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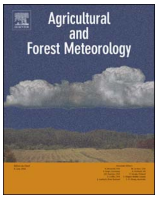

Greenhouse-gas budgets for irrigated dairy pasture and a winter-forage kale crop

Johannes Laubach*, John E. Hunt

Landcare Research, P.O. Box 69040, Lincoln 7640, New Zealand

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ABSTRACT

Managed grasslands can be net sources or sinks for three major greenhouse gases (CO_2, CH_4 and N_2O). We measured the exchange of these gases for three years over an irrigated, intensively-managed dairy pasture in New Zealand that was grazed ten times per year. We also measured the greenhouse gas (GHG) exchanges over a neighbouring dryland pasture for two years, including its conversion to a winter-forage kale crop in the second year and the grazing of that crop. From the gas exchanges, measurements of the grazed biomass, and estimates of other imports and exports we obtained annual net carbon (C) budgets and GHG budgets for these ecosystems. The irrigated pasture system (excluding cows) removed CO_2 from the atmosphere, 423 (± 23) $g\,C\,m^{-2}\,yr^{-1}$ on average, and when considering the other C inputs and outputs it was also a net C sink in each year, gaining 81 (± 27) $g\,C\,m^{-2}\,yr^{-1}$ on average. The net CO_2 uptake of the dryland in the conversion year was about half that of the irrigated pasture, and its net C budget was neutral. The irrigated pasture, without grazing cows, emitted CH_4 throughout all seasons. These emissions were about 15 times greater than emissions expected just from cow dung; we cannot discern what fractions originated from the soil and the pasture plants, respectively. At the dryland/kale site, CH_4 emissions of the same magnitude occurred. The emissions of N_2O from the irrigated pasture were 0.68 (± 0.026) $g\,N\,m^{-2}\,yr^{-1}$ on average (± standard error), and about half that from the kale crop. These results agree reasonably well with expected emissions based on the N inputs from fertiliser and excreta, using emission factors from New Zealand's national GHG inventory; however, it is unclear what fraction of the observed emissions can be considered as non-anthropogenic background fluxes. For the irrigated pasture, the global-warming potential of the N_2O emissions (expressed as CO_2-equivalent mass) was approximately equal to the net C uptake. Hence, the pasture was offsetting its own N_2O emissions. However, CH_4 emissions directly from cows (calculated from the cows' feed intake) were two to three times greater than the N_2O emissions, and about six times greater than the pasture's CH_4 emissions. Therefore, the dairy system including pasture and cows was a net GHG source.

1. Introduction

Grasslands, crops and animal agriculture influence the greenhouse gas (GHG) budget of the atmosphere directly, by exchanging carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) with it. The magnitude of these gas fluxes, and sometimes also their direction, is affected by weather, soil properties, and management. To determine the net exchange of all three GHG for an ecosystem over meaningful timescales, i.e. a year or longer, is a major experimental effort. For managed grasslands, such efforts have been undertaken by Soussana et al. (2007), Skiba et al. (2013), Hörtnagl and Wohlfahrt (2014), Merbold et al. (2014), and Jones et al. (2016). Studies that measured the exchanges of two of the three GHG and estimated those of the third include Leahy et al. (2004), Ammann et al. (2009), and Felber et al. (2016). None of these studies included pasture under irrigation, which is a rapidly spreading management practice in New Zealand (NZ) that has over the past decade contributed to widespread conversion of extensive dryland sheep and beef pastures to intensively-managed dairy pastures under rotational grazing: from 1999 to 2010, NZ's water allocations (excluding hydropower generation) nearly doubled, and in 2010, 76 % of consented irrigated areas was in pasture (Aqualinc, 2010). A second practice of NZ dairy farmers that is on the rise is the growing of winter forage crops which are then "grazed" in-situ; this enables the farmer to keep stock on-farm over winter while reducing the requirements to import feed (Westwood and Mulcock, 2012). There is an urgent need to understand the implications of both the conversion and the ongoing intensive management practices on the net GHG budget of NZ's agriculture, since the agricultural sector accounts for 49

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* Corresponding author.
E-mail address: laubachj@landcareresearch.co.nz (J. Laubach).

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% of the country's gross GHG emissions (MfE, 2016). Here, we determine the GHG budget of an irrigated pasture for three successive years, as well as that from an adjacent kale winter-forage crop for one year, following the conversion of this site from marginal dryland pasture.

It is well-established that managed grasslands generally remove more carbon dioxide (CO_2) from the atmosphere, via photosynthesis, than they return to it via respiration processes (Gilmanov et al., 2010; Rutledge et al., 2015; Jones et al., 2016), i.e. their net ecosystem exchange (NEE) is negative (following the meteorological sign convention). However, this does not necessarily imply that these ecosystems accumulate carbon (C), since large fractions of their biomass are often removed from the system on a continuous or periodic basis, primarily to serve as feed for animals. The removed biomass is not stored long-term but subjected to processes that ultimately return its C content to the atmosphere (digestion, decomposition, burning). Hence, only the C that actually remains in the ecosystem constitutes a reduction of greenhouse-gas (GHG) warming of the atmosphere. In other words, an ecosystem provides a net cooling effect if its net ecosystem carbon budget (NECB) is positive. Interestingly, positive NECB have frequently been found in managed grasslands (Byrne et al., 2007; Zeeman et al., 2010; Rutledge et al., 2015; Fornara et al., 2016), and experiments comparing different treatments have found that intensive management leads to greater C gains than extensive practices (Ammann et al., 2007, 2009; Oates and Jackson, 2014; Fornara et al., 2016). This finding, if generally true, would suggest that intensification of agricultural grassland use could potentially offer a rare win–win situation, where increased food production would be accompanied by desirable environmental effects.

However, the cooling effect associated with a positive NECB is reduced or reversed if the ecosystem is a net emitter of CH_4 and N_2O. Hence, to quantify the net GHG effects of agricultural management practices, it is essential to determine NECB and the exchanges of these two gases simultaneously (see references in the first paragraph). It can be expected that these are also influenced by management, particularly so for N_2O emissions (Flechard et al., 2007; Ammann et al., 2009; Burchill et al., 2014). These depend on nitrogen (N) availability, which is increased with N input from fertiliser and excreta, and on soil gas diffusivity (Balaine et al., 2016), which varies with soil water content and is thus modified by irrigation.

To determine NECB, we apply the detailed methodology described and tested in Hunt et al. (2016). To obtain continuous fluxes of CH_4 and N_2O, we employ a combination of two micrometeorological methods, developed and assessed by Laubach et al. (2016). In Section 2 we give a condensed description of site and methods which draws largely from these two publications. In Section 3, we combine results and discussion when we separately present the CO_2 budgets, C budgets, CH_4 exchanges and N_2O exchanges. We then put these together to net GHG budgets of the pasture and winter-forage crop ecosystems. Our approach is to construct these budgets without the grazing cows (see Section 2.3); therefore, the reported measurements of CH_4 exchange do not include the enteric emissions. Where it is necessary to attribute these emissions back to the ecosystem, we calculate them from the cows' feed intake (Section 3.7). We compare our results, specifically for N_2O emissions and the net GHG budget, to predictions that would be obtained with the methods of NZ's GHG inventory.

2. Site and methods

2.1. Farm description

2.1.1. Location

The measurement sites were located on a commercial dairy farm on the Canterbury Plains in the central South Island of New Zealand (Lat −43° 35′ 30.6″, Lon 171° 55′ 36.6″; 204 m a.s.l.). The area is flat, sloping 7 m km^{-1} to the west. The climate is temperate-maritime. Total precipitation increases from the Pacific coast in the east to the Southern Alps in the west, but summers tend to be relatively dry across the whole region, which is why most of the land has traditionally been used for extensive sheep and beef grazing. Conversions to irrigated dairying similar to our study farm have been widespread over the last decade, significantly boosting pasture production and thus increasing the stock-carrying capacity.

The soil is a Lismore silty loam (Hewitt, 2010), corresponding to Typic Dystrustepts in the SSDS (1993) classification. It is moderately stony (12 % in top 100 mm, with stone content increasing with depth). In April 2013 (during our first sampling year) the top 100 mm had a C content per surface area of 2.48 kg m^{-2} (the units were erroneously reported as "kg m^{-3}" in Hunt et al., 2016) and a C/N ratio of 10.75.

2.1.2. Animal management

The farm operates with about 900 dairy cows (Friesian-Jersey crossbreds), managed in some years as two and in others as three separate herds. The farm's milk production is of order 4 ML yr^{-1}. The milking season extends from mid- or late September to late May. Throughout the season, the cows graze outdoors, except when being milked (twice daily). While at the milking shed, the cows are usually offered feed supplements. During winter (June–August), a large fraction of the cows are off the farm; the remaining ones are fed on dedicated winter-forage areas (some consisting of grass, others of kale) and imported feeds.

2.1.3. Irrigated pasture

The farm covers a total area of 382 ha, of which 263 ha are regularly irrigated from spring (Oct or Nov) to autumn (Mar or Apr). The irrigated area is circular (Fig. 1) and the central-pivot irrigator rotates with a return period of 2–3 d. The irrigated-pasture vegetation consists mainly of ryegrass (*Lolium perenne* L.) with a minor fraction (< 5 %) of white clover (*Trifolium repens* L.). The circular pasture area is subdivided with permanent radial fences into segments which are rotationally grazed; for this, the farm managers subdivide the segments further with temporary fences, typically into paddocks of 3–6 ha. In any given location, grazing occurs about 10 times annually. Each grazing lasts between 1 and 2.5 d, at an animal density of order 100 head ha^{-1},

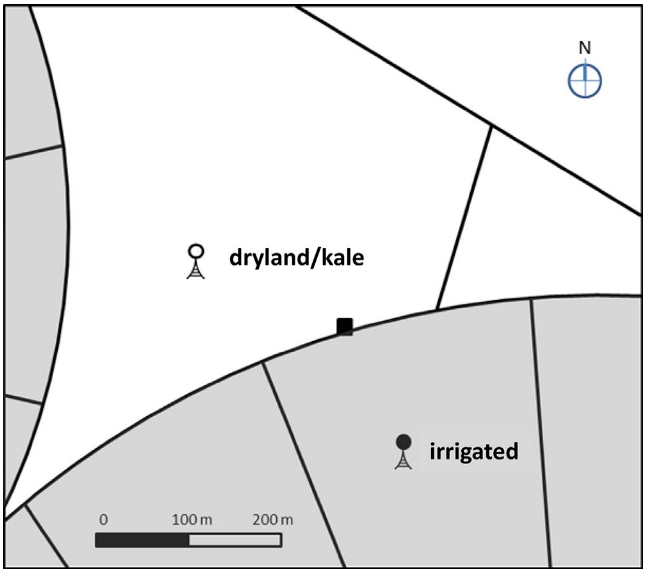

Fig. 1. Schematic of the study location (adapted from Laubach et al., 2016). The shaded areas represent parts of pivot-irrigated intensively-managed circles of dairy pasture. The white areas are not irrigated. At the two locations indicated with tower symbols, CO_2 fluxes were measured by eddy covariance, and air was sampled from two heights for multi-gas mole-fraction measurements with an FTIR spectrometer. The spectrometer was located in a temperature-controlled hut, indicated with a black square. In Year 2, the dryland pasture was converted to a kale crop used for winter forage.