Agriculture, Ecosystems and Environment 156 (2012) 49–56

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

The effect of introducing a winter forage rotation on CO_2 fluxes at a temperate grassland

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ARTICLE INFO

Article history:
Received 16 February 2011
Received in revised form 16 April 2012
Accepted 7 May 2012

Keywords:
Net ecosystem exchange
Land use
Kale
Eddy covariance
Ireland

ABSTRACT

Temperate grasslands have the potential to sequester carbon, helping to mitigate rising atmospheric CO_2 concentrations. The ability of grasslands to absorb CO_2 is influenced by site elevation, soil type, management practices, climate and climatic variability. There is a need for long-term observations and field experiments to quantify the effects of the key drivers of management and climate variability. This paper presents over 4 years of eddy covariance measurements of CO_2 flux over a managed temperate grassland site in south-east Ireland. For the first 2 years the entire study area was under grass. During the second 2 years a winter forage crop was grown over part of the site. The site was found to have a net uptake of CO_2 during all years. However, the magnitude of the CO_2 uptake varied considerably from year to year, with a maximum net uptake of 1.32 kg CO_2 m^{-2} in 2004, a year with no winter forage crop. Net uptakes were much lower in the 2 years of mixed grass and kale cultivation, but detailed analysis of the measurement footprint and statistical comparisons showed that this was not due to the introduction of the forage rotation. For a short period following sowing of the forage crop, daytime CO_2 uptake was less than that of the area under grass, but over subsequent months daytime CO_2 uptake of the kale areas recovered strongly and exceeded that of the grass areas. The net effect over the year following kale planting is close to CO_2-neutral.

1. Introduction

Grasslands cover 23% of the planet's land area, with the temperate grassland and shrubland biome representing approximately a third of this (Lal, 2004). Janzen (2004) estimated that approximately 9% of world net primary production occurs in temperate grasslands and shrublands, and that these areas contain 15% of the global soil organic carbon pool. Within Ireland, grassland is the principal land cover, occupying some 57% of the country's land area (Eaton et al., 2008).

Some established grasslands are believed to have a net uptake of atmospheric CO_2 at annual timescales (Byrne et al., 2007; Jacobs et al., 2007), but temperate, managed grasslands tend to have a net emission of CO_2 over the winter months (Jaksič et al., 2006; Skinner, 2007). A growing body of evidence suggests that long-term carbon sequestration in grassland is largely controlled by management practices (Soussana et al., 2004; Ammann et al., 2007; Skinner, 2008; Wohlfahrt et al., 2008). It follows that it should be possible to increase the rate of sequestration by optimising the site management. Lal (2004) estimated that the annual potential for carbon (C) sequestration in the world's pastures is almost a quarter of the combined annual C addition to the atmosphere due to fossil fuel burning, cement production and land use change.

CO_2 fluxes in pasture systems are influenced by management activities and by local climatic variability and it is often difficult to deconvolve these two influences in uncontrolled field observations. This is further complicated by the differing long-period variability and lagged responses to environmental factors of the different components of the CO_2 flux, namely plant respiration, soil respiration and photosynthesis (Stoy et al., 2009). In a controlled experiment on an annual Mediterranean grassland, Chou et al. (2008) observed increases in soil CO_2 efflux following artificial wetting events and suggested that the seasonal distribution of rainfall has an important influence on ecosystem CO_2 fluxes on the annual timescale. Lohila et al. (2004) examined the effects of a spring barley rotation on CO_2 exchange from a grassland on an improved peat soil in southern Finland and found a reduction in CO_2 uptake during the period of barley cultivation when compared to grass cultivation. Heavy biomass removal from a mature, temperate, North American grassland was found to render it a net C source, despite a small annual CO_2 uptake (Skinner, 2008), whereas a similar, single-year study found a partially grazed, partially harvested grassland in southern Ireland to be a small net C sink (Byrne et al., 2007).

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http://dx.doi.org/10.1016/j.agee.2012.05.001

In northwest European temperate grasslands such as those in Ireland, dairy cattle are usually housed indoors and fed on grass or cereal silages with concentrate supplements over the low productivity winter period (Hennessy et al., 2006). The practice of outdoor winter feeding on forage crop rotations, such as cereals or brassicas, has demonstrated agronomic benefits such as higher dry matter yield and improved animal body condition compared to purely grass-based winter feeding systems (Keogh et al., 2009). Despite these advantages grass silage with supplements remains the typical source of winter cattle feed in Ireland, and there have been few studies of how winter forage rotations on grasslands affect the CO_2 fluxes between such ecosystems and the atmosphere. There is evidence from a long-term experiment in Belgium that some functions of the soil biota may be lower in ley-arable rotations than in permanent grasslands (van Eekeren et al., 2008), which leads to concern that there may be a loss of soil organic carbon in such systems due to repeated soil disturbance.

The eddy covariance (EC) technique has become well-established as a method of measuring surface–atmosphere fluxes of energy and trace gases, with several sites now observing continuously for 5 years or longer (Jacobs et al., 2007; Wohlfahrt et al., 2008; Haslwanter et al., 2009). The technique is suitable for measuring fluxes in the area adjacent to the sensor, but extended networks of flux observation sites together with satellite remote sensing have helped to address the issue of quantifying CO_2 exchange at the continental scale (Xiao et al., 2008). For comparison of fluxes from different treatments, a moveable EC tower or ideally a system of paired towers may be used (Davis et al., 2010). However, in this study we use a single EC tower combined with footprint analysis to separate fluxes originating from different areas.

The aim of this article is to examine whether a winter forage crop rotation at a temperate grassland increases or decreases the net annual CO_2 uptake of the site, and to compare the difference, if any, to the always-present, climate-driven interannual variability, in the context of a long-term CO_2 flux monitoring campaign. A multi-year series of eddy covariance observations of net ecosystem exchange (NEE) of CO_2 at a managed agricultural site is used to address these aims. Flux look-up tables based on environmental factors and analysis of the eddy covariance footprint will be used to facilitate comparison between the areas under winter forage and under grass.

2. Methods

2.1. Site

The study site is at Johnstown Castle Estate, Co. Wexford, Ireland (52°18′N; 6°30′W). The measurement area is a flat grassland (predominantly *Lolium perenne*) divided by wire fences into paddocks (Fig. 1). Brown earth is the dominant soil type within the measurement area, with a mean organic carbon content of 3.9% in the top 10 cm. A lightly-used road lies approximately 200 m west of the tower behind a stone wall of 1 m height. The prevailing wind blows from the south-west.

Paddocks under grass were either (a) used for grazing throughout the season on 3–4 week rotation or (b) harvested once in late May or early June and used for grazing on 3–4 week rotation for the rest of the grazing season, or (c) cut twice, once in late May or early June, once in late July or early August and grazed late in the season. The grazing season typically runs from mid-February to late November.

Most of the paddocks were grazed in 2004, with N inputs of approximately 240 kg ha^{-1}, half of this applied as urea early in the growing season, and half as compound ammonium nitrate (CAN) in three applications between June and August. All paddocks were used for silage in 2005, with a total N application of 280 kg ha^{-1} as urea and CAN. Most of the site was used for silage in 2006 again, but a winter forage rotation was introduced to part of the site during this year. After the first grass harvest on June 8th, two paddocks (5 and 6; Fig. 1) were limed and sown with kale (*Brassica oleracea*) for winter forage and subsequently fertilised with 34 kg N ha^{-1} as CAN. The kale was grazed *in situ* between November 2006 and February 2007. In 2006 the non-kale paddocks were used for silage, cut on May 31st and again on August 3rd, and received similar fertiliser applications to the previous year. Grazing did not commence until mid-March in 2007, with paddocks 1 and 2 the first to be grazed. The kale paddocks of 2006 (5 and 6) were ploughed, rotovated, rolled and reseeded with grass in April 2007. After the first grass harvest of 2007, in late May, paddocks 1 and 2 (Fig. 1) were harrowed and then sown with kale to be used for *in situ* grazing over the winter of 2007/2008. The kale plots were fertilised in three applications between June and August 2007 with a total of 136 kg N ha^{-1}. Also in 2007, two grass paddocks for grazing (3 and 4) were tilled to a depth of 30 cm, harrowed and reseeded with grass between August 27th and 29th, having received a total of 205 kg N ha^{-1}. No kale was sown in 2008, and paddocks 1 and 2 were reseeded with grass, and paddocks 1–6 were grazed. The area beyond paddocks 1–7 to a distance of 400 m from the flux tower remained under grassland for the entire duration of the study. The main harvesting and sowing events within the measurement area are summarised in Table 1.

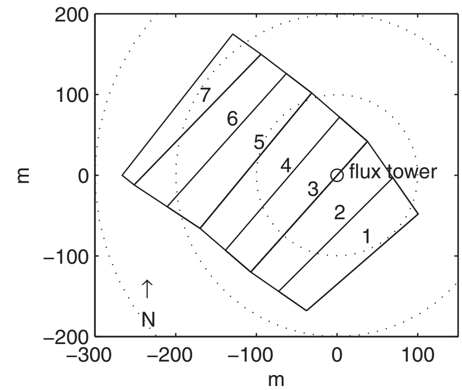

Fig. 1. Site layout showing paddock boundaries and micrometeorological tower location, ringed with dotted circles of radius 100 m, 200 m and 300 m.

2.2. Measurements

Measurements of trace gas fluxes and meteorological quantities were made from January 2004 to September 2008. CO_2 fluxes were measured using the eddy covariance technique. A fast, open-path infrared gas analyser (Li-7500, Li-Cor, USA) and an ultrasonic anemometer (RM81000, R. M. Young, USA) were placed at

Table 1
Dates of cutting and reseeding management events adjacent to the flux tower.

Date	Day of year	Paddock(s)	Event
31/05/2004	152	5, 6, 7	Grass cut
06/06/2005	157	1, 2, 3, 4, 5, 6, 7	Grass cut
01/08/2005	213	1, 2, 3, 4, 5, 6, 7	Grass cut
31/05/2006	151	1, 2, 3, 4, 5, 6, 7	Grass cut
08/06/2006	159	5, 6	Kale sown
03/08/2006	215	1, 2, 3, 4, 7	Grass cut
18/04/2007	108	5, 6	Grass sown
23/05/2007	143	1, 2, 7	Grass cut
05/06/2007	156	1, 2	Kale sown
27/07/2007	208	7	Grass cut
29/08/2007	241	3, 4	Grass resown

2.5 m above the surface in order to measure the CO_2 and water vapour concentrations and the three-dimensional wind speed at 10 Hz frequency. Fluxes were computed at a 30 min interval by a datalogger (CR23X, Campbell Scientific, USA). Measurements of photosynthetically active radiation (PAR; PAR-lite, Kipp & Zonen, The Netherlands), soil temperature, air temperature and relative humidity (HMP45C, Vaisala Inc., Finland), soil moisture (CS615, Campbell Scientific), long and short wavelength incoming and ground-reflected radiation (CNR 100, Kipp & Zonen) and rainfall (ARG 100, Campbell Scientific) were also made at the study site. Paddock boundaries were mapped using GPS surveying. The micrometeorological sign convention is used for fluxes throughout this paper, with a positive flux indicating transfer to the atmosphere from the surface. The site is part of a long-term flux monitoring project on an operational farm, and management was therefore largely outside the control of the flux measurement team. Therefore the layout of the treatments was not optimal for conducting a scientific experiment. Overcoming this limitation necessitated careful data analysis.

2.3. Data analysis and quality control

Raw 10 Hz wind, temperature, H_2O and CO_2 values were pre-filtered by the datalogger to remove extreme values outside the reliable range of the instruments or which were unrealistic in this environment. Horizontal wind (u, v) speed values greater than 25 m s^{-1} were excluded, as were vertical (w) speed values greater than 5 m s^{-1}. Sonic temperature values outside the range [−10, 40] °C; CO_2 concentrations outside [5, 35] μmol m^{-3}; H_2O concentrations outside [50, 1050] mmol m^{-3} were also excluded. If any one sample of a quantity failed one of the above tests, the corresponding samples of all the others were also excluded. In addition, if more than 25% values were excluded from any 30-min interval, the entire interval was treated as a gap.

After pre-filtering, interval means and covariances were calculated using custom routines written in the Matlab programming environment (Mathworks, USA). Flux data were double rotated for yaw and pitch correction (Wilczak et al., 2001). Temperatures and heat fluxes derived from ultrasonic measurements were corrected for non-zero humidity (Massman and Lee, 2002). Measured 30 min gas fluxes were also corrected by the addition of the WPL term (Webb et al., 1980). Processed flux values were subjected to several quality control tests and were discarded if any of the following criteria were met:

- Flux values outside of the expected range for this ecosystem (*e.g.* uptake fluxes at night-time and values outside the prescribed seasonal ranges in Table 2) were ignored.
- Values corresponding to u_* (frictional velocity) value of less than 0.15 m s^{-1}.
- Values where either the yaw or pitch rotation was greater than 0.15 radian.
- Values calculated during intervals where the mean horizontal wind speed was greater than 25 m s^{-1}, the coefficient of variation of CO_2 or water vapour concentration was greater than 20%.
- Values from intervals where the quotient $\langle u'w' \rangle / |\overline{u}|^2$ was greater than 0.25.

Prolonged gaps due to instrumental malfunctions occurred in 2004 (day numbers 231–237 and 270–302), 2005 (days 109–117), 2006 (days 324–336), 2007 (days 247–255) and 2008 (days 192–205).

2.4. Gap filling procedure

Gaps in measured CO_2 fluxes were filled using a look-up table procedure. Each complete year was divided into six periods, with the period boundaries being determined by site management decisions and phenology (Table 2). The first period of each year runs from the start of the year to the beginning of the growing season, usually indicated by a net daily uptake of CO_2. The second period runs from the start of the growing season to the first grass harvest. The third period runs from the first harvest through to the recovery of the ecosystem's leaf area, as indicated by a net daily uptake of CO_2. The fourth period covers the period from leaf recovery to the second harvest. The fifth period runs from the second harvest to the beginning of the autumnal downturn. This is defined as the time when daily NEE turns from negative to positive (due to the reduction in gross primary productivity). The sixth and final period covers the low productivity period from autumn to the end of the year, characterised by net emission fluxes as respiration dominates the NEE.

A two-dimensional look-up table was then derived from measured data within each period. The two independent variables used to derive the look-up tables were soil temperature measured at 5 cm below the surface and above-canopy PAR. The set of available flux measurements were classified into 64 subsets based on eight ranges of PAR and eight ranges of soil temperature. The lowest PAR range was specified to run from zero to 50 μmol quanta m^{-2} s^{-1}, in order to contain all fluxes measured under low-light conditions or at nighttime. The boundaries of the remaining seven PAR bins were set such that each bin accounted for an equal mass of measured CO_2 flux. Soil temperature range boundaries were specified such that each bin contained the same mass of measured nighttime flux.

A look-up table offers several advantages over regression-based gap filling methods (*e.g.* (Novick et al., 2004; Jaksič et al., 2006)): it is purely data-driven and therefore requires no assumptions to be made about the functioning of the ecosystem processes; it obviates the need for separate daytime and nighttime gap filling functions as the PAR bin boundaries can be set to differentiate between daytime and nighttime fluxes; and it can implicitly allow for net daytime respiration, unlike some univariate nonlinear regressions, for example a PAR-saturation curve such as a nonrectangular hyperbola (*e.g.* (Haxeltine and Prentice, 1996)) which can only produce uptake fluxes. The values in the tables corresponding to the lowest PAR range are effectively a nighttime look-up table in a single variable, namely soil temperature. The look-up table is a useful gap filling method when the quantity of interest is fluxes measured over timescales of longer than one day. It has the further advantage of allowing groupwise comparisons between flux measurements from the same PAR, soil temperature bins across different years. The technique has been found to compare well with other gap filling methods over short and long timescales (Moffat et al., 2007).

In this study, the look-up table performed two functions. Firstly, it was used in the usual way to estimate fluxes from the controlling environmental parameters (*e.g.* PAR, T_{soil}) during periods of missing or poor quality flux data. However, gap-filling with a look-up table is not without disadvantages. There is a trade-off between the number of PAR and soil temperature bins chosen and the number of good flux measurements available in each bin to derive the table. Therefore, due to the limited number of bins, the small-scale variation in gap filled flux values within each bin is lost with this method. A further disadvantage is that if fixed boundaries are prescribed for the bins of the independent variables, there is no guarantee that every bin will be populated by good flux measurements, as the independent variables may not be evenly distributed across the bins. This poses the problem of selecting a suitable flux value to assign to these empty bins, should a corresponding gap in the flux record occur. For the purposes of calculating the annual flux totals over the entire measurement area, including both land uses, when a look-up table bin was unpopulated the 5-day average of the flux value for that time of day was used to fill the gap. The reader is referred to

Table 2
(a) Start and end day numbers defining periods for allowable seasonal flux magnitude ranges and for generating gap filling look-up tables for each year; (b) acceptance ranges in μmol m^{-2} s^{-1} for daytime and nighttime CO_2 fluxes in each period.

	Period					
	1	2	3	4	5	6
(a)						
2004	1–75	76–120	121–152	153–210	211–280	281–365
2005	1–100	101–156	157–172	173–213	214–280	281–365
2006	1–100	101–151	152–172	173–215	216–280	281–365
2007	1–100	101–156	157–190	191–240	241–310	311–365
2008	1–90	91–158	159–211	212–246	–	–
(b)						
Day	[−15, 5]	[−25, 10]	[−35, 15]	[−35, 15]	[−25, 10]	[−15, 5]
Night	[0, 7]	[0, 10]	[0, 15]	[0, 15]	[0, 10]	[0, 7]

the studies of Falge et al. (2001), Reichstein et al. (2005) and Moffat et al. (2007) for a full discussion of flux gap filling techniques. The second use of the look-up table was to enable like-for like comparisons of fluxes emanating from the two different land uses within the same soil temperature and PAR bins. In this way, management effects can largely be separated from effects of climatic variability.

2.5. Comparing fluxes of different land uses

The approximate analytical model of Hsieh et al. (2000) was used to estimate the areas contributing to the observed CO_2 flux (Fig. 2). The model produces a vector of cumulative source strength as a function of distance from the sensor. This allows the dominant crop cover associated with each measurement to be determined. For each 30-min flux interval, the footprint model was run and the source strength vector was used in combination with the measured wind direction to calculate the proportion of the flux originating in areas under grass and under kale. The source strength vector was integrated along its intersection with the polygon enclosing the crop type area. If one crop accounted for 66% or more of the flux for a given interval, then that interval was assigned to that particular crop type. Any intervals during which neither crop type was dominant (*i.e.* neither land use area accounting for more than 66% of the source flux) were ignored in subsequent analyses. No attempt was made to account for the effects of inhomogenous surface cover, for example the week when the footprint was partially covered by cut grass and partially bare, immediately after kale sowing in 2007.

This resulted in two time series of data: one for the grassland target area and one for the kale target area. Both series were then binned based on PAR and soil temperature bins as described in Section 2.4, within the time periods specified in Table 2. Flux observations in corresponding PAR, soil temperature bins in the kale and non-kale populations were compared groupwise using the Mann–Whitney *U*-test from the Matlab statistics toolbox (Mathworks, USA). This test was chosen as it does not require the samples under comparison to be normally distributed when sample sizes are small (Devore, 1995). The null hypothesis in each comparison was that the observations in corresponding grass and kale bins were drawn from the same population, and the chosen significance level (P) for rejection was 0.05. The method allows confounding environmental factors (PAR and soil temperature) to be largely discounted and a direct comparison of CO_2 fluxes from areas under grass and kale to be made. The observations in each series were also compared in aggregate, *i.e.* over all bins within a period, in order to determine if the two complete sets of observations differed.

In summary, the approach taken to comparing the flux from the different land use areas was:

(1) Divide the flux time series into sub-annual time periods, as specified in Table 2.
(2) Classify each flux observation based on the instantaneous fetch and wind direction: series G (where grass land cover dominates) and series K (where kale dominates).
(3) Build a look-up table based on PAR and soil temperature (as described above) for each series within each period.
(4) Statistically compare the average fluxes in like-for-like bins of the look-up tables for series G and series K.

An annual flux estimate from each land use type for the year 2007/2008 was also calculated by separately gap filling series G and series K over the entire year. For each individual 30-min flux measurement, the associated uncertainty was estimated by the corresponding standard deviation within the relevant bin in the look-up tables. Uncertainty estimates for the full year were then obtained by combining the 30-min measurement uncertainties in quadrature.

3. Results

The mean ratio of the modelled fetch distance (distance from the sensor incorporating 90% of flux) to sensor height ranged between 273 (2008) and 295 (2006). There was considerable interannual variability in the environmental parameters (PAR, soil temperature, rainfall and soil moisture; Fig. 3) and in monthly CO_2 fluxes (Fig. 4). Summer 2004 was dry, with soil water filled pore space (WFPS) content remaining below 60% for much of May, June and July. Both 2005 and 2006 were characterised by heavy spring and early summer precipitation, with high soil moisture levels persisting until early June of each of the 2 years. After a relatively dry April, the summer of 2007 was extremely wet compared to other years, estimated as the wettest in at least 9 years by Met Éireann, with high amounts of precipitation received between May and early August, and soil WFPS remained above 60% during the same period. The large variations in March and April rainfall across all years did not translate into large variations in soil moisture as most rainfall runs off at this time of year. Moisture stress was not encountered during the study period, with moisture content well above wilting point (*ca.* 12 % of total volume) throughout. For the single-crop years of 2004, 2005 and 2006, the largest net annual CO_2 uptake occurred in 2004 and the lowest in 2006 (Table 3).

Table 3
Annual sums of gap filled net ecosystem exchange of CO_2 over the entire measurement area with associated uncertainty estimates, percentage of the annual record that was gap-filled, and number of observations originating from each vegetation cover for the complete measurement years 2004–2007.

Year	N_g	N_k	Gap-filled (%)	NEE (g CO_2 m^{-2})
2004	8167	0	63	−1321 ± 220
2005	10,376	0	53	−1261 ± 283
2006	10,361	0	50	−658 ± 208
2007	11,605	1490	47	−75 ± 188

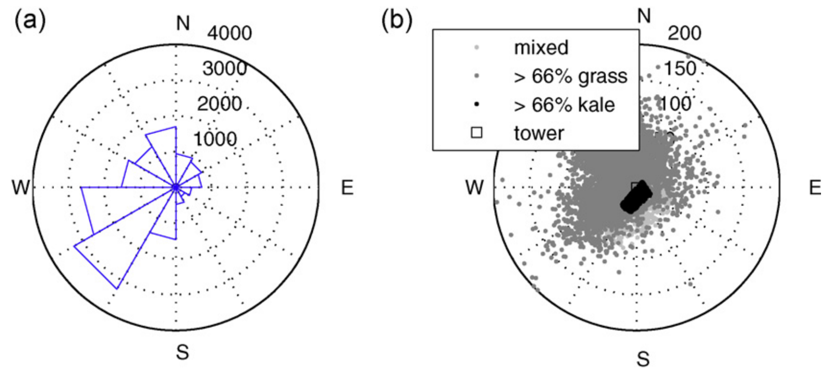

Fig. 2. (a) Windrose for 2007 (number of 30-min intervals *versus* sector angle) and (b) illustration of flux partitioning by land use type from calculated peak fetch distance (m) and wind direction for 2007. The dots represent the peak fetch distance and mean wind direction corresponding to each 30-min flux measurement.

In 2006, the first year when kale was sown, none of the flux measurements were found to be dominated by the kale area (Table 3). This was due to the location of the kale paddocks relative to the flux tower, with the nearest boundary being located outside the prevailing wind sector, approximately 100 m north-west of the tower, and separated from it by an area of grassland. In 2007, when kale was sown in two paddocks adjacent to the tower, lying mainly in the southwest to southeast quadrant, 1490 of 17,520 half hourly flux measurements were from the kale area, 11,605 from the grass area and the remainder could not be ascribed to a dominant land use type, either because neither area dominated, or due to missing or poor quality data (Table 3).

Mann–Whitney *U* tests of sets of flux measurements (aggregated over all bins of the look-up tables) over kale areas *versus* grass areas for periods three to six of 2007 (cf. Table 2) did not result in a rejection of the null hypothesis, that the two sets of fluxes were drawn from the same distribution. However, when the observed fluxes within corresponding T_{soil} and PAR bins were compared across grass and kale series, a majority of the paired bins exhibited a statistically significant difference in periods four and five (Table 4). Therefore flux observations over kale and grass during these periods, controlled for environmental factors, are likely to be drawn from different distributions.

If the two series of flux observations are separately gap filled and cumulatively summed, the cumulative difference in NEE between each area can be compared (Fig. 5). For the first 40–50 days after kale was sown, the grass areas had a higher CO_2 uptake than the kale areas, however this trend reversed for the following 30–40 days, and both areas had similar NEE for the remainder of the year. However, it should be noted that the period from day 247 to 255 was 100% gap filled due to instrumental downtime. At the end of the year, the annual NEE is −500 g CO_2 m^{-2} for the grass area and −398 g CO_2 m^{-2} for the kale area, therefore the difference in NEE is

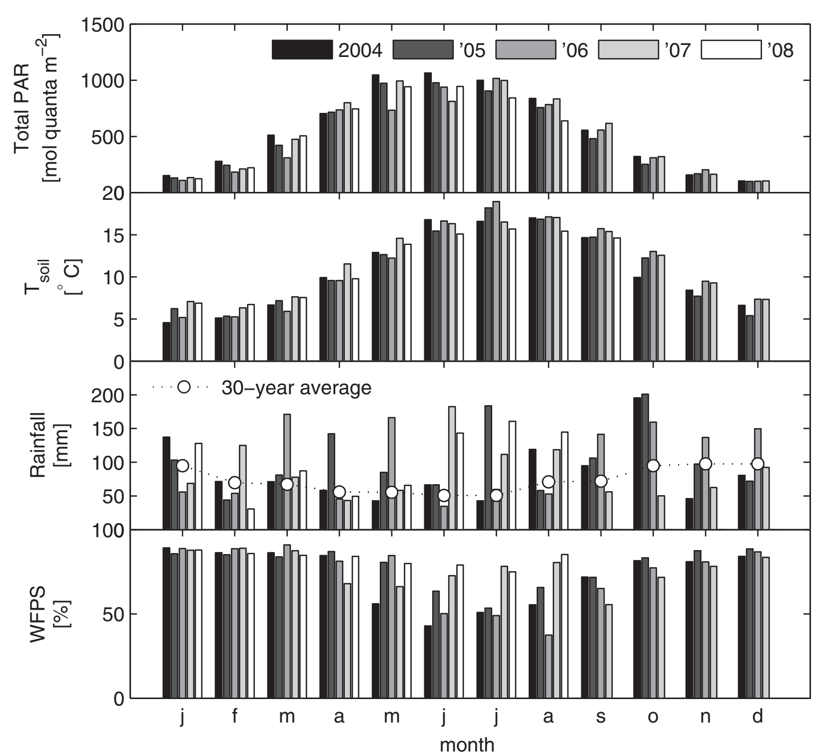

Fig. 3. Monthly total PAR, mean soil temperature at 5 cm depth, total rainfall and mean soil water filled pore space (WFPS) at 5 cm depth, January 2004–August 2008.

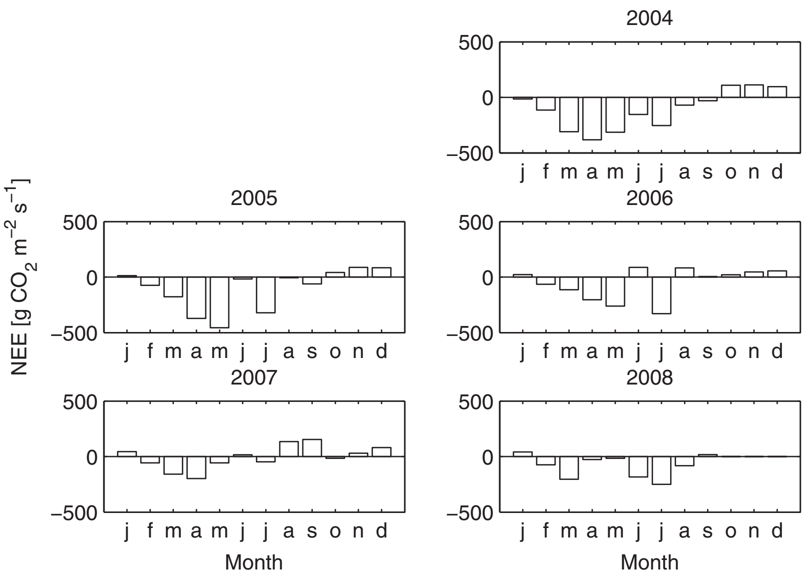

Fig. 4. Monthly gap filled net ecosystem exchange totals.

Table 4
Mean daytime and nighttime non-gapfilled CO_2 fluxes (μmol CO_2 m^{-2} s^{-1}) over grass- and kale-dominated areas during periods of 2007; percentage of non-empty grass and kale flux bins which differed at the 95% significance level. The period boundaries are listed in Table 2.

Period	Mean flux (grass)		Mean flux (kale)		Significance of difference
	Daytime	Nighttime	Daytime	Nighttime	% bins significantly different
Period 3	−3.8	4.7	−0.6	4.3	36
Period 4	−1.5	3.7	−4.1	4.9	58
Period 5	−0.5	2.6	−5.8	3.2	68
Period 6	−2.9	1.5	−3.2	2.3	22

ca. 100 g CO_2 m^{-2}, less than the overall uncertainty in the difference of annual flux sums (± 338 g CO_2 m^{-2}).

4. Discussion

The years 2004 and 2005 showed strong annual CO_2 uptake, under 100% grass cover. In early August 2005 a second silage cut

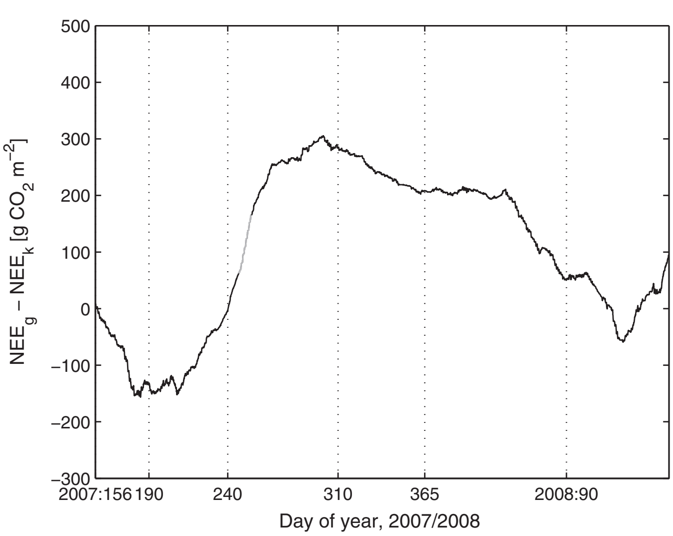

Fig. 5. Difference between NEE measured over grass (NEE_g) and kale (NEE_k) paddocks for 1 year from planting in 2007 (day number 156). Gap filling season boundaries are illustrated by the dashed vertical lines; the grey portion represents a period of 100% gap filling during 2007 due to an instrumental malfunction.

was taken from most of the study area, but monthly NEE during the subsequent months was similar to the corresponding months of 2004, when there was only a single cut in May. Annual rainfall totals were close to the long-term average for both 2004 and 2005 (Met Éireann, 2004–2008). Lower annual uptakes were recorded in the two subsequent years under mixed usage (2006 and 2007) and part of 2008. The extremely wet spring of 2006, with 131% of normal rainfall (Met Éireann, 2004–2008), delayed the onset of peak biomass accumulation, which was compounded by lower than average PAR levels during May (Fig. 3). June CO_2 fluxes were variable between 2004 and 2008, probably mainly due to variation in harvesting dates (Fig. 4 and Table 1). There was a net emission of CO_2 flux during the extremely wet June of 2007, when 223% of the normal monthly rainfall was received (Met Éireann, 2004–2008); however this is likely to be at least partially due to the reseeding of part of the measurement area with winter kale. PAR was also below average in June of 2007. June 2006 saw net emissions of CO_2 under different climatic conditions to 2007 (drier soils) but similar management conditions. In 2007 and 2008, the wet summer conditions may have suppressed biomass recovery after the first silage cut. CO_2 uptake in July 2007 was less than in previous years and for most of the remainder of 2007 there were net monthly emissions, possibly due to the extremely wet conditions following the 2007 harvest. Conditions during 2008 were close to normal, but June was extremely wet, with 225% of average rainfall (Met Éireann, 2004–2008).

The number of kale-dominated measurement intervals in 2007 was a fraction of the number of grass-dominated measurements, hence caution is necessary when attempting to compare the results from each area. Nevertheless, statistical tests of difference show some evidence for a difference between the two areas in periods three through five of 2007 (approximately June through October;

Table 4), when many of the measured fluxes in corresponding kale and grass bins differ significantly. Immediately after the kale was sown on June 5th (day 156), the kale areas emitted more CO_2 than the grass areas (Fig. 5). This is expected as the grass areas, although harvested only 1 week before the kale was sown, would have retained some above-ground biomass, and the kale areas would have been subjected to below-ground disturbance, stimulating soil respiration. However, 2 months after kale planting, daytime uptake fluxes appear to be stronger in the kale area, but nighttime emissions are also larger. The cumulative difference in NEE between the two cultivation areas diminished as the comparison period was extended into the winter months (Fig. 5). This pattern bears some similarities to a study of net ecosystem exchange of spring barley and perennial grass on a peatland in Finland, where higher uptakes were observed from the barley crop than from the grass during the peak growing season, but the grass exhibited CO_2 uptake over a longer period due to its longer growing season (Lohila et al., 2004). Unlike our study, the annual NEE of the barley cropped area greatly exceeded that of the grass area. A comparison of three management systems: no-till barley forage; conventional till barley forage; and undisturbed perennial grass–alfalfa mixture, also found elevated soil CO_2 fluxes in the conventionally tilled forage plot compared to undisturbed perennial forage for several months after tilling (Jabro et al., 2008). The measurements of Willems et al. (2011) at an adjacent site, showed that ploughed areas actually exhibited lower CO_2 emissions than undisturbed areas, apart from a brief emission peak lasting for less than 1 day after ploughing. This implies that soil disturbance plays a minor role and that biomass is the dominant influence on overall fluxes, thus suggesting that the difference between grass and kale fluxes in our study is primarily due to the difference in crop cover.

Although a statistically significant difference has been demonstrated between the corresponding bins of flux observations, this in itself does not conclusively prove that the land cover is the main, or only, cause of the difference. The tilling and reseeding of two of the grass paddocks in August 2007 introduced a further disturbance into the system and may contribute to the large net CO_2 emission of that month and the low mean daytime uptake fluxes over grass areas in period four of 2007 (Table 4). It has been shown elsewhere that the practice of adding lime affects soil CO_2 emissions (Biasi et al., 2008), but in this study only the paddocks under kale in 2006 were limed, therefore the 2007 grassland/kale comparison was not affected by liming. Heterogeneity of soil properties is another factor not considered here which could potentially contribute to a difference in NEE between the two areas.

Despite some evidence from the evolution of the difference in cumulative NEE recorded over grass and kale areas, the overall difference is small 1 year after kale sowing (Fig. 5) and lies within the measurement uncertainty. The bias introduced by the different percentage of gap filling for each subseries may be an influence here, and the possibility also exists that delayed effects of the previous kale rotation reduced productivity during these years, although it should be noted that the paddocks under kale in 2006 occupied only a small proportion of the area sampled by the EC system, so any such delayed effect would have been minimal in the case of 2007.

As EC measurements form part of a time series rather than a set of completely independent observations, the use of statistical comparisons should be approached with caution, however it has been attempted to control for variability in environmental factors by means of partitioning flux observations into bins of PAR and soil temperature. It should be noted that soil temperature is not a completely independent variable as the sowing of the winter forage crop affects the soil temperature through the removal of vegetation cover. Furthermore, the effects of soil moisture are not explicitly included in the look-up tables. The gap filling procedure exhibited some systemic bias, and tended to underestimate high emission fluxes, implying that the annual fluxes presented in Table 3 may be underestimated. The slopes of linear regressions of annual sets of 30-min fluxes modelled using the look-up tables to contemporaneous measured fluxes were in the range 0.7–0.8. Due to the chosen approach of separately gap filling flux series measured over grass and kale, the difference in proportions of the flux data requiring gap-filling between grassland years (2004–2005; 2008) and the mixed grass/kale cultivation years (2006 and 2007), is a possible further source of bias in the final, gap-filled figures.

5. Conclusion

CO_2 fluxes from an area under year round grassland cultivation and an adjacent, similar area under a kale winter forage rotation have been measured and compared. Interannual climatic variability and its impact on the timing of grass harvesting introduce variations in the magnitude, and sometimes even the sign, of grassland NEE between the same months of different years. The largest differences in net annual fluxes were between years with different crop cover. In general, annual uptakes were much larger in the 2 years of grass cultivation than in the years of mixed grass/kale cultivation.

The effect of climatic variability on the flux observations was isolated by binning flux observations into classes of soil temperature and PAR and deriving flux look-up tables based on these bins to calculate annual flux sums. Annual CO_2 uptakes ranged from 75 g CO_2 m^{-2} to 1321 g CO_2 m^{-2}. Although there is evidence for increased respiration and reduced CO_2 uptake in the first weeks after kale sowing in this managed temperate grassland site, the CO_2 uptake of the kale area recovers strongly in the months after sowing, and subsequently exceeds that of the grass area. Overall, this agronomically desireable winter forage rotation does not result in increased CO_2 emissions at least in the first year following sowing. It is recommended that further work be carried out in a controlled, replicated field experiment in order to quantify a complete C budget for each management practice.

Acknowledgements

The authors wish to thank Adrian Birkby, Kilian Murphy and Viacheslav Voronovich of UCC and Deirdre Fay, Owen Carton, Donal Doyle and Gary Lanigan of Teagasc for assistance. This work was funded by the Irish Environmental Protection Agency's STRIVE programme (project Celticflux; 2001-CD-C2-M1) and the EU 6th Framework project CarboEurope-IP. Paul Leahy also acknowledges the support of the Environmental Protection Agency and the Stokes Lectureship programme of Science Foundation Ireland.

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