Managed grasslands: A greenhouse gas sink or source?

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[1] We describe a unique, one year investigation of CO2 and N2O fluxes over a fertilized grassland in Ireland using two eddy covariance systems. As the global warming potential (GWP) of N2O is 296 (100 year time horizon), relatively small N2O emissions have a potentially large impact on overall radiative forcing. Therefore nitrogen fertilizer application practices may possibly turn a site with a net CO2 uptake into a net radiative forcing source. We observed a net annual uptake of 9.45 T CO2 ha\(^{-1}\). N2O emissions equivalent to 5.42 T ha\(^{-1}\) CO2 GWP counteracted 57% of the effect of the CO2 uptake. Estimated methane emissions from ruminants (3.74 T ha\(^{-1}\) CO2 GWP) further counteract the CO2 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 CO2, N2O and CH4 in the atmosphere are contributing to climate change through increased radiative forcing [IPCC, 2001]. Finding economical GHG mitigation strategies for 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 CO2 and N2O at a managed grassland site for a year with the aim of quantifying the contribution of N2O emissions to the overall global warming potential (GWP).

[3] Studies to date have shown that grasslands may act as either sources or sinks of CO2 [Gilmanov et al., 2003; Novick et al., 2004; Xu and Baldocchi, 2004]. Grasslands absorb CO2 through photosynthesis and release CO2 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] N2O 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 N2O-N ha\(^{-1}\) per year. Since the radiative forcing effect of N2O is 296 times greater than that of CO2 on a per unit mass basis over a 100-year time horizon [IPCC, 2001], this is equivalent to a CO2 emission in the range of 3 to 6 T ha\(^{-1}\). Therefore, relatively small emissions of N2O can exert a strong influence on the total radiative forcing budget of an ecosystem.

[5] N2O 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 nitrites and nitrates 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 N2O 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 N2O fluxes have become possible [Liville 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 N2O 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 CH4 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 CO2 fluxes arising directly from the site — sources such as...
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
summer 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 measure-
ments. The first consisted of a closed path TDL trace
gas analyzer (Campbell Scientific, USA) to measure N₂O
concentrations and a 3-D sonic anemometer (CSAT-3,
Campbell Scientific, USA) to measure wind speeds. In the
second system CO₂ and H₂O 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
CO₂/H₂O sensor was mounted 10 m above ground level
and the N₂O sensor intake was mounted 6 m above ground.
Although the CO₂ footprint was larger than the N₂O
footprint, the homogeneity of the landscape and the simi-
liarity of management practices across the entire site ensures
that comparisons between the two are valid.

[11] The CO₂/H₂O analyzer was factory calibrated and
subsequently regularly user calibrated according to the
manufacturer’s instructions. The N₂O TGA uses a reference
gas cell to maintain its calibration in situ. The wind speeds
from the CO₂ sonic anemometer were double rotated such
that the mean vertical wind speed was set to zero. CO₂
fluxes were Webb corrected. The angular offset of the N₂O
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 N₂O analyzer was
determined by calculating the peak correlation between
vertical wind speeds and N₂O 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
fractional 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 CO₂ fluxes. The CO₂ 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 N₂O 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] Measurements of slurry and fertilizer to the site and
glass cutting and grazing were recorded on a monthly
basis. Commercially-prepared mineral fertilizer mixtures
were used, consisting of almost equal parts NH₄-N and
NO₃-N. Soil moisture was continuously measured between
0 cm and 30 cm depth within a 25 m² area close to the flux
tower using time domain reflectometry probes (CS615,
Campbell Scientific, USA). Soil temperatures were continu-
ously 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 CO₂ uptake occurs in the spring and
early summer (Table 1 and Figure 1). Between March and
June there is a net CO₂ 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 CO₂ 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 CO₂ to the atmosphere. For
the full year the net uptake was 9.45 T CO₂ ha⁻¹.

[16] The bulk of the N₂O emission occurs in summer
(Table 1), and 55% of the annual total occurs during the two
months of June and July. N₂O 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 N₂O 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.

Table 1. Seasonal Totals of N Applications, CO₂ and N₂O
Emissions and Combined GWP

<table>
<thead>
<tr>
<th>Season</th>
<th>N Application, kg ha⁻¹</th>
<th>CO₂, T ha⁻¹</th>
<th>N₂O, kg ha⁻¹</th>
<th>Overall GWP, T CO₂ equiv. ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring (Feb–Apr)</td>
<td>188.3</td>
<td>-5.18</td>
<td>3.92</td>
<td>-4.02</td>
</tr>
<tr>
<td>Summer (May–Jul)</td>
<td>90.5</td>
<td>-6.03</td>
<td>10.84</td>
<td>-2.82</td>
</tr>
<tr>
<td>Autumn (Aug–Oct)</td>
<td>66.8</td>
<td>-1.44</td>
<td>2.50</td>
<td>-7.00</td>
</tr>
<tr>
<td>Winter (Nov–Jan)</td>
<td>0</td>
<td>3.20</td>
<td>1.06</td>
<td>3.51</td>
</tr>
<tr>
<td>Total</td>
<td>346</td>
<td>-9.45</td>
<td>18.32</td>
<td>-4.03</td>
</tr>
</tbody>
</table>

*Winter values are the total values for the months January, November and
December 2003.
When the CO₂ and N₂O fluxes are combined in terms of their relative GWPs (CO₂ = 1, N₂O = 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 N₂O emissions are dominant.

5. Discussion and Conclusions

The cumulative annual emission of 11.6 kg N₂O-N ha⁻¹ was equivalent to 3.4% of the applied N. This includes non-anthropogenic N₂O 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 N₂O emission given by Bouwman et al. [1995] would only account for 4% of the observed N₂O 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%. N₂O 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 N₂O emission takes place in the summer season when soil temperatures are higher.

Emissions of methane from grazing cattle may also have an impact on the overall site GWP. CH₄ 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 CH₄ head⁻¹ year⁻¹ [Houghton et al., 1997]. As the GWP for CH₄ is 23 (100 year time horizon, IPCC [2001]) we estimate the CH₄ emission equivalent to be approximately 3.74 T CO₂ ha⁻¹ year⁻¹. This estimate, when added to the...
GWP for the N\textsubscript{2}O emissions almost completely counteracts the GWP of the CO\textsubscript{2} uptake.

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\textsubscript{2}O 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\textsubscript{2} uptake through decreased productivity while simultaneously decreasing N\textsubscript{2}O 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\textsuperscript{-1} year\textsuperscript{-1} will lead to a reduction of 20% in dry matter production. Assuming the CO\textsubscript{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\textsubscript{2} + N\textsubscript{2}O) GWP becoming more negative by 32%. In such a scenario, CH\textsubscript{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.

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.

We conclude that CO\textsubscript{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\textsubscript{2} uptake of 9.45 T ha\textsuperscript{-1} was counteracted by N\textsubscript{2}O emissions equivalent to 5.42 T CO\textsubscript{2} ha\textsuperscript{-1}. Estimated CH\textsubscript{4} emissions equivalent to 3.74 T CO\textsubscript{2} ha\textsuperscript{-1} counteracted a further 40% of the CO\textsubscript{2} uptake. Therefore, overall radiative forcing is sensitive to management practices, with CH\textsubscript{4} release governed by the density of the cattle herd, and fertilizer-derived N\textsubscript{2}O emission playing a key role in determining the balance as to whether this grassland is a GWP source or sink.

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References


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