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Variations in CO_2 exchange for dairy farms with year-round rotational grazing on drained peatlands

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ABSTRACT

It is commonly assumed that agricultural peatlands are net sources of CO_2 to the atmosphere because of lowered water tables and intensive land management altering the balance of plant productivity and respiration. Yet actual farm-scale fluxes of CO_2 have been infrequently quantified. We measured net ecosystem exchange of CO_2 (NEE) using a permanent and a mobile eddy covariance tower installed over dairy farms with year-round rotational grazing on deep peats in New Zealand. The permanent tower was in place for one year and the mobile tower was deployed for periods of 3–4 weeks at three other farms on peat between spring and autumn. At all sites, grazing cycles caused large variations in pasture biomass and consequent daytime NEE and we accounted for these variations using an index of photosynthesising biomass (phytomass index, Lohila et al., 2004) automatically derived from daily CO_2 flux measurements. We estimated annual CO_2 loss of 190 gC m^{-2} yr^{-1} for the permanent site, which is in broad agreement with other agricultural peatland studies. Including other farm-scale exports of C, overall net ecosystem carbon loss estimated for the permanent site was 294 gC m^{-2} yr^{-1}. Accounting for changes in phytomass index, daytime NEE was similar for permanent-mobile site farm pairings, except when there were very large differences in water table depths between farms in autumn. In contrast, night-time respiration losses were almost identical between farms even when water tables were markedly different, suggesting that spatial differences in NEE in these agricultural peatlands are caused by reduced photosynthesis in dry periods, due to plant water stress, rather than increased respiration. Comparisons between permanent and mobile towers appeared a useful approach for determining spatial variability of CO_2 fluxes from peat soils. Taken together, our results suggested that the CO_2 losses measured at the permanent site were representative of CO_2 losses for farmed peats in the Waikato region when the water table was within ~0.5 m of the surface. Where water tables were deeper net CO_2 losses would be expected to be greater due to reduced pasture photosynthesis and production. Maintaining higher water tables might achieve dual benefits of increasing pasture productivity and reducing CO_2 losses.

1. Introduction

Globally peatlands represent 3% of land surface area yet store carbon (C) equivalent to 30% of the global soil C stock (Blodau, 2002). The C stored in peatlands has accumulated over thousands of years because of net CO_2—C uptake via photosynthesis exceeding C losses via decomposition processes (Frolking et al., 2011), and their overall greenhouse gas (GHG) balance has had a net cooling effect on global climate throughout the Holocene, despite being significant sources of methane (Frolking and Roulet, 2007). In contrast, peatlands developed for agriculture are generally CO_2 sources due to lowering of the water table and improved soil fertility altering the balance between gross primary productivity (GPP) and ecosystem respiration (ER). Lowered peatland water tables leads to altered peat decomposition rates, both directly via a deeper layer of peat exposed to oxygen, and indirectly because of changes to microbial populations (Mäkiranta et al., 2009). Because human activities have led to net CO_2 losses within drained peatlands and, usually, increased N_2O emissions, they must be accounted for in national greenhouse gas inventories (Couwenberg, 2011).

While conversion of natural ecosystems for agriculture alone has had major impacts on the net ecosystem exchange of CO_2 (NEE = ER–GPP), ongoing management of agricultural systems involves an increase in disturbance regimes that can lead to

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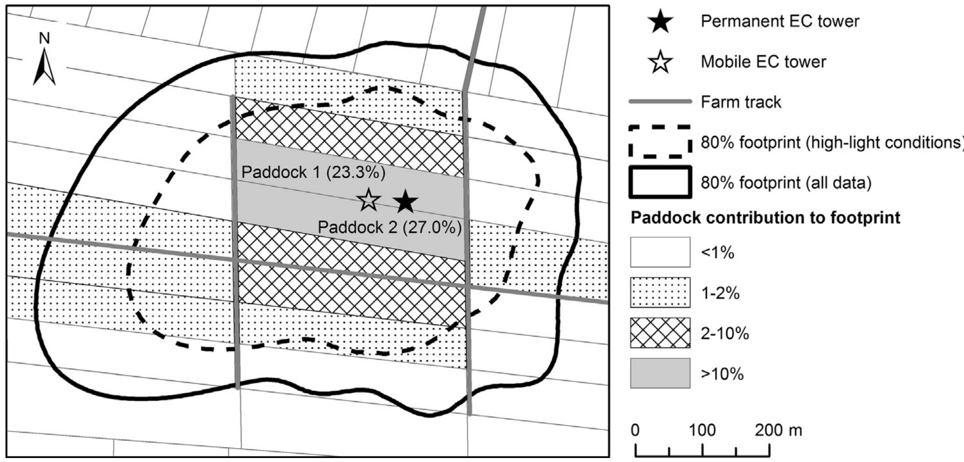

Fig. 1. Map of the Rukuhia dairy farm site showing the location of the permanent and mobile EC towers in relation to field boundaries/drains and farm roads. Shading represents the calculated contribution of each paddock to the CO_2 flux measured by the permanent tower during the whole study period, while the contour lines contain the areas contributing 80% of NEE for all data (solid line) and 80% of daytime high-light NEE used to calculate the phytomass index (dashed line). For the two paddocks adjacent to the EC tower sites, percentages give their contribution to the overall flux footprint. Paddocks are each approximately 2 ha area.

additional alteration of annual NEE, typically by increasing ER relative to GPP (Baldocchi, 2008). In managed pastoral ecosystems, for instance, above-ground plant biomass is periodically removed by animal grazing and harvesting, temporarily interrupting plant production. In addition, trampling by animals can reduce effective leaf area and photosynthesis (Soussana et al., 2007). When green plant biomass is removed or damaged, photosynthesis is significantly reduced but soil respiration continues (Nieveen et al., 2005; Rogiers et al., 2005; Rutledge et al., 2014). For example, Nieveen et al. (2005) demonstrated that following a one-time grazing on peat soils there was net loss of CO_2 of about 24 gC m^{-2} over one month. Recovery of the plant canopy takes time, so that periodically cut or grazed pastoral systems are characterised by a saw-tooth pattern of NEE (e.g. Soussana et al., 2007; Wohlfahrt et al., 2008; Merbold et al., 2014). Biomass removal via harvesting or grazing occurs under a wide range of intensities, from once or twice per year (Lohila et al., 2004; Lloyd, 2006; Rogiers et al., 2008) up to six times during the growing season for more intensive European systems (Veenendaal et al., 2007; Merbold et al., 2014). In New Zealand, a mild temperate climate allows year-round pasture growth and 8–12 grazings per year at high cow densities for short durations (e.g. 80 cows ha^{-1}, Moir et al., 2010). Since the light response of NEE is often highly correlated with leaf area index (LAI) (Veenendaal et al., 2007), depending on the timing and amount of biomass removal by grazing or cutting, annual NEE and the net ecosystem C balance (NECB) can be severely affected (Lohila et al., 2004; Nieveen et al., 2005; Soussana et al., 2007; Veenendaal et al., 2007), although few studies have attempted to quantify the effect of grazing frequency and intensity on annual NEE (Lecain et al., 2000; Soussana et al., 2010; Kang et al., 2013; Jérôme et al., 2014).

Quantification of farm-scale exchanges of CO_2 is challenging, with most studies on agricultural peatlands having used small chambers, where vegetation or bare soil are enclosed for short periods of time and CO_2 fluxes measured from rate of change of headspace CO_2 concentration (e.g. Lohila et al., 2003; Beetz et al., 2013; Leiber-Sauheitl et al., 2014). While chambers may provide good information about spatial variations of fluxes that can be combined to yield farm-scale estimates (Schrier-Uijl et al., 2010), they are less useful for investigating the impact of grazing events on NEE. Also, isolation of the soil and plants from the atmospheric environment may lead to biased estimates of CO_2 fluxes (Couwenberg, 2011; Gorres et al., 2014). In contrast, the eddy covariance (EC) technique can measure field to farm-scale CO_2 fluxes at timescales ranging from half-hour to annual, including disturbance events such as grazing or cultivation, but there have been relatively few studies that have applied EC to intensively farmed peatlands. For instance, Maljanen et al. (2010) reviewed more than 40 studies reporting GHG fluxes from agricultural peatlands in Nordic countries, but this review only included two studies that used the EC technique. While EC is well suited to ecosystem-scale studies, it is important to account for the dynamic flux footprint across a heterogeneous managed landscape, especially when plant biomass is changing relatively rapidly due to intensive grazing or harvesting. Also, continually changing plant biomass presents challenges for standard methods used to analyze the response of NEE to environmental drivers, for parameterising models necessary for gap-filling NEE to allow daily to annual sums to be compiled, and for comparing NEE across multiple sites. For instance, Merbold et al. (2014) showed enormous variability in the light response of GPP caused by repeated harvesting of pasture, and adopted a relatively complicated method for gap-filling that relied on careful recording of management interventions. As yet there are no automated ways to account for this changing biomass but Lohila et al. (2004) proposed calculating a “phytomass index”, based on the difference between night time and day time NEE, to account for seasonal crop development and biomass removal through harvesting.

In the Waikato region of New Zealand, where approximately one third of the country’s dairy production occurs, around 75,000 ha of former peat wetlands have been drained (Pronger et al., 2014), mostly for year round grazing by dairy cows. By measuring changes in peat mass through time, Schipper and McLeod (2002) estimated annual loss of farmed peatland soil C of 370 gC m^{-2} yr^{-1} during the first 40 years following initial development, which appears to be ongoing although at lower rates (Pronger et al., 2014). In order to improve management of New Zealand agricultural peatlands, from both farm system sustainability and greenhouse gas accounting perspectives, knowledge of their net CO_2 balances is required. Toward this goal, improved understanding of the impacts of key farm management practices, such as water table management and grazing frequency and intensity, is necessary.

Our current understanding of CO_2 losses from agricultural peatlands in New Zealand is from a single year-long study on a dairy farm (Nieveen et al., 2005) and the spatial representativeness of this measurement is questionable. Alongside the original work of Nieveen et al. (2005), but not reported, NEE was also measured