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Carbon balance of an intensively grazed temperate dairy pasture over four years

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ABSTRACT

We estimated the net ecosystem carbon (C) balance (NECB) of a temperate pasture in the North Island of New Zealand for four years (2008–2011). The pasture was intensively managed with addition of fertiliser and year-round rotational grazing by dairy cows. Climatic conditions and management practices had a large impact on CO_2 exchange, with a severe drought in one year and cultivation in another both causing large short-term (~3 months) net losses of CO_2–C (100–200 g C m^{-2}). However, CO_2 was regained later in both of these years so that on annual timescales, the site was a CO_2 sink or CO_2 neutral. Management practices such as effluent application and harvesting silage also influenced non-CO_2–C fluxes, and had a large impact on annual NECB. Despite these major environmental or management perturbations, both NEP and NECB were relatively constant on annual timescales. It is likely that this apparent resilience of the CO_2 and C balance to perturbations was at least partly attributable to the relatively warm temperatures, also in winter, providing good growing conditions year-round (in the absence of major perturbations such as moisture stress). In several instances, the farmer's decisions aimed at maintaining a constant milk yield between years also appeared to contribute to a relatively stable C balance.

Averaged over the full four-year study period, the site was a net sink for both CO_2 (NEP = 165 ± 51 g C m^{-2} y^{-1}), and total C (NECB = 61 ± 53 g C m^{-2} y^{-1}) after non-CO_2–C fluxes were accounted for. Annual NEP and NECB values were similar to results collated from other managed temperate grasslands on mineral soils globally, for which average NEP and NECB were 188 ± 44 g C m^{-2} y^{-1} and 44 ± 33 g C m^{-2} y^{-1}, respectively. In the global dataset, we noted a general trend for increased C sequestration with increasing NEP, suggesting that it may be possible to meet the dual goal of increased pasture production (thus milk, meat and fiber production) and increasing soil C storage in managed temperate grasslands. Identification of management practices that increase C storage while maintaining or enhancing pasture production requires more standardised reporting between NECB studies, and experiments involving side-by-side comparison of treatment and control plots.

1. Introduction

Temperate grasslands, which cover 1.25×10^9 ha globally, are important stores of soil organic carbon (C), containing approximately 12% of the global soil organic carbon (SOC) pool (Watson et al., 2000; Lal, 2004b). Long-term studies in permanent temperate grasslands have found increases, decreases or no change in SOC storage over time (Bellamy et al., 2005; Meersmans et al., 2009; van Wesemael et al., 2010; Schipper et al., 2014), with causes for these different findings often remaining largely unresolved. Recent research has shown that appropriate management of grasslands may aid the sequestration of C in soil organic matter, thereby increasing soil quality, offsetting CO_2 emissions to the atmosphere and mitigating climate change (Conant et al., 2001; Lal, 2004b; Soussana et al., 2010). For example, increasing pasture productivity through fertiliser application or irrigation, improved grazing management, introduction of legumes or increasing the duration of grass leys, may increase soil C stocks

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under grasslands (Conant et al., 2001; Schnabel et al., 2001; Freibauer et al., 2004; Soussana et al., 2004; Smith et al., 2008; Jones, 2010). It is crucial to improve our understanding of the impact of management practices and climatic conditions on soil C dynamics in temperate grasslands, so that the effects of future management and changing climate conditions on these grasslands can be evaluated.

Quantifying short-term (<5 years) changes in soil organic matter storage using repeated soil sampling over time is difficult because of the generally large background pool of SOC and high spatial variability (Smith, 2004; Rees et al., 2005). Consequently, changes in SOC storage can generally only be determined if there are at least several years between repeated samplings and/or many replicates. However, short-term (≥1 year) C balances of ecosystems can be studied using the net ecosystem carbon balance (NECB) method (e.g., Byrne et al., 2007; Smith et al., 2010; Soussana et al., 2010). This technique requires the determination of all inputs and outputs of C to and from an ecosystem to deduce any changes in C stocks in the ecosystem. In natural, unmanaged ecosystems, uptake and release of CO_2 (by photosynthesis and respiration) are likely to be the main processes affecting the C balance. In managed agricultural ecosystems, additional non-CO_2–C inputs (e.g., feed, applied manure or effluent) and outputs (e.g., harvested biomass or milk) may also be significant contributors to the NECB (Soussana et al., 2010; Zeeman et al., 2010; Mudge et al., 2011).

Previous studies of the C balance of managed temperate grasslands have found variable results, and reported sites to be C sinks (e.g., Allard et al., 2007; Byrne et al., 2007), C sources (e.g., Veenendaal et al., 2007; Skinner, 2008), or C-neutral (e.g., Prescher et al., 2010). If there are indeed C gains and losses, it is important to understand what climatic conditions or management practices might be responsible for these trends. To help with answering these questions, we determined the C balance of a grazed pasture in New Zealand over four years.

In New Zealand, pastoral agriculture is the dominant land use, with dairy cows grazing about 14% of pastoral land. Dairy farms are typically located on the flattest and most productive land, with the remainder of New Zealand's pastoral land grazed by sheep, beef cattle, deer and young dairy cattle. Mild climatic conditions allow year-round rotational grazing on dairy farms, without a need for housing cattle over winter, which is a common practice for many Northern Hemisphere pasture systems. The New Zealand dairy industry has undergone substantial intensification in recent decades with increasing stocking rates and use of fertiliser, irrigation and supplemental feed (MacLeod and Moller, 2006; Clark et al., 2007). For flat to rolling land (where most dairy farms are situated), recent research has shown decreases in soil C over the last twenty to thirty years for some soil orders, whereas soil C remained stable for others (Schipper et al., 2014). While long-term changes in soil C stocks have been documented in some pastoral soils, there is still poor understanding of underlying temporal trends, or causes for these changes. This research gap requires more detailed measurement campaigns to identify factors causing changes in soil C, which will aid development of approaches to mitigate C losses, or increase C sequestration.

In previous work, we described net ecosystem production (NEP) and net ecosystem carbon balances (NECB) for two years at an intensively managed pasture site on a mineral soil in New Zealand (Mudge et al., 2011). Despite a severe drought in the first year and below-normal temperatures for much of the second year, the site was a net sink for CO_2 and total C over the two years. We also measured short-term (~40 day) CO_2 fluxes following cultivation at the same site, and found that net C losses ranged from 2 to 6 g C $m^{-2}\,d^{-1}$ depending on soil moisture content (Rutledge et al., 2014).

The current paper extends the research of Mudge et al. (2011) by describing an additional two years of measurements (2008–2011) at the same site. The extended study period allowed us to evaluate the impact of a wider range of typical management practices such grazing by cattle, cutting for silage production and pasture renewal (including cultivation) on NEP and NECB. We compared our findings to a global dataset collated from studies carried out in temperate pasture systems.

2. Methods

2.1. Site description

This study took place at Scott Farm, a research dairy farm owned and operated by dairy industry research organisation DairyNZ. The farm is located to the east of Hamilton in the Waikato region on the North Island of New Zealand (37°46′13″S, 175°22′41″E, 41 m a.s.l.), and has been used for dairy farming for more than 95 years. Average annual rainfall and air temperature are 1126 mm and 13.8 °C, respectively. Soil in the flux footprint of the eddy covariance (EC) system is the Matangi silt loam (Typic Orthic Gley Soil, Hewitt, 1993). This soil has imperfect to poor drainage and a bulk density (0–75 mm) of 780 $kg\,m^{-3}$. Total porosity of the Ap horizon (0–250 mm) was 0.66 $m^3\,m^{-3}$, field capacity (10 kPa) 0.54 $m^3\,m^{-3}$ and permanent wilting point (1500 kPa) 0.25 $m\,m^{-3}$. Total C and N in the topsoil (0–100 mm) were 7.7% and 0.72%, respectively.

2.2. Farm management

Scott Farm is made up of small (0.5 ha) paddocks, which are rotationally grazed year round with an average stocking density of ~3 dairy cows/ha. Overall stocking rate and management were similar to commercial dairy farms in the Waikato region, with paddocks generally receiving 150 kg N ha^{-1} per year. In spring, when pasture growth exceeded cow demand, pasture from some of the paddocks was cut for silage. When feed demand exceeded pasture growth (typically autumn, winter, and early spring) supplementary feed was fed to cows in the paddocks. During this study, supplementary feed consisted of the silage cut on the farm in spring, maize grown on the farm over summer and additional palm kernel expeller (PKE) brought in from outside the farm.

Management of the pasture and cows at Scott Farm was controlled by DairyNZ researchers and farm staff, and largely outside the control of the C flux measurement team. Over the measurement period, the size of grazing herds ranged from 8 to more than 100 cows per paddock. On average, paddocks in the EC flux footprint (hereafter referred to as 'EC footprint') were grazed approximately seven times per year. Because paddocks within the EC footprint were not always grazed at the same time, different paddocks had different pasture covers at any given time. In general, grazing took place with larger herds from mid-2009 onwards. From October 2010 onwards, grazing was more synchronised between paddocks. Before March 2010, plant cover in all paddocks of the EC footprint was perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). In 2010, a change in DairyNZ research trials required renewal of the pasture in some of the paddocks in the EC footprint (Fig. 1). Pasture renewal involved spraying the existing sward with herbicide (22 February), application of effluent, mouldboard ploughing to 200–250 mm depth (22 March), application of lime, power harrowing to prepare the seed bed, and then sowing either a high diversity sward, or a low diversity sward (26 March). See Rutledge et al. (2014) for more details about cultivation and sowing. The high diversity sward comprised of a grass component, either perennial ryegrass, high sugar ryegrass, or tall fescue (*Festuca arundinacea*), and white clover, plantain (*Plantago lanceolata*), chicory (*Cichorium intybus*) and lucerne