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Managed grasslands: A greenhouse gas sink or source?

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[1] We describe a unique, one year investigation of CO_2 and N_2O fluxes over a fertilized grassland in Ireland using two eddy covariance systems. As the global warming potential (GWP) of N_2O is 296 (100 year time horizon), relatively small N_2O emissions have a potentially large impact on overall radiative forcing. Therefore nitrogen fertilizer application practices may possibly turn a site with a net CO_2 uptake into a net radiative forcing source. We observed a net annual uptake of 9.45 T CO_2 ha^{-1}. N_2O emissions equivalent to 5.42 T ha^{-1} CO_2 GWP counteracted 57% of the effect of the CO_2 uptake. Estimated methane emissions from ruminants (3.74 T ha^{-1} CO_2 GWP) further counteract the CO_2 uptake, making the overall GWP nearly neutral. This delicate balance of the greenhouse gas fluxes underscores the significance of fertilizer application strategies in determining whether a managed grassland is a net GWP source or sink. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1803 Hydrology: Anthropogenic effects; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Leahy, P., G. Kiely, and T. M. Scanlon (2004), Managed grasslands: A greenhouse gas sink or source?, *Geophys. Res. Lett.*, *31*, L20507, doi:10.1029/2004GL021161.

1. Introduction

[2] Rising concentrations of greenhouse gases (GHGs) such as CO_2, N_2O and CH_4 in the atmosphere are contributing to climate change through increased radiative forcing [*IPCC*, 2001]. Finding economical GHG mitigation strategies is a strong motivation for studying the effects of grassland management on GHG fluxes [*Groffman et al.*, 2000] and this issue is of global and regional significance since temperate grasslands represent a considerable fraction of the earth's land area (c. 8% [*Bouwman*, 1990]) and approximately 45% of the area of Ireland [*Gardiner and Radford*, 1980]. We have measured the fluxes of CO_2 and N_2O at a managed grassland site for a year with the aim of quantifying the contribution of N_2O emissions to the overall global warming potential (GWP).

[3] Studies to date have shown that grasslands may act as either sources or sinks of CO_2 [*Gilmanov et al.*, 2003; *Novick et al.*, 2004; *Xu and Baldocchi*, 2004]. Grasslands absorb CO_2 through photosynthesis and release CO_2 by respiration, which can be divided into autotrophic and heterotrophic components. Photosynthesis is controlled by factors such as photosynthetically active radiation, temperature, soil moisture availability and leaf area index. Autotrophic respiration is related to the rate of photosynthetic production. Heterotrophic respiration is influenced by soil temperature and moisture [*Novick et al.*, 2004].

[4] N_2O fluxes, although less widely measured, may be an important contributor to overall radiative forcing from managed grasslands. An initial estimate suggests that this may indeed be the case: an intensively managed grassland may receive fertilization in the range of 300 to 600 kg N ha^{-1} per year. Applying a typical emission factor of 2.2% [*Dobbie et al.*, 1999] leads to an emission of 6.6 to 13.2 kg N_2O-N ha^{-1}. Since the radiative forcing effect of N_2O is 296 times greater than that of CO_2 on a per unit mass basis over a 100-year time horizon [*IPCC*, 2001], this is equivalent to a CO_2 emission in the range of 3 to 6 T ha^{-1}. Therefore, relatively small emissions of N_2O can exert a strong influence on the total radiative forcing budget of an ecosystem.

[5] N_2O is emitted from soils as a result of denitrification and also, to a lesser extent, by nitrification [*Trogler*, 1999]. These bacterial processes are regulated by temperature, soil pH, soil moisture and the availability of N in the soil [*Maag and Vinther*, 1996]. Denitrification tends to occur in bursts under anaerobic conditions, when nitrates and nitrites are the predominant oxidizing agents available to denitrifiers. Denitrification is inhibited by dry conditions and/or soil temperatures below 5°C. Nitrification is limited by the availability of organic C substrate in the soil and by temperatures below 10°C [*Whitehead*, 1995]. Application of liquid animal waste and chemical fertilizers such as ammonium nitrate increases the supply of reactants for these processes.

[6] There are few long-term studies of grassland N_2O emissions and most of these are based upon chamber measurements [e.g., *Dobbie et al.*, 1999; *Williams et al.*, 1999]. However, with the advent of tunable diode laser (TDL) trace gas analyzer systems [*Edwards et al.*, 2003], eddy covariance (EC) measurements of N_2O fluxes have become possible [*Laville et al.*, 1999]. The EC technique allows the flux to be continuously measured at the landscape scale, ideal for an ecosystem GHG flux comparison study, where the large temporal and spatial fluctuations of soil N_2O emissions [*Smith and Dobbie*, 2001; *Scanlon and Kiely*, 2003] can be integrated to provide annual flux totals.

[7] We calculate the contribution to radiative forcing from each gas over the year and the combined radiative forcing budget for the ecosystem. We also estimate the effect on overall GWP of reducing N applications to the soil. Emissions of CH_4 from cattle grazed on or fed from the site are estimated and their impact on the overall ecosystem GWP is discussed. We limit our discussion to CO_2 fluxes arising directly from the site – sources such as

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Table 1. Seasonal Totals of N Applications, CO_2 and N_2O Emissions and Combined GWP

Season	N Application, kg ha^{-1}	CO_2, T ha^{-1}	N_2O, kg ha^{-1}	Overall GWP, T CO_2 equiv. ha^{-1}
Spring (Feb–Apr)	188.3	−5.18	3.92	−4.02
Summer (May–Jul)	90.5	−6.03	10.84	−2.82
Autumn (Aug–Oct)	66.8	−1.44	2.50	−7.00
Winter (Nov–Jan)[a]	0	3.20	1.06	3.51
Total	346	−9.45	18.32	−4.03

[a]Winter values are the total values for the months January, November and December 2003.

respiration from animals fed offsite from grass harvested within the site are not addressed.

2. Site

[8] The measurement site is a managed, intensively grazed grassland in Co. Cork in southern Ireland (Latitude: 52.14°N, Longitude: 8.66°W). The site has an average elevation of 180 m above sea level. The climate is temperate maritime and typical average rainfall for the site is 1470 mm year^{-1}. The year 2003 was drier than normal, with a total rainfall of 1210 mm. January and July average daytime air temperatures in 2003 were 5.5°C and 14.3°C respectively. The dominant soil types are peaty podzols and brown podzolics. Most of the site is well drained with a small area (~10% of the footprint) prone to seasonal waterlogging. The flux footprint was estimated based on a fetch to sensor height ratio of 100:1 combined with the probability density distribution of the wind direction.

[9] The footprint area is partitioned into 19 small fields and paddocks to facilitate rotation of grazing cattle. Management practices are broadly similar across the whole footprint but the timing of fertilizer applications and grass cuttings varies. The dominant grass species is perennial ryegrass (*Lolium perenne*).

3. Methods

[10] Two EC systems were used for GHG flux measurements. The first consisted of a closed path TDL trace gas analyzer (Campbell Scientific, USA) to measure N_2O concentrations and a 3-D sonic anemometer (CSAT-3, Campbell Scientific, USA) to measure wind speeds. In the second system CO_2 and H_2O concentrations were measured with an open path infrared gas analyzer (LI-7500, Li-Cor, USA) and the wind speed was measured with a 3-D sonic anemometer (Model 81000, R. M. Young, USA). All concentrations and wind speeds were logged at 10 Hz and flux values were calculated at 30-minute intervals. The CO_2/H_2O sensor was mounted 10 m above ground level and the N_2O sensor intake was mounted 6 m above ground. Although the CO_2 footprint was larger than the N_2O footprint, the homogeneity of the landscape and the similarity of management practices across the entire site ensures that comparisons between the two are valid.

[11] The CO_2/H_2O analyzer was factory calibrated and subsequently regularly user calibrated according to the manufacturer's instructions. The N_2O TGA uses a reference gas cell to maintain its calibration in situ. The wind speeds from the CO_2 sonic anemometer were double rotated such that the mean vertical wind speed was set to zero. CO_2 fluxes were Webb corrected. The angular offset of the N_2O anemometer was negligible, therefore co-ordinate rotation was not necessary in this case. The time lag due to the distance traveled by the air samples to the N_2O analyzer was determined by calculating the peak correlation between vertical wind speeds and N_2O concentrations [*Laville et al.*, 1999]. We use the standard micrometeorological convention in which fluxes out of the ground are positive.

[12] In periods of high atmospheric stability there is a lack of turbulent mixing near the surface and EC does not always yield reliable results. Nocturnal fluxes corresponding to frictional velocities less than 0.2 m s^{-1} were excluded and replaced by an exponential function of the soil temperature. A function of the photosynthetic photon flux density was used to replace missing daytime CO_2 fluxes. The CO_2 flux gap filling techniques are discussed in detail by *Jaksic* [2004].

[13] A stationarity test based on that of *Foken and Wichura* [1996] was used to filter spurious N_2O flux values. The mean vertical wind velocity was calculated for two 15-minute subintervals of each 30-minute averaging period. If the two means differed by more than 0.1 m s^{-1} the value was discarded. Fluxes were averaged on a daily basis. If less than 12 half-hour values were available for a given day a moving average of fluxes from adjacent days was used to replace the value for that day. There were two gaps longer than 5 days, which occurred during periods of low soil water filled pore space (WFPS) and thus were unlikely to be coincident with emission pulses. Gaps amounted to 21% of the total number of data points.

[14] Applications of slurry and fertilizer to the site and grass cutting and grazing were recorded on a monthly basis. Commercially-prepared mineral fertilizer mixtures were used, consisting of almost equal parts NH_4^+-N and NO_3^-- N. Soil moisture was continuously measured between 0 cm and 30 cm depth within a 25 m^2 area close to the flux tower using time domain reflectometry probes (CS615, Campbell Scientific, USA). Soil temperatures were continuously measured at a depth of 75 mm near the flux tower using a thermistor probe (CS107, Campbell Scientific, USA).

4. Results

[15] Most of the CO_2 uptake occurs in the spring and early summer (Table 1 and Figure 1). Between March and June there is a net CO_2 uptake of 10.60 T ha^{-1}. The rate of uptake decreases abruptly at the end of June and it remains at this rate between the months of July and September (Figure 2), resulting in a net uptake of 2.20 T CO_2 ha^{-1} for this period. The reduced uptake rate follows a loss of standing biomass due to harvesting of grass and increased grazing from late June onwards. For the remainder of the year there is a net emission of CO_2 to the atmosphere. For the full year the net uptake was 9.45 T CO_2 ha^{-1}.

[16] The bulk of the N_2O emission occurs in summer (Table 1), and 55% of the annual total occurs during the two months of June and July. N_2O emission pulses can be seen following heavy rainfall in the spring and summer (Figure 1). *Dobbie et al.* [1999] observed that soil WFPS is a controlling factor for N_2O emissions and we found that 57% of the total flux occurred while estimated WFPS was within the range 65% to 75%, or just 34% of the dataset.

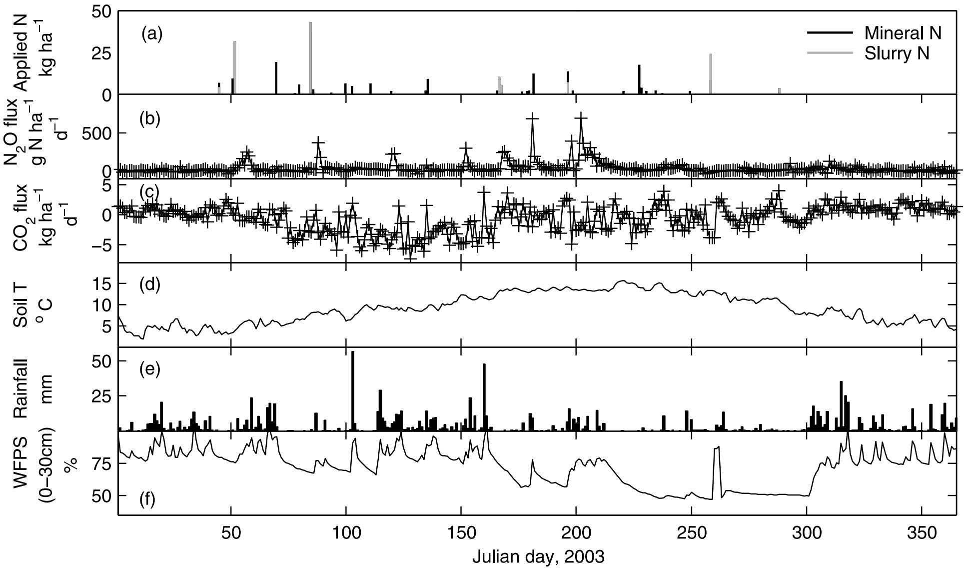

Figure 1. (a) Mineral fertilizer and slurry nitrogen applications, (b) daily N_2O flux, (c) daily CO_2 flux, (d) soil temperature, (e) daily precipitation, (f) WFPS (0–30 cm).

[17] When the CO_2 and N_2O fluxes are combined in terms of their relative GWPs (CO_2 = 1, N_2O = 296) it can be seen from the time history of cumulative GWP (Figure 2) that a GWP-negative process (carbon fixation by photosynthesis) strongly dominates during the March–June growing season. For the remainder of the year, GWP-positive phenomena such as respiration and soil N_2O emissions are dominant.

5. Discussion and Conclusions

[18] The cumulative annual emission of 11.6 kg N_2O-N ha^{-1} was equivalent to 3.4% of the applied N. This includes non-anthropogenic N_2O emissions but these are likely to be a small proportion of the total. The estimate of 0.5 kg N ha^{-1} year^{-1} background N_2O emission given by *Bouwman et al.* [1995] would only account for 4% of the observed N_2O flux in this case. The emission factor we observed is higher than the IPCC guideline factor of 1.25 ± 1.0% [*Houghton et al.*, 1997]. An analysis of emissions from several grassland sites in Scotland over several years [*Dobbie et al.*, 1999] found emission factors between 0.2% and 5.8%, with an average annual emission factor across all seasons and sites of 2.2%. N_2O emissions lag the applications of nitrogen in time. It can be seen from Figure 3 and Table 1 that the bulk of N applications are made in the spring period while most of the N_2O emission takes place in the summer season when soil temperatures are higher.

[19] Emissions of methane from grazing cattle may also have an impact on the overall site GWP. CH_4 fluxes were not measured but we present an estimate based on national average figures. The average site grazing density is 2.2 cattle ha^{-1}. A mix of 50% dairy and 50% non-dairy cattle is assumed, giving an average emission of 74 kg CH_4 head^{-1} year^{-1} [*Houghton et al.*, 1997]. As the GWP for CH_4 is 23 (100 year time horizon, *IPCC* [2001]) we estimate the CH_4 emission equivalent to be approximately 3.74 T CO_2 ha^{-1} year^{-1}. This estimate, when added to the

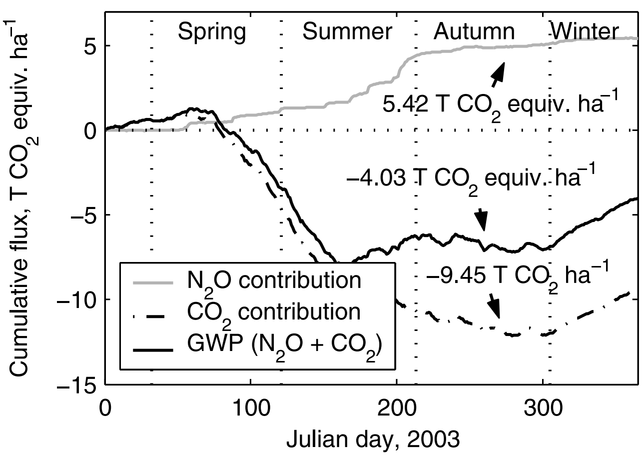

Figure 2. Cumulative N_2O and CO_2 fluxes and combined net GWP for 2003 in CO_2 equivalents (N_2O time horizon = 100 year).

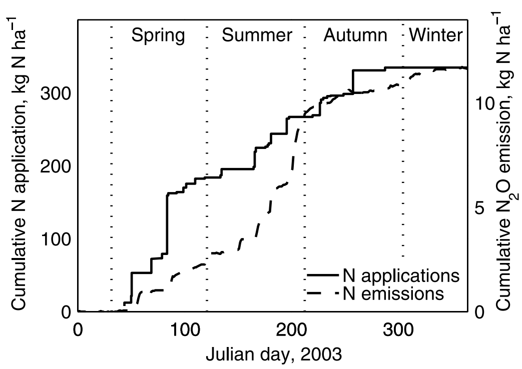

Figure 3. Cumulative nitrogen applications and N_2O emissions, 2003.

GWP for the N_2O emissions almost completely counteracts the GWP of the CO_2 uptake.

[20] Implementation of the EU nitrates directive [*CEC*, 1991], currently under way, will reduce the amount of mineral N fertilizers applied to sites such as this one. The aim of the directive is to improve water quality, but a reduction in atmospheric N_2O emissions is a likely side effect. Predicting the size of this reduction is difficult as the relationship between the magnitude of N applications and the overall GHG budget is complicated by the fact that the reduced fertilization may decrease CO_2 uptake through decreased productivity while simultaneously decreasing N_2O emissions. The results of *Murphy and O'Donnell* [1989] suggest that a 50% reduction in N applications from the current level at our site of 345 kg ha^{-1} $year^{-1}$ will lead to a reduction of 20% in dry matter production. Assuming the CO_2 uptake decreases linearly with dry matter production and applying the observed 3.4% emission factor to the reduced N application results in the combined (CO_2 + N_2O) GWP becoming more negative by 32%. In such a scenario, CH_4 emissions from ruminants will also decrease (as lower dry matter production will force less intensive grazing and harvesting for feed). However, optimizing the timing of fertilizer applications may be sufficient to reduce overall GWP without having a severe impact on cattle yields.

[21] In order to meet the GHG reduction targets set by the Kyoto Protocol, future grassland management schemes may have to take the adverse effects of high nitrogen fertilization into account in order to reduce contributions to global warming, particularly in humid climates. These findings suggest the need for policymakers to consider incentives for reducing or optimizing the use of nitrogen fertilizers.

[22] We conclude that CO_2 exchange alone is not sufficient for the estimation of the GWP of a managed grassland ecosystem. In this study, 57% of a net CO_2 uptake of 9.45 T ha^{-1} was counteracted by N_2O emissions equivalent to 5.42 T CO_2 ha^{-1}. Estimated CH_4 emissions equivalent to 3.74 T CO_2 ha^{-1} counteracted a further 40% of the CO_2 uptake. Therefore, overall radiative forcing is sensitive to management practices, with CH_4 release governed by the density of the cattle herd, and fertilizer-derived N_2O emission playing a key role in determining the balance as to whether this grassland is a GWP source or sink.

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