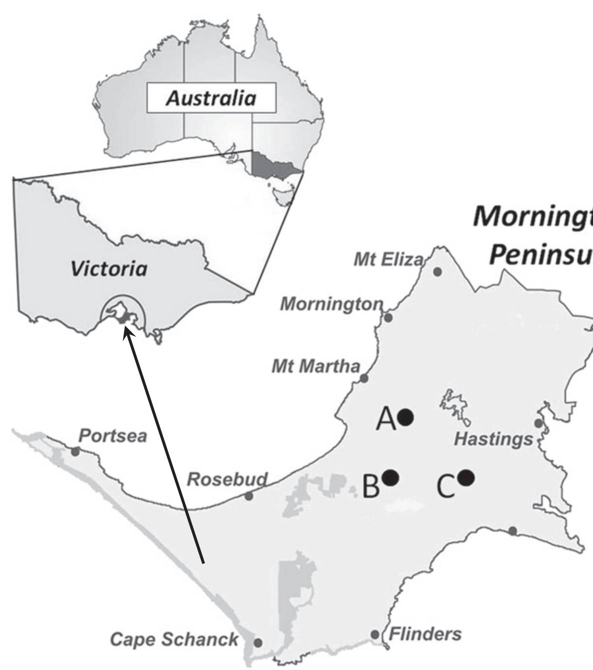

Fig. 1. The Mornington Peninsula in Victoria, Australia separates Port Phillip Bay to the north-west from Westernport Bay to the south-east. Three properties were selected for this study, Tuerong (A) Dunns Creek (B) and Buckleys (C).