



## Management and climate effects on carbon dioxide and energy exchanges in a maritime grassland

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### ABSTRACT

This study investigated the effects of grassland management and climate on the exchanges of carbon dioxide (CO<sub>2</sub>) (i.e. net ecosystem CO<sub>2</sub> exchange, NEE; gross ecosystem production, GEP; and ecosystem respiration, ER) and energy (i.e. latent heat flux, LE; sensible heat flux, *H*; and Bowen ratio,  $\beta$ ) in an intensively managed grassland in the maritime climate of southeast Ireland using six years (2004–2009) of eddy-covariance data. The observed effects on CO<sub>2</sub> (reduction of net CO<sub>2</sub> uptake (i.e. NEE), GEP and ER) and energy exchanges (LE decreased while *H* and  $\beta$  increased) were more pronounced following harvest compared to grazing practices and were further dependent on their seasonal timing. Most importantly, a net loss of CO<sub>2</sub> occurred for 2–3 weeks following harvest whereas net uptake continued during grazing periods. Whereas the environmental conditions were in general non-constraining and similar among years, the predominant annual management regime varied widely among years including cattle grazing, grass harvesting, kale planting, and grass re-seeding. For the years 2004–2009, the NEE was –385, –202, –109, +134, –101, and –201 g C m<sup>-2</sup> year<sup>-1</sup> (negative sign indicating uptake) and the mean growing season midday  $\beta$  was 0.97, 0.66, 0.82, 1.07, 0.78 and 0.79. During similar environmental conditions, about twice as much annual CO<sub>2</sub> uptake and greater *H* flux occurred under the cattle grazing regime in 2004 compared to the grass harvesting regime in 2005. Kale planting and re-seeding during the early summer likely caused the reduced annual CO<sub>2</sub> uptake in 2006 and net emission combined with a greater  $\beta$  in 2007. A 2-week drought period in summer 2006 further affected GEP, ER and energy fluxes, while its impact on NEE was limited. Recognizing additional effects from climate, this study finds that the choice of grassland management regime is a key control on grassland ecosystem carbon, water, and energy exchanges in this maritime climate region.

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### 1. Introduction

Managed grasslands constitute a considerable fraction of landscapes and agricultural production in temperate regions (e.g. ~60% of Irish lands; Eaton et al., 2008), and affect local and regional dynamics in climate, carbon (C) and water cycling through processes related to plant photosynthesis, respiration and energy partitioning (Ryszkowski and Kędziora, 1987; White et al., 2000; Rosset et al., 2001; Pielke et al., 2002; Janssens et al., 2005; Gilmanov et al., 2010). A distinct feature of intensively managed grassland ecosystems is the disruption of natural vegetation growth patterns as well as high external C and nitrogen (N) input/output through grazing, harvesting, and N fertilizer application events

(Snaydon, 1987). Altogether, the type, frequency, intensity and timing of these management practices may, in addition to environmental controls, considerably modify the seasonal and inter-annual dynamics of carbon dioxide (CO<sub>2</sub>) and energy fluxes (i.e. latent heat, LE; sensible heat, *H*) (Rogiers et al., 2005; Allard et al., 2007; Hammerle et al., 2008; Wohlfahrt et al., 2008a,b; Schmitt et al., 2010; Zeeman et al., 2010). Thus, understanding the response and restoration behaviour of these fluxes following such management events, is essential to improve our understanding of the implications from current and future management regimes on regional carbon, water and energy exchanges.

Grass harvesting (i.e. silage cutting) affects the net ecosystem exchange (NEE) of CO<sub>2</sub> and energy partitioning in grasslands primarily through its step change reduction of plant biomass and leaf area index (LAI) as well as through alterations of the surface resistance and albedo (Dugas et al., 1999; Novick et al., 2004; Hammerle et al., 2008; Harding and Lloyd, 2008; Schmitt et al., 2010; Zheng et al., 2010). In contrast, grazing effects may be more variable depending on the stocking density and length of the

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grazing period. Some studies reported considerable impacts of grazing on the annual energy balance due to reduced evapotranspiration (ET) (Li et al., 2000; Frank, 2003), while others found no difference in energy partitioning between grazed and non-grazed grasslands (e.g. Chen et al., 2009). Furthermore, variations in form and rates of nitrogen input from fertilizer or cattle excreta may also affect grassland CO<sub>2</sub> exchange (Jones et al., 2006; Allard et al., 2007; Ammann et al., 2007; Shimizu et al., 2009).

On a multi-annual scale, the cycle of periodic re-seeding, fallow periods and intermittent forage crop cultivation among individual paddock fields is a common practice of grassland cultivation systems (Barnes et al., 2007). Grass re-seeding and planting of kale (for winter cattle grazing) during spring or early summer is associated with initial soil disturbance through ploughing and rotavating and results in a severe reduction of plant biomass and subsequent modifications in the seasonal development of vegetation growth and land surface cover (Harper and Compton, 1980). Therefore, such activities may alter grassland CO<sub>2</sub> and energy exchanges over a multi-year time frame (e.g. Vellinga et al., 2004; Willems et al., 2011).

During the past decades, many experimental studies have investigated grazing and harvest effects on plant growth and C dynamics on the plot or plant level (e.g. through clipping experiments) (Snaydon, 1987; Ferraro and Oesterheld, 2002). With the introduction of the eddy covariance (EC) technique, it has become feasible to explore these effects at the ecosystem scale (Baldocchi et al., 2001). To date, a considerable number of studies have investigated seasonal dynamics and annual budgets of CO<sub>2</sub> and energy exchanges in managed grasslands using the EC technique (Li et al., 2005; Byrne et al., 2007; Jacobs et al., 2007; Ryu et al., 2008; Chen et al., 2009; Ciais et al., 2010; Gilmanov et al., 2010). However, in-depth studies assessing the impacts of specific management events on grassland CO<sub>2</sub> and energy fluxes are less abundant and mostly conducted in mountainous or summer-dry regions with primarily extensive management (Dugas et al., 1999; Novick et al., 2004; Hammerle et al., 2008; Harding and Lloyd, 2008; Schmitt et al., 2010; Zheng et al., 2010). By comparison, knowledge is still limited for intensively managed grasslands in the maritime region (but see Jaksic et al., 2006; Harding and Lloyd, 2008; Peichl et al., 2011). Moreover, management effects in previous studies often tend to be masked by environmental constraints (e.g. through seasonal soil water deficits). Meanwhile, investigating grassland management implications in the maritime region that is less prone to temperature or water stress, may allow for more clearly segregating the effects of management practices given the potentially reduced additional impact from environmental constraints.

The aim of this study was to investigate the effects of climate and management practices on short-term flux patterns and annual exchanges of CO<sub>2</sub>, latent heat (LE) and sensible heat (H), using six years (2004–2009) of EC data collected in intensively managed grassland in southeast Ireland. In detail, the study aimed at assessing: (i) the absolute changes and recovery times of CO<sub>2</sub> and energy fluxes related to harvest and grazing events and (ii) the effect of climate and annual management regime (i.e. harvest, cattle grazing, kale planting, re-seeding) on the inter-annual variability in annual CO<sub>2</sub> and energy exchanges for an intensively managed grassland that is representative of Irish grassland management practices.

## 2. Materials and methods

### 2.1. Study site description

The study was conducted at the Wexford grassland research station which is located near the city of Wexford, in southeast Ireland (52°30'N; 6°40'W; 57 m above sea level). The grassland is owned

and managed by the Johnstown Castle Agriculture Research Institute (Teagasc).

#### 2.1.1. Climate

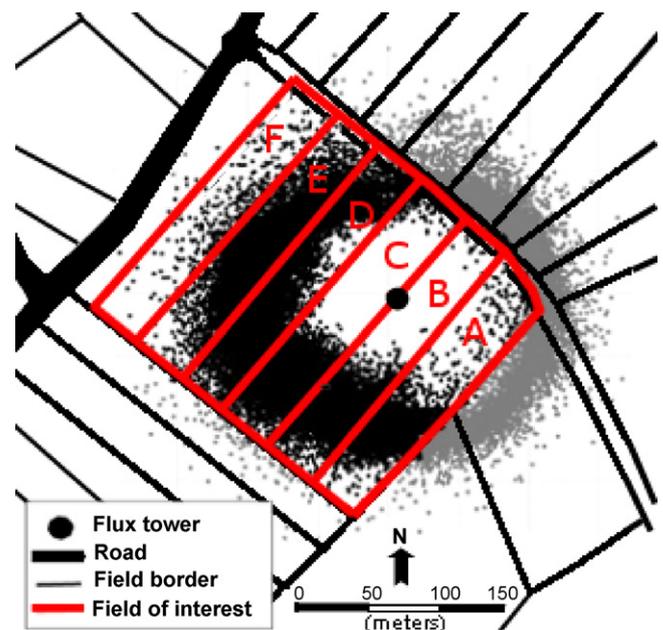
The 30-year annual mean air temperature and total precipitation in this region is 10.1 °C and 877 mm, respectively (Met Eireann, 1961–1990 climate norms at Rosslare Meteorological Station). However the six-year (2004–2009) mean annual precipitation measured at our study site was 1207 mm. The seasonal range in daily mean temperatures is limited, with a mean daily minimum of 3.8 °C in February and a mean daily maximum of 17.9 °C in July/August. Days with pronounced heat or freezing temperatures are uncommon in this region. Precipitation occurs evenly distributed over the year. The prevailing wind direction is from the southwest.

#### 2.1.2. Vegetation and soil characteristics

The grassland is used as pasture and meadow, with perennial ryegrass (*Lolium perenne* L.) being the dominant plant species. Vegetation height reaches a maximum height of about 40 cm in the summer prior to harvesting. However, more detailed data of vegetation height and leaf area index (LAI) were not available. The soil in the proximity (<150 m) of the EC flux tower is a moderately to imperfectly drained Gley (FAO classification: Gleyic Cambisol), with a transition to moderately or well drained Brown Earth (Cambisol) towards the far edge of the footprint of interest (i.e. fields A–F, Fig. 1). The soil texture is loam with 18% coarse sand, 26% fine sand, 38% silt, 18% clay. The permanent wilting point, field capacity and saturated water content were estimated using the SPAW Model (<http://hydrolab.arsusda.gov/SPAW/Index.htm>) as 0.15, 0.30 and 0.54 m<sup>3</sup> m<sup>-3</sup>, respectively. Bulk density is 1.23 g cm<sup>-3</sup>, soil C and nitrogen (N) concentrations are 3.2 and 0.28%, respectively (Hyde et al., 2006).

#### 2.1.3. Footprint of interest

In this study, we focused our analysis on six evenly sized fields of about 0.7–0.9 ha surrounding the flux tower (fields A–F, Fig. 1) for



**Fig. 1.** Map of the Wexford Grassland Research Station outlining tower location, the footprint of interest consisting of the fields A–F (red outlines), and 90% fetch distances for accepted (black dots) and rejected (grey dots) half hourly fluxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

**Table 1**  
Summary of management practices (i.e. average number of grazing days from March 1 to October 31 and harvest cuts per field; fraction of fields planted with kale; fraction of fields re-seeded with grass) averaged for the footprint of interest (fields A–F) during the years 2004–2009.

Management practice	2004	2005	2006	2007	2008	2009
Grass harvest (cuts per field)	0.3	2	1.7	0.3	Not quantified <sup>a</sup>	Not quantified <sup>a</sup>
Grazing (days per field)	15.3	5.8	9.2	27.7	Not quantified <sup>a</sup>	Not quantified <sup>a</sup>
Kale planting (fraction area)	0	0	0.3	0.3	0	0
Grass re-seeding (fraction area)	0	0	0	0.7	0	0

<sup>a</sup> Both grazing and harvest occurred in each of the years 2008 and 2009, however, details on the frequency and intensity of these management practices were not available for these two years.

which detailed management information existed (Table A1). For this purpose we defined a footprint of interest by excluding half hourly fluxes for which the distance of the 90% cumulative fetch was outside the boundaries of these fields using the Kljun footprint model (Kljun et al., 2004). An average roughness length of 0.03 m was used as model input parameter. The variation of the planetary boundary layer (PBL) height as a required input parameter in this model had limited impact and PBL was subsequently set to a height of 1000 m. Moreover, the model is valid only given a friction velocity ( $u_*$ )  $\geq 0.2 \text{ m s}^{-1}$  and atmospheric stability (measurement height,  $z_m$ , over Monin–Obukhov length,  $L$ ) of  $-200 \leq z_m/L \leq 1$ . We therefore disregarded fluxes that did not meet these criteria if they originated from the wind sector with limited fetch (0 and 180°), but accepted all fluxes with  $0.15 < u_* < 0.20 \text{ m s}^{-1}$  ( $u_{*th}$  of  $0.15 \text{ m s}^{-1}$  was the general threshold for filtering out low turbulence data, see Section 2.2.2) and  $z_m/L$  originating from the remaining wind sector (see Fig. 1). The threshold distance for the 90% cumulative fetch was determined for each 5–10° section surrounding the tower, based on the mean distance between the tower and respective boundary of the footprint of interest. In total, this filtering removed 9% of all half hourly fluxes.

The remaining area beyond the footprint of interest that contributed at most 10% to the total flux was also grassland under similar management (detailed management information for those remote fields were not available, hence we minimized their contribution in the current analysis). Naturally, the relative contribution of the individual fields to the total flux somewhat varies spatially (primarily field F contributed less than the other five fields) and temporally (i.e. with fluctuations of the wind direction). However, frequencies of wind direction are more or less constant among years and significant implications from the uneven contribution from individual fields were not evident within the specific context of our analysis.

#### 2.1.4. Management practices

A summary of the type and frequency of various management practices (i.e. grass harvest, grazing, kale planting and grass re-seeding) averaged for the footprint of interest during the years of 2004–2009 is shown in Table 1. A more detailed overview on the specific management events that occurred at the individual fields (A–F) is given in Table A1. Generally, the predominant management regime (defined as the annual sum and combination of individual management practices, see Tables 1 and A1) in each of the years was:

- In 2004, all fields were grazed (with an average stocking density of  $3.5 \text{ livestock units (LU) ha}^{-1}$ ) with moderate frequency throughout the year. In addition, the fields E and F were cut once on the last day of May.
- In 2005, all fields were cut twice (June 6 and August 4) and occasionally grazed. Generally, individual harvest cuts yield ranged from 4 to 6 t dry matter (DM)  $\text{ha}^{-1}$  per cut. Once cut, the grass was removed and used for silage.
- In 2006, one or two cuts per field and occasional grazing occurred. In addition, the fields E and F were used for the cultivation of

winter kale (*Brassica oleracea*) as forage fodder which is a common feature of improved pasture management (Barnes et al., 2007). The kale planting typically included power-harrowing or rotavating of the field in spring/early summer prior to kale seeding. The kale grew mainly throughout the late summer season and was grazed by cattle from late November to the end of January.

- In 2007, frequent grazing occurred across the fields in combination with harvest and kale planting (fields A and B). In addition, fields C–F were ploughed/subsoiled, power-harrowed/rotavated, rolled and re-seeded with grass during spring (fields E and F) and summer (fields C and D).
- In 2008 and 2009, both grazing and grass harvesting occurred on individual fields, however, detailed management information on the frequency, timing and intensity were not available for these two years. Data from these two years are therefore excluded from detailed analysis and discussion but presented as further reference for the grassland  $\text{CO}_2$  and energy exchange patterns under conventional grazing and harvesting management (i.e. excluding kale planting and re-seeding practices).

Industrial inorganic N fertilizers and slurry was applied each year in equal amounts to all fields, totalling  $\sim 200\text{--}280 \text{ kg inorganic N ha}^{-1} \text{ year}^{-1}$  and  $\sim 30\text{--}50 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  of slurry (slurry N content varies largely depending on animal diet and slurry composition, but on average equals  $3.4 \text{ kg N m}^{-3}$ , of which 30% is available for plant uptake after spreading; O’Bric, 1991). Depending on the number of grazing days, N input via cattle excreta ranged between  $\sim 10$  and  $40 \text{ kg N ha}^{-1} \text{ year}^{-1}$ . Overall, the amount, type and frequency of N fertilizer application were similar among years.

The individual management of the fields resulted in spatial and temporal variations within the footprint and in their relative contribution to the total flux. In 2004 however, two grazing events (14 days in July and 20 days in August) occurred across all six fields. In addition, both harvest cuts in 2005 as well as the first cut in 2006 were carried out simultaneously across all fields (Table A1). We therefore focused our analysis on these specific events which provided the unique opportunity to study the short-term effects of harvest and grazing events on ecosystem  $\text{CO}_2$  and energy fluxes in more detail. For harvesting events, the mean of daily fluxes or environmental conditions over the two weeks prior to the event was chosen as a robust pre-harvest reference and compared to weekly means following the event. The weekly resolution following the harvest was chosen to capture detailed post-harvest development patterns of the investigated variables.

## 2.2. Micrometeorological measurements

### 2.2.1. Instrumentation

Net  $\text{CO}_2$  and  $\text{H}_2\text{O}$  flux densities were measured using a LI-7500 open path infrared gas analyser (IRGA) (LICOR Inc., Lincoln, NE, USA) that in combination with a 3-D sonic anemometer data (RM Young, model 81000, Traverse City, MI, USA) resulted in estimates of the net ecosystem  $\text{CO}_2$  exchange (NEE), latent heat (LE) and sensible heat ( $H$ ). The eddy-covariance (EC) data were collected at

a frequency of 10 Hz and averaged over 30 min intervals. The EC sensors were mounted at a height of 2.5 m.

Measurements of meteorological variables included air temperature ( $T_a$ ) and relative humidity (RH) (HMP45A; Vaisala, Helsinki, Finland), global radiation ( $R_g$ ) and net radiation ( $R_n$ ) (CNR1, Kipp & Zonen, Delft, The Netherlands), and photosynthetically active radiation (PAR) (PAR LITE sensor, Kipp & Zonen, Delft, The Netherlands). Precipitation (PPT) data were collected with two CS-ARG100 rain gauges. Soil temperature ( $T_s$ ) at 2, 5, 10, 20, 30 and 50 cm depths and volumetric soil water content (SWC) at 5, 20, 30, 50 cm depths were measured using Campbell Scientific (CS) 107 temperature probes and CS 615 time domain reflectometers, respectively. One additional CS615 sensor was inserted vertically and measurements averaged over 0–30 cm depth. Two soil heat flux plates (HFPO1, Hukseflux, CS) were installed at a depth of 4 cm and soil ground heat flux ( $G$ ) was calculated from heat flux at 4 cm depth corrected for changes in heat storage in the soil layer above following Oliphant et al. (2004). Short gaps in the meteorological data resulting from power failure or sensor malfunctioning were filled with data from nearby weather stations (~8 km to Rosslare and ~1 km to Johnstown, Met Eireann Meteorological Stations).

### 2.2.2. Flux data processing and gap-filling

Data quality control and processing included outlier removal (Papale et al., 2006), double rotation of the wind vectors (Wilczak et al., 2001), and the correction for air density fluctuations (Webb et al., 1980). A threshold ( $u_{*th}$ ) of  $0.15 \text{ m s}^{-1}$  was determined for friction velocity ( $u_*$ ) based on the regression of night time fluxes against friction velocity (Massman and Lee, 2002) and fluxes were discarded during periods with  $u_* < u_{*th}$ .

We followed Barr et al. (2004) to separate NEE into ecosystem respiration (ER) and gross ecosystem production (GEP), and to gap-fill periods with missing data. This method uses a correction factor (determined from the comparison of observed versus predicted values over a 100-point moving window) to adjust predicted values from empirical relationships between fluxes and environmental parameters. This gap-filling method previously proved suitable for managed grassland with high spatial and temporal heterogeneity due to management activities within the footprint (Peichl et al., 2011).

From two weeks prior until three weeks after each harvest event in 2005 and after the first harvest of 2006, the parameters for soil temperature response of ER (i.e. base respiration at  $10^\circ\text{C}$ ,  $R_{10}$ ; sensitivity to a temperature increase of  $10^\circ\text{C}$ ,  $Q_{10}$ ) and the light response of GEP (i.e. maximum net assimilation rate,  $A_{max}$ ; photosynthetic efficiency,  $\alpha$ ) were derived on a daily basis from Van't Hoff-type exponential (Eq. (1)) and rectangular hyperbola (Eq. (2)) functions, respectively.

$$ER = R_{10} \times Q_{10}^{(T-T_{10}/T_{10})} \quad (1)$$

$$GEP = \frac{\alpha \times Q \times A_{max}}{\alpha \times Q + A_{max}} \quad (2)$$

where  $T$  is soil temperature ( $^\circ\text{C}$ ) at 5 cm depth,  $T_{10}$  is the reference temperature of  $10^\circ\text{C}$ , and  $Q$  is photosynthetically active radiation ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ).

Gaps in LE and  $H$  were filled based on their respective regressions to available energy ( $R_n - G$ ) over a 240 point moving window, following Amiro et al. (2006). In 2004, an extended gap in  $R_n$  data due to malfunctioning of the radiation sensor hampered the gap-filling of LE and  $H$ . We therefore excluded the annual totals of energy fluxes for that year due to the associated high uncertainty.

Within the enclosed area of the tower ( $4 \text{ m} \times 4 \text{ m}$ ), the grass was cut at the same time as the adjacent fields were cut or grazed. There were however times when management practices carried out on fields at some distance away from the tower (e.g. fields A, D, and E)

differed from those at the adjacent fields (i.e. fields B and C). While such management practices at the remote fields affected the  $H$  and LE fluxes, they did not influence the  $R_n$  and  $G$  measurements made a few metres away from tower. Therefore, such spatially heterogeneous management practices caused an imbalance between the measured energy fluxes and  $R_n$  on the annual scale. The controls of  $R_n$  and  $G$  on the annual energy partitioning were therefore not further explored in this study. This limitation of  $R_n$  and  $G$  measurements due to the spatial heterogeneity of management events also explains and limits the use of the relatively low 5-year (2005–2009) mean energy balance closure of 64% as quality assurance parameter on the annual scale. However, this limitation did not affect our analysis of events carried out over the entire footprint or the gap-filling of the  $H$  and LE fluxes.

The midday Bowen ratio ( $\beta$ ) was calculated as the ratio of  $H$  to LE between the hours of 10:00 and 14:00 of each day. In this study, we use the micrometeorological sign convention in which fluxes from the atmosphere to the ecosystem surface are negative and emission fluxes are positive. However, we present GEP (according to the definition of a negative flux) in absolute values ( $|GEP|$ ) to facilitate the direct comparison with ER.

### 2.3. Uncertainty and statistical analysis

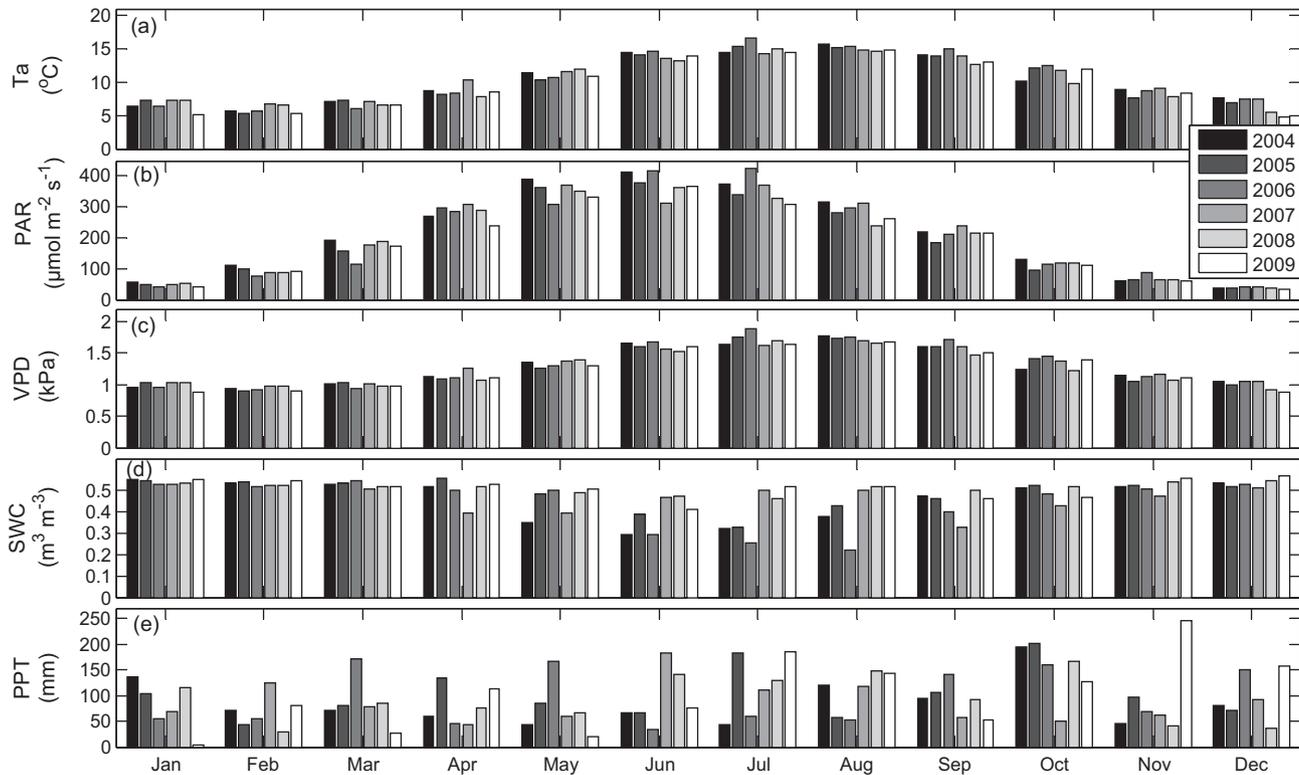
The uncertainty for monthly and annual totals of NEE, GEP, ER,  $H$ , LE and evapotranspiration (ET) was estimated with a bootstrapping approach based on the method described by Hagen et al. (2006). In this approach, residuals from the initial regression models are re-sampled and added back to the fitted values to create  $N=1000$  artificial bootstrap replicates of the data. A new regression model is then refitted to each replicate resulting in  $N$  estimates of the gap-filled time series. The uncertainty was finally estimated from the 90% prediction limits for monthly and annual sums of these  $N$  series. In addition to the annual totals for the footprint of interest, totals were also computed using all available fluxes to evaluate the robustness and footprint filtering effects on inter-annual flux patterns.

Statistical differences among log-transformed weekly means of daily pre- and post-harvest fluxes or environmental conditions were assessed with a repeated measures analysis of variance (ANOVA) followed by the Dunnett's test for multiple comparisons of the individual 'treatment' group means (i.e. post-harvest weeks) against that of the 'reference' group (i.e. the pre-harvest period). Linear regression slopes were evaluated for significant differences using the Student's  $t$  distribution.

## 3. Results

### 3.1. Environmental conditions during the study period

The patterns and magnitudes of monthly mean values were generally similar among years for each of the variables  $T_a$ , PAR, and VPD, except the mean monthly PAR somewhat varied among years for the months May to July (Fig. 2a–c). The growing season patterns of monthly mean SWC values were similar among years while magnitudes of SWC and PPT were lower for June to August for 2004–2006 compared to 2007–2009 (Fig. 2d and e). In 2006, a prolonged period of reduced rainfall resulted in lower monthly mean SWC values in summer 2006 compared to other years, reaching the wilting point of  $0.15 \text{ m}^3 \text{ m}^{-3}$  in August. Besides this drought event in 2006, other climatic extreme events (e.g. heat stress, freezing and/or severe soil water deficits) which may constrain plant and microbial functioning and thereby affect C and water fluxes were not evident during the study period. On the annual scale, averages ( $\pm$  standard deviation) were within a narrow range for the main environmental variables  $T_a$  ( $10.3 \pm 0.4^\circ\text{C}$ ), PAR



**Fig. 2.** Monthly means of (a) air temperature ( $T_a$ ), (b) photosynthetically active radiation (PAR), (c) vapour pressure deficit (VPD), (d) volumetric soil water content (SWC; 0–30 cm depth), and (e) monthly totals of precipitation (PPT) from 2004 to 2009.

( $200 \pm 9 \mu\text{mol m}^{-2} \text{s}^{-1}$ ), VPD ( $1.29 \pm 0.03 \text{ kPa}$ ), SWC ( $0.37 \pm 0.04$ ) and PPT ( $1207 \pm 104 \text{ mm}$ ) among the six study years (Table 2).

### 3.2. Seasonal patterns of $\text{CO}_2$ and energy exchanges

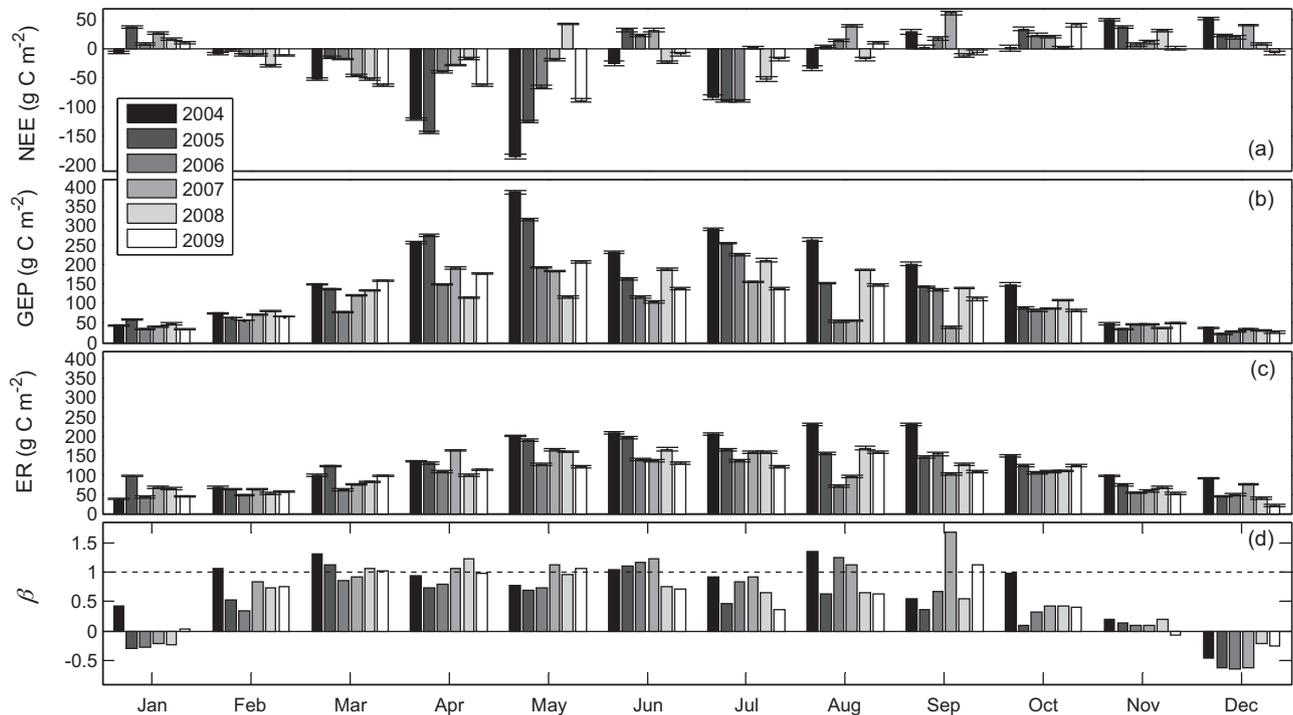
The maximum monthly net uptake of  $\text{CO}_2$  occurred during the two months of April and May (up to  $-186 \text{ g C m}^{-2}$ ). Following re-seeding in mid-April 2007 and an early harvest cut in April/May

2008, considerably lower  $\text{CO}_2$  uptake and a net loss occurred in May 2007 and 2008, respectively (Fig. 3a). The month of June was characterized by reduced net  $\text{CO}_2$  uptake (in 2004 and 2009) and a net  $\text{CO}_2$  loss in the years 2005–2007, coinciding with grass harvest, re-seeding and/or kale planting events. A second peak in net  $\text{CO}_2$  uptake occurred in July for all years except for 2007 when the grassland remained a source of  $\text{CO}_2$  from June 2007 onwards. Compared to other years, the GEP and ER were considerably higher for

**Table 2**  
(a) Annual means of air temperature ( $T_a$ ), photosynthetically active radiation (PAR), vapour pressure deficit (VPD), soil water content averaged over 0–30 cm depth (SWC); annual totals of precipitation (PPT), and (b) annual sums of net ecosystem exchange (NEE), gross ecosystem production (GEP), ecosystem respiration (ER), sensible heat flux ( $H$ ), latent heat flux (LE) and evapotranspiration (ET), growing season (March 1–October 31) means of midday (10:00–14:00 h) Bowen ratio ( $\beta$ ) for the footprint of interest; values in parentheses indicate uncertainty as described in Section 2.3. Numbers in square brackets are annual values estimated with all available data (i.e. including fluxes whose 90% fetch distance extends beyond the footprint of interest; see also Fig. 1). Note that GEP is shown in absolute values (i.e.  $|\text{GEP}|$ ); N/A = not available.<sup>a</sup>

(a) Environmental variable	Unit	2004	2005	2006	2007	2008	2009
$T_a$	$^{\circ}\text{C}$	10.4	10.3	10.6	10.7	9.9	9.8
PAR	$\mu\text{mol m}^{-2} \text{s}^{-1}$	214	196	202	205	195	187
VPD	kPa	1.30	1.29	1.33	1.31	1.25	1.25
SWC	$\text{m}^3 \text{m}^{-3}$	0.46	0.49	0.44	0.46	0.51	0.51
PPT	$\text{mm year}^{-1}$	1265	1233	1338	1047	1125	1231
(b) $\text{CO}_2$ , water and energy fluxes	Unit	2004	2005	2006	2007	2008	2009
NEE	$\text{g C m}^{-2} \text{year}^{-1}$	−385 (38) [−404]	−202 (25) [−225]	−109 (23) [−59]	134 (24) [116]	−101 (23) [−110]	−201 (40) [−188]
GEP	$\text{g C m}^{-2} \text{year}^{-1}$	2137 (39) [2099]	1707 (26) [1739]	1199 (23) [1175]	1133 (23) [1113]	1396 (19) [1395]	1345 (24) [1338]
ER	$\text{g C m}^{-2} \text{year}^{-1}$	1752 (24) [1695]	1505 (28) [1514]	1090 (25) [1116]	1267 (30) [1229]	1295 (25) [1286]	1146 (29) [1153]
$H$	$\text{MJ m}^{-2} \text{year}^{-1}$	N/A	25 (11) [36]	75 (13) [75]	222 (17) [213]	121 (18) [113]	62 (20) [28]
LE	$\text{MJ m}^{-2} \text{year}^{-1}$	N/A	877 (13) [911]	734 (14) [755]	743 (12) [747]	808 (14) [799]	695 (16) [692]
ET	$\text{mm year}^{-1}$	N/A	358 (5) [372]	300 (6) [308]	303 (5) [305]	330 (6) [326]	284 (6) [282]
$\beta$ (midday)	Unitless	0.98 [0.96]	0.65 [0.68]	0.83 [0.85]	1.06 [1.07]	0.78 [0.85]	0.79 [0.79]

<sup>a</sup> Annual sums of  $H$ , LE and ET were not computed for 2004 as malfunctioning of the radiation sensor inhibited the gap-filling of missing values.



**Fig. 3.** Monthly totals of (a) net ecosystem exchange (NEE), (b) gross ecosystem production (GEP), (c) ecosystem respiration (ER), and (d) monthly means of the midday (10:00–14:00 h) Bowen Ratio ( $\beta$ ) from 2004 to 2009. Note that GEP is shown in absolute values  $|GEP|$ . Error bars indicate uncertainty as described in Section 2.3. Horizontal line in (d) shows  $\beta = 1$  to highlight periods when latent heat flux exceeds sensible heat flux and vice versa.

April/May to September of 2004 whereas GEP was greatly reduced in June to September of 2007 (but ER was similar) (Fig. 3b and c).

The monthly means of  $\beta$  increased from  $<0$  to 1 between December and March (Fig. 3d). For months with intensive vegetation growth and cover (e.g. May–July)  $\beta$  ranged mostly between 0.5 and 0.8 but exceeded  $>1$  around May (2007–2009) or June (2004–2007) following harvesting, kale planting and re-seeding events. Moreover,  $\beta$  remained close to 1 or  $>1$  for the entire growing season in 2007 (the year in which most kale planting and grass re-seeding events occurred) reaching a maximum of 1.7 in September. Furthermore,  $\beta$  was higher throughout the heavily grazed late growing season (July–October) of 2004 compared to the same period in 2005 which experienced less intensive grazing but similar environmental conditions.

### 3.3. Short-term environmental controls on $CO_2$ and energy fluxes in the dry summer of 2006

The short-term patterns of GEP,  $H$  and LE generally responded directly to those of  $T_a$  and PAR, except for periods following management events (Fig. 4). During the drought period in August 2006, (i.e. SWC dropped below the wilting point) both GEP and ER decreased simultaneously resulting in more or less unaltered NEE. This response was in contrast to harvest events at the end of May and at the beginning of the August drought period which resulted in a reduction of GEP and a net  $CO_2$  loss (i.e. positive NEE). Furthermore, the 2006 summer drought coincided with a reduction in LE and an increase in  $H$  resulting in  $\beta > 2$  throughout the entire drought period.

### 3.4. Harvesting effects on $CO_2$ and energy fluxes

#### 3.4.1. Pre- and post-harvest environmental conditions

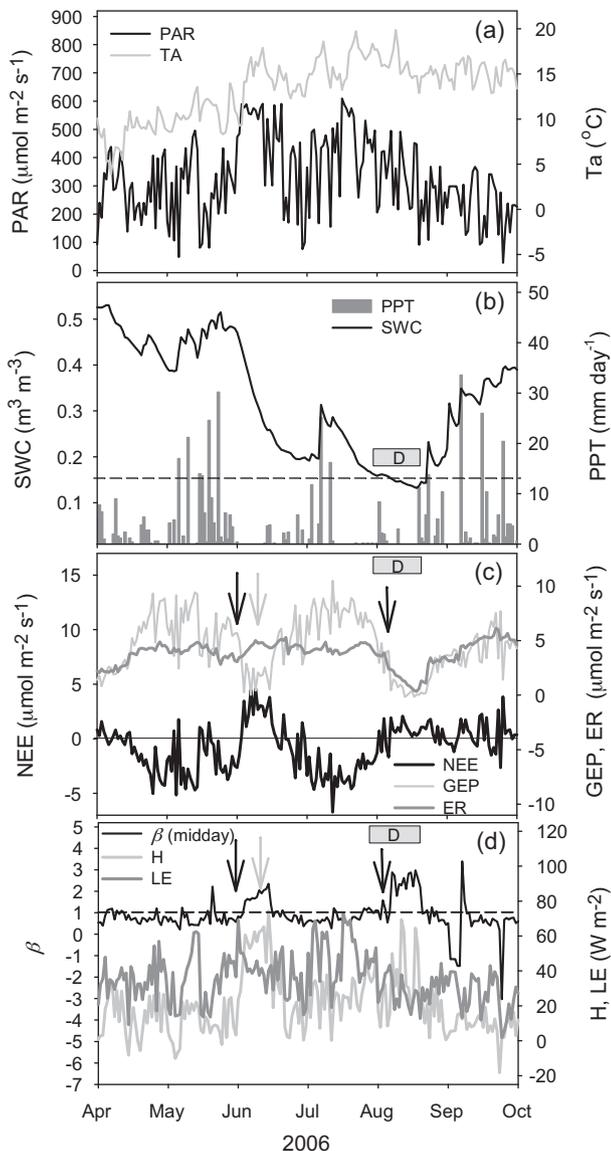
Compared to the 2-week pre-harvest averages of  $T_a$  and VPD preceding the first and second harvesting event in 2005, the mean

$T_a$  and VPD of the first post-harvest week were not significantly different, whereas the mean  $T_a$  and VPD of the second and third post-harvest week were significantly greater (Fig. 5). No significant differences were observed between the pre- and post-harvest means of PAR for either one of the two harvest events in 2005. Although weekly means of SWC significantly decreased following the first cut, overall the SWC remained at high enough levels ( $>0.30 m^3 m^{-3}$ ) to exclude constraining effects from soil water stress on plant growth and evapotranspiration. In contrast, the three weeks following the harvest event in 2006 coincided with significantly higher  $T_a$ , PAR (only for the first and second week), and VPD combined with lower SWC compared to the 2-week pre-harvest averages of these variables.

#### 3.4.2. Pre- and post-harvest $CO_2$ fluxes

The daily NEE switched from net uptake of  $CO_2$  ( $-3.5 g C m^{-2} day^{-1}$ ) before the first harvest in 2005 to a net loss of  $CO_2$  ( $4-5 g C m^{-2} day^{-1}$ ) during the first two weeks ( $p < 0.01$ ) after the harvest, but recovered to similar uptake values ( $p > 0.05$ ) by the third post-harvest week (Fig. 6). GEP decreased significantly from  $\sim 12 g C m^{-2} day^{-1}$  before the harvest to  $\sim 3 g C m^{-2} day^{-1}$  during the first two weeks after the harvest. While GEP started to increase again in the third post-harvest week, its full recovery was only reached in the fourth post-harvest week (not shown). Similarly, pre-harvest ER of  $\sim 8 g C m^{-2} day^{-1}$  significantly decreased to  $\sim 6 g C m^{-2} day^{-1}$  during the second and third week after the harvest, despite an increase in temperature (recall Fig. 5). ER started to recover from the fourth post-harvest week onwards (not shown), indicating a lag of about one week relative to the GEP pattern.

The patterns in pre- and post-harvest NEE and GEP were similar for both harvest events in 2005, although the magnitudes of change were smaller (primarily due to lower pre-harvest values) following the second harvest event (Fig. 6). In contrast, there was no significant decrease in ER following the second harvest. Instead,



**Fig. 4.** Daily means of (a) air temperature ( $T_a$ ) and photosynthetically active radiation (PAR), (b) daily means of volumetric soil water content (SWC; 0–30 cm depth) and daily totals of precipitation (PPT), (c) daily means of net ecosystem exchange (NEE), gross ecosystem production (GEP) and ecosystem respiration (ER), and (d) latent heat (LE) and sensible heat ( $H$ ) fluxes and midday (10:00–14:00 h) Bowen ratio ( $\beta$ ) from April to October 2006; grey horizontal bar denoted with 'D' highlights a drought period with SWC < wilting point of  $0.15 \text{ m}^3 \text{ m}^{-3}$ , the latter one indicated as dotted horizontal line in (b); downward arrows indicate timing of harvest cuts (black) and kale planting (grey). Note that GEP is shown in absolute values  $|\text{GEP}|$ .

ER increased during the second and third post-harvest week coinciding with an increase in air temperature (see Fig. 5).

Between years, patterns in pre- and post-harvest NEE and GEP were similar for the respective first harvest events (Fig. 6). However, compared to 2005, the post-harvest ER in 2006 was significantly higher than the pre-harvest ER which also coincided with a significant post-harvest increase in  $T_a$ , VPD, and PAR (Fig. 6, see also Fig. 5).

### 3.4.3. Pre- and post-harvest temperature and light responses of ER and GEP

The response of ER to soil temperature ( $T_s$ ) was significantly reduced after the first harvest in 2005 (Fig. 7), with pre-harvest medians of daily  $R_{10}$  and  $Q_{10}$  values of 2.8 and 1.9 decreasing to

2.3 and 1.5 by the third post-harvest week, respectively (Fig. 8). In contrast, the temperature response of ER (Fig. 6) and its equation parameters  $R_{10}$  and  $Q_{10}$  (Fig. 8) remained similar following the second harvest in the late summer of 2005. Despite a masking effect from higher post-harvest  $T_a$  (recall Fig. 6), post-harvest  $R_{10}$  and  $Q_{10}$  showed a small but significant decrease compared to pre-harvest values in 2006 (Fig. 8).

Contrary to the ER– $T_s$  response, the GEP at a given PAR was reduced after each harvest event (Fig. 7). In the first week after the harvest, the median values of the daily light response parameters  $\alpha$  and  $A_{\max}$  were as low as  $\sim 0.02 \mu\text{mol } \mu\text{mol}^{-1}$  and  $\sim 5 \mu\text{mol } \text{m}^{-2} \text{ s}^{-1}$ , respectively, but subsequently increased to  $\sim 0.05 \mu\text{mol } \mu\text{mol}^{-1}$  and  $18\text{--}23 \mu\text{mol } \text{m}^{-2} \text{ s}^{-1}$ , respectively, by the third post-harvest week (Fig. 8).

### 3.4.4. Pre- and post-harvest energy fluxes

Pre-harvest LE values of  $\sim 5 \text{ MJ } \text{m}^{-2} \text{ day}^{-1}$  significantly decreased to about  $3.5 \text{ MJ } \text{m}^{-2} \text{ day}^{-1}$  during the first week after the first harvest in 2005, but recovered to pre-harvest values by the second post-harvest week (Fig. 6). In contrast, LE did not differ before and after either the second harvest in the late summer of 2005 or the first harvest in 2006.

Pre-harvest  $H$  values of  $\sim 2 \text{ MJ } \text{m}^{-2} \text{ day}^{-1}$  significantly increased during the two weeks following the first harvest in 2005 to about  $4.5 \text{ MJ } \text{m}^{-2} \text{ day}^{-1}$ , and recovered only by the third post-harvest week (Fig. 6). Similar patterns were observed for the other two investigated harvest events, however, the effect was smaller for the second harvest in 2005 while being much more pronounced in 2006 compared to the first harvest in 2005.

Due to the concurrent negative and positive changes in LE and  $H$ , respectively,  $\beta$  increased significantly from pre-harvest values of  $\sim 0.7$  to almost 2.0 following the first harvests in both 2005 and 2006, with a tendency to return close to pre-harvest values by the third post-harvest week (Fig. 6). By comparison, the difference between pre- and post-harvest  $\beta$  was smaller (but significant) following the second harvest in 2005 and solely driven by the increase of  $H$ .

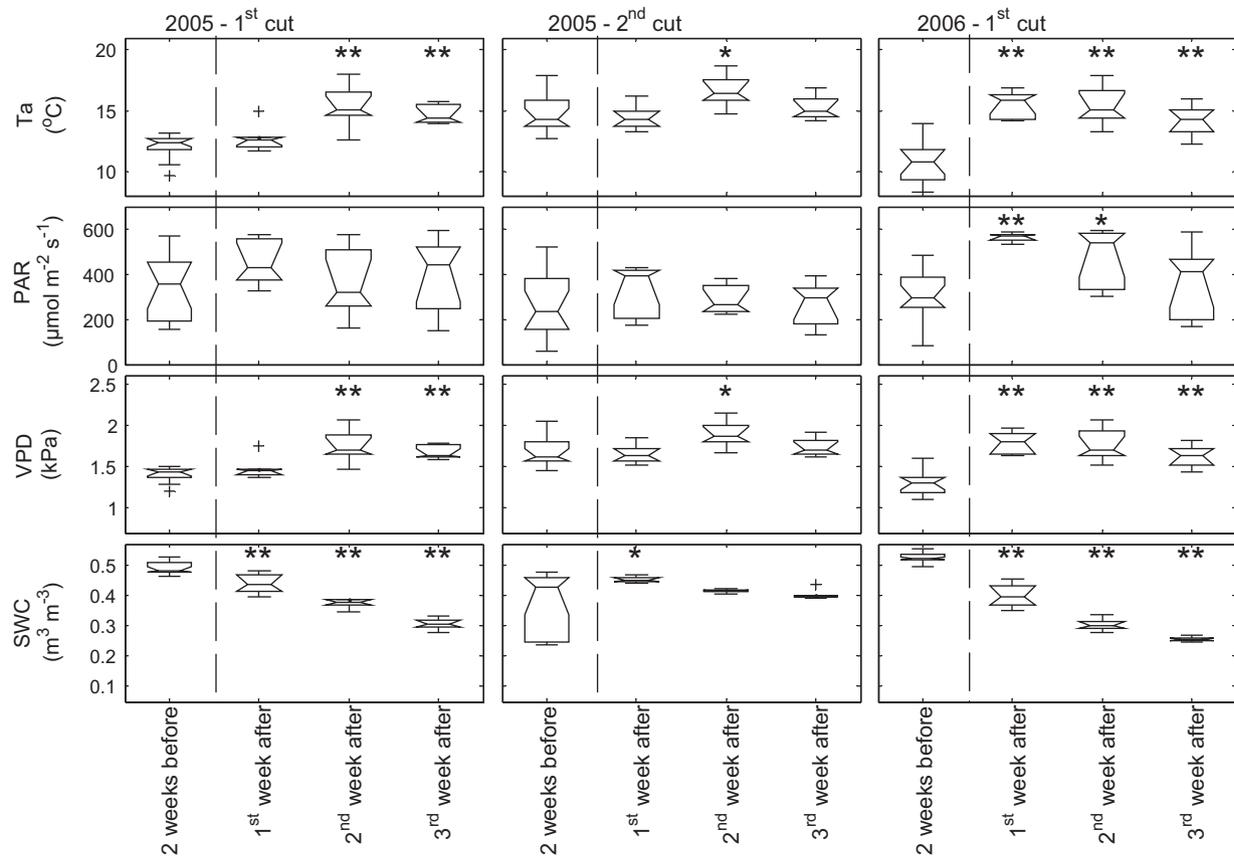
## 3.5. Grazing effects on $\text{CO}_2$ and energy fluxes

### 3.5.1. Environmental conditions before, during and after grazing periods

In the summer period 2004 (DOY 170–248), two (mid-summer and late-summer) grazing periods occurred (Fig. 9). The pre-grazing (DOY 170–185) daily mean  $T_a$  increased throughout the mid-summer grazing period (DOY 185–200) to a peak just before the start of the late summer grazing period (DOY 215–233) throughout which  $T_a$  subsequently decreased (Fig. 9a). In contrast, the pre-grazing daily mean PAR tended to gradually decrease throughout the mid- and late summer grazing periods (Fig. 9b). For most of the investigated period, SWC and PPT varied little, except for a wet period occurring at the end of the late-summer grazing period that caused SWC to increase and to remain relatively high throughout the remaining period (Fig. 9c).

### 3.5.2. Grazing effects on $\text{CO}_2$ fluxes

Pre grazing net  $\text{CO}_2$  uptake of about  $4 \text{ g C } \text{m}^{-2} \text{ day}^{-1}$  decreased to around zero within the first week of the mid-summer grazing period but subsequently recovered to pre-grazing values by the end of the first post-grazing week (Fig. 9d). Relative to the pre-grazing period, the net  $\text{CO}_2$  uptake also decreased during the late-summer grazing periods but thereafter remained at this lower level throughout the following two post-grazing weeks. These changes in NEE coincided with a reduction of GEP within the first week of grazing which was more pronounced for the mid-summer grazing period compared to the late-summer grazing period (Fig. 9d). In



**Fig. 5.** Daily means of air temperature ( $T_a$ ), photosynthetically active radiation (PAR), vapour pressure deficit (VPD), and soil water content (SWC; 0–30 cm depth) averaged over 2 weeks before and over the 1st week, 2nd week, and 3rd week after the cutting events in 2005 (1st and 2nd cut) and 2006 (1st cut). The bottom and top of each box plot show the lower and upper quartile, the centre line is the median, and whiskers indicate adjacent values within 1.5 times the interquartile range from the ends of the box, with outlier values beyond this range displayed with a + sign. The width of the box plot notches represent the 95% confidence interval for the median. Significant differences between pre-harvest mean and weekly post-harvest means (based on Dunnett's test) are noted with asterisks (\* $p < 0.05$ ; \*\* $p < 0.01$ ). Dotted vertical lines indicate the timing of the harvest event.

contrast to GEP, ER did not show any pattern related to grazing activity during either one of the two grazing periods and instead followed primarily the pattern of  $T_a$  (compare Fig. 9a and d). Thus, possibly enhanced ER due to cattle respiration was not apparent in the daily ER fluxes.

### 3.5.3. Grazing effects on energy fluxes

Pre-grazing midday means of LE and  $H$  were of the same magnitude (Fig. 9e), with  $\beta$  close to 1 (not shown).  $H$  exceeded LE during the first week of the mid-summer grazing period but was similar or somewhat lower than LE during the second grazing week. In contrast to the mid-summer grazing period, effects on the energy fluxes were absent during the first week of the late-summer grazing period. However,  $H$  fluxes rapidly increased and exceeded LE fluxes throughout the second week of grazing and the first post-grazing week, indicating an enhanced effect of grazing on  $\beta$  during the late summer.

### 3.6. Annual totals of $CO_2$ and energy fluxes in relation to management regime

The annual  $CO_2$  and energy fluxes for the entire tower footprint and the footprint of interest generally showed some differences in absolute magnitudes but consistent trends in their inter-annual variation, suggesting that fluxes from the footprint of interest largely determined the annual flux totals for the entire grassland (Table 2).

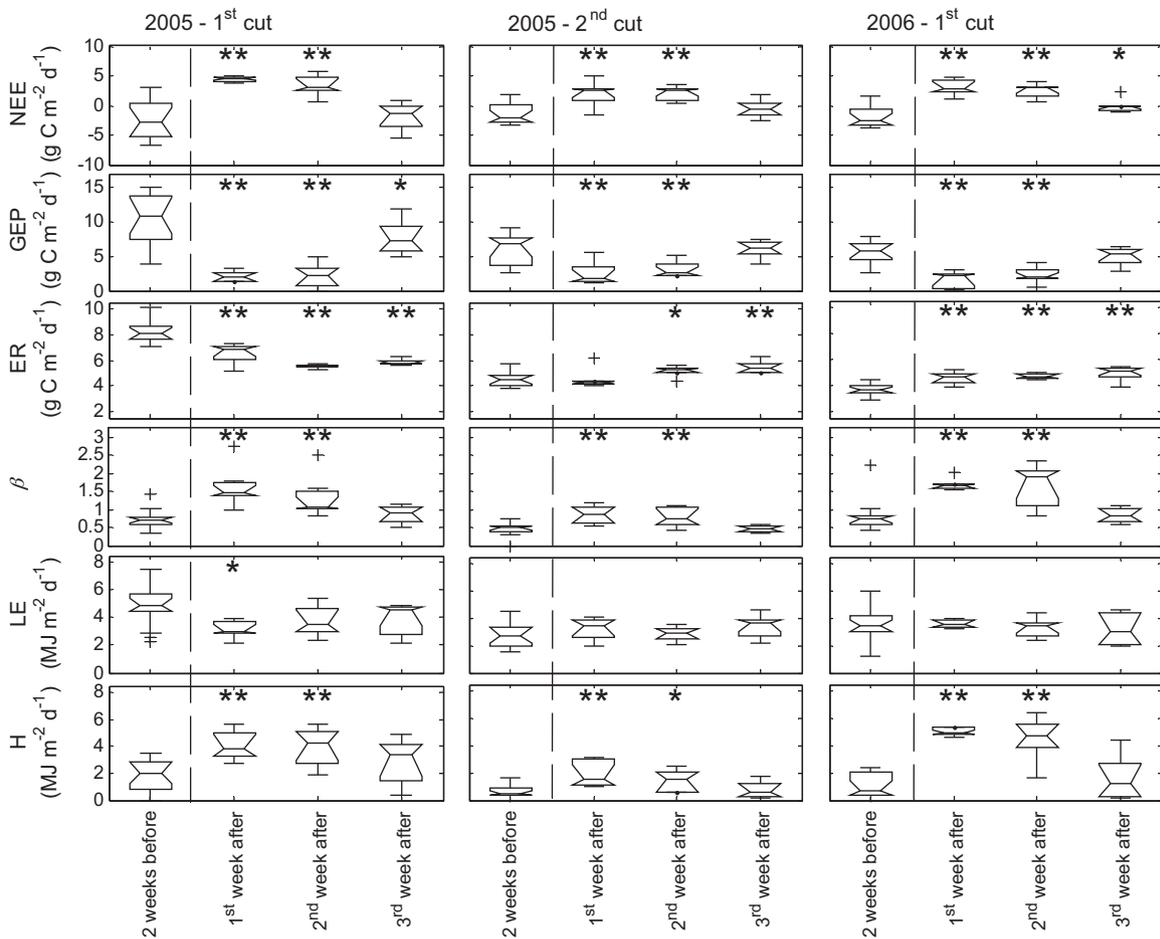
The annual NEE ranged from a large net uptake of  $CO_2$  ( $-385 \text{ g C m}^{-2} \text{ year}^{-1}$ ) in 2004 to net emission of  $CO_2$  ( $134 \text{ g C m}^{-2} \text{ year}^{-1}$ ) in 2007 (Table 2). The annual net uptake of  $CO_2$  in 2004 (predominantly grazing) was about twice as much as that in 2005 (two harvest cuts, limited grazing). The annual GEP and ER were highest in 2004, while GEP was considerably reduced in the years 2006 and 2007 in which kale planting and re-seeding events occurred. ER was lowest in 2006 but similar among the years 2007–2009.

For the years 2005–2007, the annual totals of  $H$  and growing season mean midday  $\beta$  increased with management intensity (compare Tables 1 and 2) from 25 to  $222 \text{ MJ m}^{-2} \text{ year}^{-1}$  and from 0.65 to 1.06, respectively. However, the second highest growing season mean midday  $\beta$  was observed in 2004 when grazing was the dominant management practice. Relative to the annual ET of 358 mm in 2005 (and 330 mm in 2008), the annual ET of about 300 mm was lower in the years 2006 and 2007 in which kale planting and re-seeding of individual fields occurred (Tables 1 and 2). The lowest ET occurred in 2009 coinciding with the lowest annual means of  $T_a$ , PAR, and VPD (Table 2).

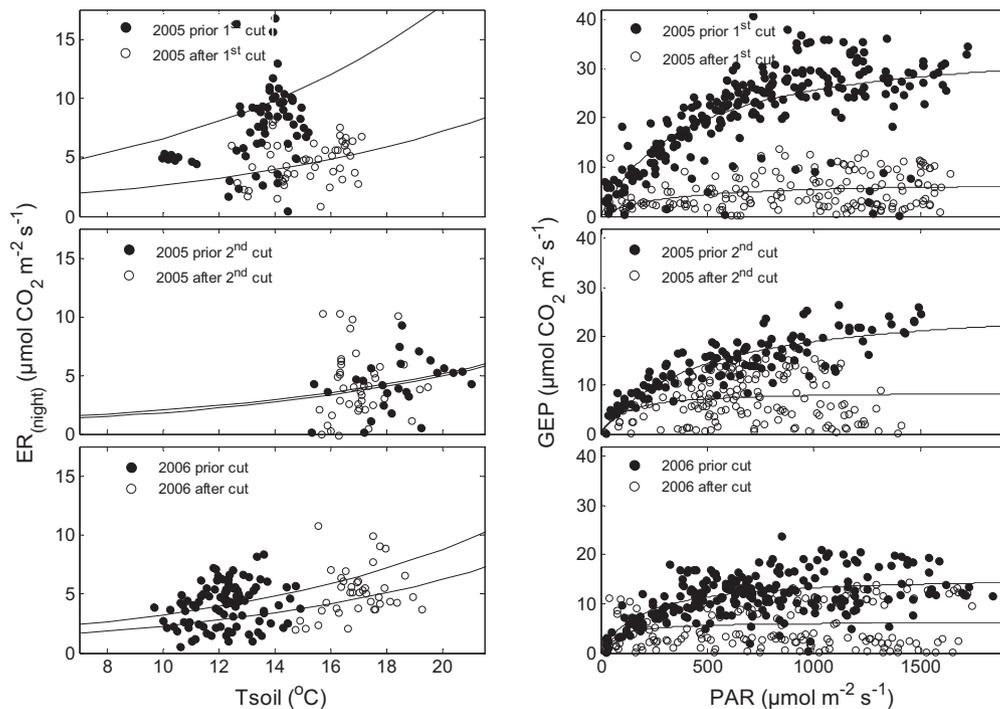
## 4. Discussion

### 4.1. Management effects on seasonal $CO_2$ and energy exchanges

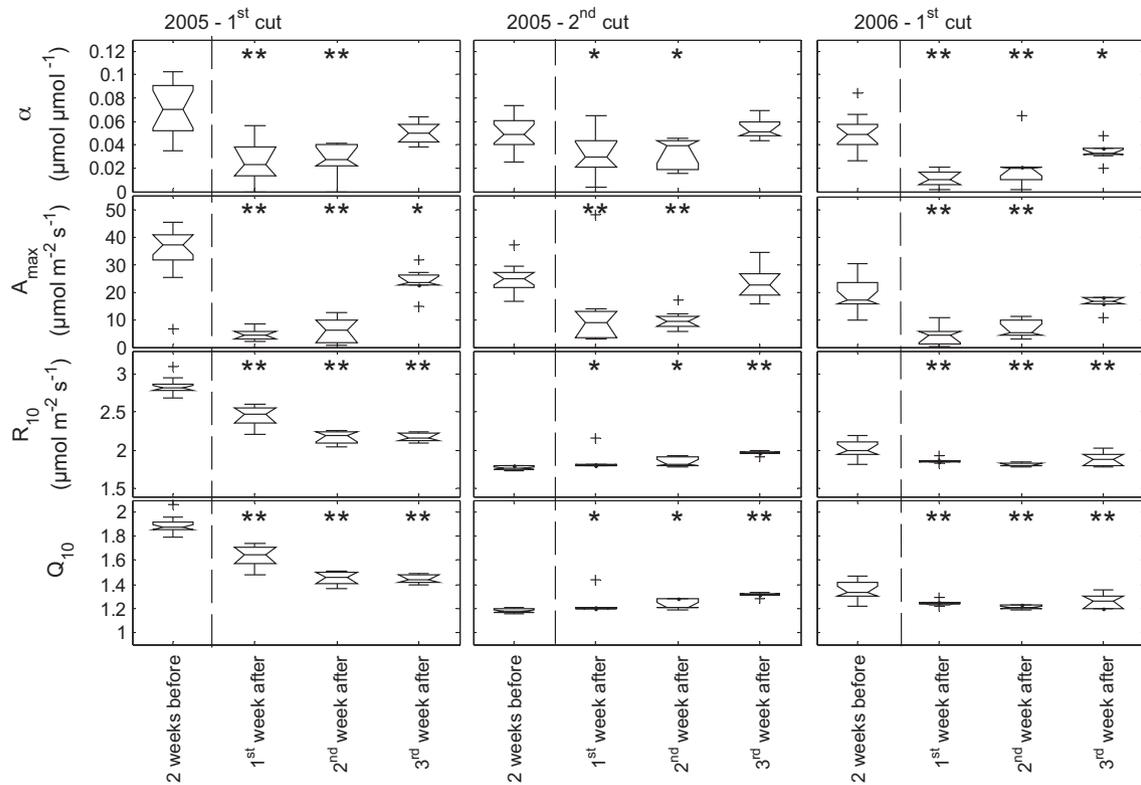
Given the lack of replication and a true control in the observational study design, harvest effects on  $CO_2$  and energy exchanges were evaluated based on the difference between pre- and



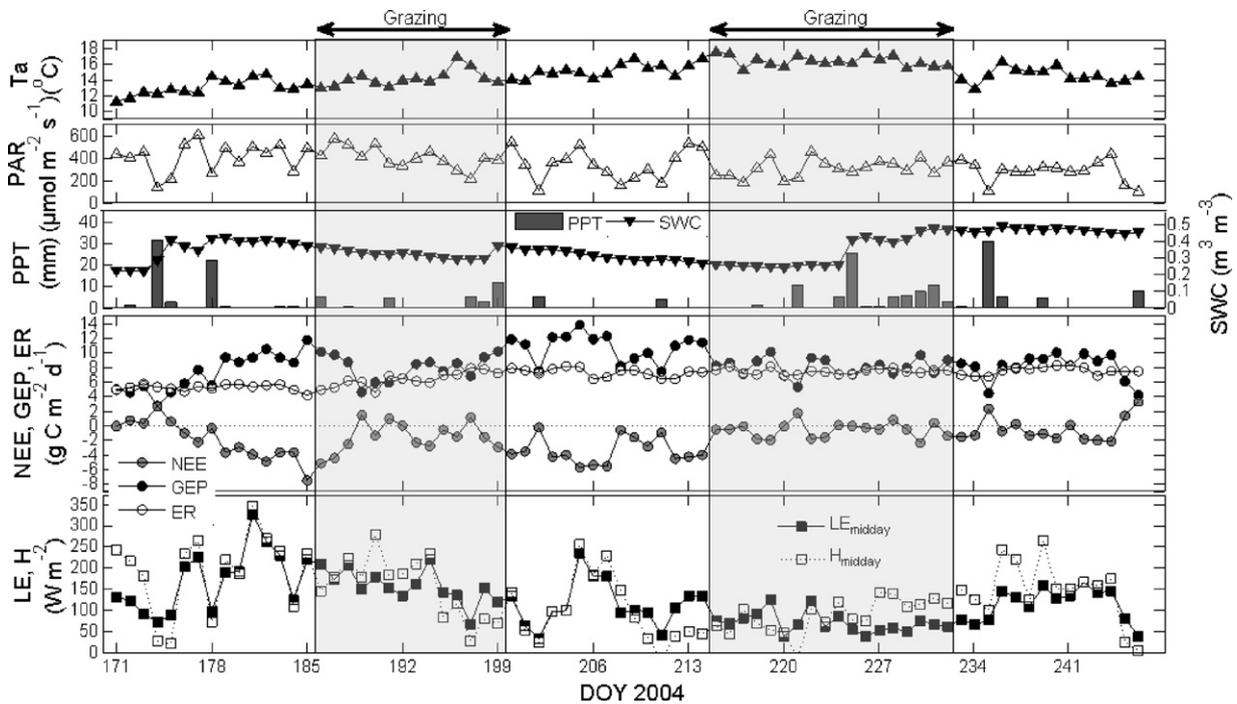
**Fig. 6.** Daily totals of net ecosystem exchange (NEE), ecosystem respiration (ER), gross ecosystem production (GEP), latent heat (LE), sensible heat ( $H$ ), and daily means of the midday (10:00–14:00 h) Bowen Ratio ( $\beta$ ) averaged over 2 weeks before and over the 1st week, 2nd week, and 3rd week after the cutting events in 2005 (1st and 2nd cut) and 2006 (1st cut). See Fig. 5 caption for explanation of box plot information, asterisks, and dotted vertical lines. Note that GEP is shown in absolute values  $|GEP|$ .



**Fig. 7.** Relationship of ecosystem respiration (ER) with soil temperature ( $T_s$ ) and of gross ecosystem production (GEP) with photosynthetically active radiation (PAR) during two weeks before and after the cutting events in 2005 (1st and 2nd cut) and 2006 (1st cut). Solid and dotted lines represent fit (exponential for ER- $T_s$ ; rectangular hyperbola for GEP-PAR) before and after the harvest event, respectively. Note that GEP is shown in absolute values  $|GEP|$ .



**Fig. 8.** Function parameters light use efficiency ( $\alpha$ ) and maximum assimilation rate ( $A_{\text{max}}$ ) in the relationship of gross ecosystem production (GEP) to photosynthetically active radiation (PAR), and base respiration ( $R_{10}$ ) and sensitivity of respiration to a 10 °C increase in soil temperature ( $Q_{10}$ ) in the relationship of ecosystem respiration (ER) to soil temperature (Ts) during the 2 weeks before and during the 1st week, 2nd week, and 3rd week after the cutting events in 2005 (1st and 2nd cut) and 2006 (1st cut). See Fig. 5 caption for explanation of box plot information, asterisks, and dotted vertical lines.



**Fig. 9.** Daily means of (a) air temperature ( $T_a$ ) and (b) photosynthetically active radiation (PAR), (c) daily totals of precipitation (PPT) and daily means of volumetric soil water content (SWC), (d) daily totals of net ecosystem exchange (NEE), gross ecosystem production (GEP) and ecosystem respiration (ER), and (e) daily means of midday (10:00–14:00 h) latent heat (LE) and sensible heat (H) fluxes before and after grazing events (shaded sections) in 2004; DOY, day of year. Note that GEP is shown in absolute values |GEP|.

post-harvest patterns under similar environmental conditions. In 2006, the different pre- and post-harvest environmental conditions likely masked the harvest effect on CO<sub>2</sub> and energy fluxes. We therefore focus our discussion on the harvest events in 2005 which showed similar pre- and post-harvest environmental conditions.

#### 4.1.1. Harvest effects on CO<sub>2</sub> exchange

The post-harvest reductions of GEP, ER, and NEE noted in our study have also been found and linked to decreases in LAI and leaf biomass in previous studies (Dugas et al., 1999; Novick et al., 2004; Hammerle et al., 2008; Schmitt et al., 2010; Zheng et al., 2010). However, the post-harvest recovery periods of two to three weeks observed in our study were considerably longer than the commonly less than 10 days reported in the above studies (of less intensively managed grasslands). This indicates a more pronounced and sustained impact of harvest events on CO<sub>2</sub> exchange in intensively managed and productive grasslands in the maritime climate, possibly conditioned by relatively greater pre-harvest flux magnitudes that require longer times of re-growth to reach full recovery. In contrast to Novick et al. (2004) who reported a negligible impact of harvest on the annual NEE of a warm temperate grassland, we estimate that the first and second harvest cut in 2005 decreased the annual NEE by 98 and 70 g C m<sup>-2</sup> year<sup>-1</sup>, respectively, which together accounts for most of the difference between the annual NEE in 2004 and 2005.

The temperature and light response of ER and GEP are crucial relationships in ecosystem models which allows us to understand the functional response of NEE to environmental changes. The temporary reduction in the temperature and light response parameters ( $R_{10}$ ,  $Q_{10}$ ,  $\alpha$ ,  $A_{\max}$ ) following harvest noted in our study agrees with findings from studies of mountain grasslands (Rogiers et al., 2005; Ammann et al., 2007) and highlights the strong biotic (i.e. biomass removal) and abiotic (e.g. increases in soil temperature and altered soil moisture regimes) controls on these functional relationships (e.g. Bahn et al., 2006; Li and Sun, 2011; Lin et al., 2011). In contrast to our study however, the decreased light response following harvest and cattle grazing in the study by Rogiers et al. (2005) resulted from lower post-harvest  $A_{\max}$ , whereas the  $\alpha$  parameter values were unaffected by the management practices. Furthermore, they did not find any management impact on the ER–temperature response. In further contrast, Novick et al. (2004) did not observe any harvest effect on ER in a warm temperate grassland in North Carolina, USA, while in our study ER and its temperature response parameters decreased following the first cut in 2005 but not after the second cut. A possible explanation for these partly contrasting observations between studies and cutting dates could be (i) a temporal shift in the ratio of autotrophic and heterotrophic respiration throughout the growing season making the harvest effects dependent on the timing of the event and (ii) masking effects from environmental parameters.

#### 4.1.2. Harvest effects on energy exchange

Relative to harvest events during the early growing season, lower amounts of biomass, reduced plant growth and thus generally lower pre-harvest transpiration and less drastic changes in albedo during the later growing season may explain the lack of effect on LE and smaller increases in  $H$  and  $\beta$  following late harvest events. Similar findings were reported for a mountain meadow in the study of Hammerle et al. (2008). Thus, the timing of grass harvesting events may heavily impact the response patterns in energy fluxes due to seasonal dynamics in vegetation growth and transpiration activity.

#### 4.1.3. Grazing effects on CO<sub>2</sub> exchange

In contrast to harvest events which cause a step-change reduction of biomass and cover within a few hours, the grazing cycle

continues over several days to weeks and its effects on CO<sub>2</sub> and energy fluxes are not as dramatic temporally at the ecosystem scale. This is because re-growth of vegetation within the initially grazed fields has occurred by the time the last fields have been grazed within one rotational grazing period, thereby diminishing the signal that could be expected immediately after the grazing of an individual field.

Nevertheless, our results suggest a distinctly different response of ecosystem CO<sub>2</sub> exchange to grazing compared to harvesting events. Firstly, a comparably smaller reduction in GEP caused NEE to remain negative during and after each grazing period suggesting a continuous net CO<sub>2</sub> uptake as opposed to a net CO<sub>2</sub> loss observed following harvest events. Secondly, in contrast to the decline in ER after harvest cuts, ER was not affected during or after the grazing periods in this study. Similarly, Rogiers et al. (2005) did not observe any effect of cattle grazing on ER in subalpine grassland. We suspect that reduced autotrophic plant respiration following biomass removal may have been counterbalanced by the additional C losses from cattle respiration during the grazing periods and/or elevated heterotrophic respiration as a result of an increase in soil temperatures. A combination of opposing effects was also proposed by Lin et al. (2011) who did not find any significant effect of grazing on ER in a Tibetan alpine grassland.

#### 4.1.4. Grazing effects on energy exchange

We noted strong effects of grazing on  $H$  and LE, primarily during the late growing season. During that time, reduced biomass, vegetation growth and transpiring capacities may lead to enhanced partitioning of radiation energy into  $H$  resulting in relatively higher  $\beta$  compared to the earlier parts of the growing season. Furthermore, higher  $\beta$  throughout the grazed growing season in 2004 compared to the harvest growing season in 2005 was likely due to comparably lower vegetation height which is kept continuously short by frequent grazing. Our results are in agreement with Frank (2003) who reported reduced ET in a grazed versus a non-grazed mixed-grass prairie. In contrast, Chen et al. (2009) did not observe any differences in energy partitioning in arid grazed versus non-grazed steppe. Meanwhile, Li et al. (2000) found that grazing intensity correlated positively with  $\beta$  and negatively with LE and surface albedo in a dry sandy grassland. Thus, the magnitude and patterns of grazing impacts may further depend on water availability and/or grazing intensity (i.e. stocking density and grazing frequency).

#### 4.2. Climatic constraints on seasonal CO<sub>2</sub> and energy exchanges

Although environmental conditions were mostly non-limiting for plant growth for most of the study period, the short summer drought in 2006 had a notable impact on transient CO<sub>2</sub> and energy fluxes. Moreover, the observed simultaneous decrease in GEP and ER and limited effect on NEE during this period were in contrast to the patterns observed following management events. As opposed to the sudden decrease in GEP following biomass removal during harvest and grazing, climate constraints tend to develop gradually over time during which autotrophic respiration may respond accordingly to the decreasing GEP which limits the net effect on NEE.

In comparison to NEE, the drought effect on the energy fluxes was more pronounced. Reduced soil water availability for evaporation and suppressed plant transpiration due to stomata closure likely resulted in lower potential for LE. In combination with commonly high temperatures and radiation energy supply during drought periods, more energy was thus partitioned into  $H$ , which may explain the higher  $\beta$  during that period.

Previous studies reported that differences in the frequency and distribution of rainfall events and variations in SWC may considerably affect short term ecosystem processes including plant

growth, soil respiration and LE (e.g. Lee et al., 2004; Xu et al., 2004; Fay et al., 2011). However, after accounting for the effects of temperature and PAR on GEP and ER, residuals were evenly distributed (not shown) along the observed range of SWC (for  $SWC > 0.15 \text{ m}^3 \text{ m}^{-3}$ , i.e. wilting point) suggesting a limited control of SWC variations during periods with non-constraining soil water conditions in our study. Moreover, we could not find any clear relationship between PPT and observed flux patterns and suspect that management practices overruled the impact of such PPT driven transient effects on the seasonal to annual scale. Similarly, Jaksic et al. (2006) did not observe any difference in the annual NEE between a wet and a dry year at another maritime grassland site.

#### 4.3. Management regime versus climate variability as a control on the annual $\text{CO}_2$ and energy exchanges

Annual  $\text{CO}_2$  and energy exchanges commonly co-vary with the inter-annual variability of environmental conditions and growing season length in regions with periodic climatic constraints (Ma et al., 2007; Ryu et al., 2008; Wohlfahrt et al., 2008a,b; Zhang et al., 2010), which may mask their dependence on the management regime. However, besides the short summer drought in 2006 (which had limited impact on NEE), severe weather conditions (e.g. drought, heat wave, snow and freezing periods) which might have constrained ecosystem processes were not evident during the remaining period of this study. Moreover, while inter-annual climate variations were rather small, the range of annual NEE exceeded  $500 \text{ g C m}^{-2} \text{ year}^{-1}$  and GEP, ER,  $H$  and  $\beta$  varied by 1.5–2 times over the six years. Thus, while variations in environmental conditions may have modified grassland  $\text{CO}_2$  and energy fluxes to some extent, our findings suggest that the differences in the management regime may be the main factor explaining the contrasting annual net  $\text{CO}_2$  and energy exchanges in this maritime grassland. In support of this argument, another multi-year (2003–2009; i.e. covering the same years) study in another Irish grassland found that annual NEE was little affected by inter-annual variations in environmental conditions given a constant management regime (one third harvest, two thirds grazed) (Peichl et al., 2011). It is noteworthy however that compared to NEE, the interpretation of management effects on annual GEP and ER in our study may be less certain because even moderate inter-annual climate variability in the maritime region may affect these two component fluxes (Peichl et al., 2011).

##### 4.3.1. Climate effects versus harvest and grazing effects

The predominant control of the management regime over climate on NEE and  $\beta$  in this maritime grassland is evident when comparing the years 2004 and 2005 which experienced no climatic constraints and rather similar seasonal patterns of the main environmental variables (i.e. temperature, radiation, VPD and soil moisture) but were subject to different management regimes, namely grazing in 2004 and harvest in 2005. This comparison suggests that grazing led to considerably greater annual net  $\text{CO}_2$  uptake, GEP, ER and  $\beta$  when compared to grassland managed for silage. The contrasting  $\text{CO}_2$  and energy fluxes may be explained by differences in vegetation dynamics. For instance, frequent vegetation re-growth periods during and following grazing may stimulate and maintain maximum growth rates and thus enhance GEP as well as autotrophic respiration. Furthermore, relative to silage management that allows grass to continuously grow (but with slowly decreasing productivity) until harvest, frequent grazing may result in an overall lower vegetation height and more dark soil exposure and thus reduced transpiration and albedo. The implications from these effects include more available energy being transferred into  $H$  but also higher water use efficiency in grazed grassland. The annual net  $\text{CO}_2$  uptake ( $\sim 200\text{--}400 \text{ g C m}^{-2} \text{ year}^{-1}$ ) under grazing

and silage management in this grassland is at the upper end of the range for global grasslands (Gilmanov et al., 2010) and well within the range of  $245\text{--}352 \text{ g C m}^{-2} \text{ year}^{-1}$  over six years reported for another maritime grassland managed for grazing and silage (Peichl et al., 2011).

##### 4.3.2. Climate effects versus kale planting and grass re-seeding effects

The predominant control of management regime over environmental conditions on the annual  $\text{CO}_2$  and energy exchanges is also apparent when comparing the years 2006 and 2007. Opposite to the common expectations of limited resource (i.e. water) availability effects on plant growth and energy partitioning, we noted greater GEP, net  $\text{CO}_2$  uptake and lower  $H$  in 2006 despite its relatively drier summer. Instead, a net  $\text{CO}_2$  loss and a more than two times greater  $H$  flux occurred in 2007 which, while similar to the remaining years, did not experience any environmental constraints. We therefore relate these contrasting patterns in annual fluxes to the impact from increased management intensity including kale planting and re-seeding in 2007. Furthermore, lower monthly and annual GEP in 2006 and 2007 and ER in 2006 compared to other years indicate that both kale planting and grass re-seeding decreased the potential for photosynthesis and autotrophic respiration through reducing biomass and vegetation cover. Although, enhanced soil C losses due to soil disturbance from ploughing (Vellinga et al., 2004; Willems et al., 2011), may have partly compensated for the reduction in autotrophic respiration and may explain the limited reduction of ER in 2007. In addition, while more frequent summer rainfall events in 2007 may have triggered enhanced soil respiration (Lee et al., 2004; Xu et al., 2004) and LE, similar ER and  $\beta$  during the wet summer period (June–August) in 2007 and the dry summer of 2006 as well as lower ER and  $\beta$  in 2007 compared to the wet summers of 2008 and 2009 (see Figs. 2 and 3) suggest limited effects from the different patterns in PPT. Instead, higher ER and  $\beta$  in April and May 2007 following re-seeding (fields E and F) and kale planting (fields A and B) events compared to 2006 indicate a major control from these management practices. Thus, although we cannot exclude additional environmental effects, there is strong evidence for a severe impact from the frequent disturbances via management practices (specifically kale planting and re-seeding, but also frequent grazing and harvest) on the grassland net  $\text{CO}_2$  uptake and energy exchange.

## 5. Conclusions

This study investigated management and climate effects on seasonal and annual  $\text{CO}_2$  and energy exchanges in an intensively managed grassland in the maritime climate of southeast Ireland using six years of eddy-covariance data. Although variations and constraints in environmental conditions affected transient  $\text{CO}_2$  and energy fluxes and in some cases masked the direct effects from individual management practices, we conclude that the management regime was the primary control on the patterns in seasonal and annual  $\text{CO}_2$  and energy exchanges in this maritime grassland.

Specifically, our study highlights that given similar and non-constraining environmental conditions, the observed effects on  $\text{CO}_2$  and energy fluxes from biomass removal via harvest and grazing differed in magnitude and duration between these two management practices. Moreover, the effects from these practices were dependent on their timing which we relate to the seasonal change in biomass and surface cover, plant (re-)growth and transpiration capacities. On the annual scale, we found that greater annual  $\text{CO}_2$  uptake and enhanced  $H$  fluxes (i.e. warming effect) occurred under grazing compared to the harvest (silage) regime which was likely the result of enhanced plant productivity through frequent

**Table A1**  
Harvesting, grazing, kale planting and re-seeding events at the Wexford grassland in 2004–2009.

Date	DOY	Management activity	Field codes + annual management regime <sup>a</sup> + management events <sup>b</sup>					
			Field A G	Field B G	Field C G	Field D G	Field E S1	Field F S1
<b>2004</b>								
Feb		Grazing	15–17.2	15–18.2	18–20.2	19–22.2	23–25.2	25–27.2
April/May		Grazing	11.13.5	25–26.4	27–28.4	7–9.5		
May 31	152	1st cut silage					1st cut	1st cut
June		Grazing	15–16.6	6–8.6	8–10.6	12–14.6	10–12.6	
July		Grazing	5.7	4–5.7	6.7	14–16.7	12–14.7	17–18.7
August		Grazing	2–7.8	7–13.8	14–17.8	16–19.8	18–19.8	19–20.2
September		Grazing		1–3.9	2–8.9	5–8.9	4–6.9	7–10.9
October		Grazing	15–17.10	17–18.10	18–19.10	19–20.10	20–21.10	22.10
November		Grazing	12.11	13.11	14.11	15.11	16–17.11	18.11
Date	DOY	Management activity	Field codes + annual management regime <sup>a</sup> + management events <sup>b</sup>					
			Field A S2	Field B S2	Field C S2	Field D S2	Field E S2'	Field F S2
<b>2005</b>								
February		Grazing	3–9.2	10–13.2	14–19.2	17–25.2	27.2–4.3	22.2–2.3
June 6	157	1st cut silage	1st cut	1st cut	1st cut	1st cut	1st cut	1st cut
June		Grazing	8.6	8.6	9.6	9.6	9.6	9.6
August 4	216	2nd cut silage	2nd cut	2nd cut	2nd cut	2nd cut	2nd cut	2nd cut
September		Grazing	8–11.9	12–16.9	15–17.9	18–20.9	20–22.9	22–24.9
November		Grazing	29–30.10	30–31.10	10–14.11	15.11	20–24.11	25–29.11
Date	DOY	Management activity	Field codes + annual management regime <sup>a</sup> + management events <sup>b</sup>					
			Field A S2	Field B S2	Field C S2	Field D S2	Field E S1/K	Field F S1/K
<b>2006</b>								
May 31	151	1st cut silage	1st cut	1st cut	1st cut	1st cut	1st cut	1st cut
June 8	159	Rotavated + sowed					Rotavated + kale seed	Rotavated + kale seed
August 3	215	2nd cut silage	2nd cut	2nd cut	2nd cut	2nd cut		
September		Grazing	3–4.9	3–4.9	1–4.9	1–2.9		
October		Grazing	20–29.9	20–29.9				
November/December		Grazing (kale)	20–29.10	20–29.10	21–31.10	21–31.10	21.11–31.12	
Date	DOY	Management activity	Field codes + annual management regime <sup>a</sup> + management events <sup>b</sup>					
			Field A S1/K	Field B S1/K	Field C G/RS	Field D G/RS	Field E G/RS	Field F G/RS
<b>2007</b>								
January/February		Grazing (kale)					1.1–19.2	1.1–19.2
Mar		Grazing	16–22.3	16–22.3				
April		Grazing	6–14.4	6–14.4				
April 11	101	Ploughed + rolled					Ploughed	Ploughed
April 16	106	Rotavated + rolled					Rotavated	Rotavated
April 18	108	Sowed grass					Grass seed	Grass seed
May		Grazing	25–26.5	25–26.5				
May 23	143	1st cut silage	1st cut	1st cut				
June 5	156	Harrowed + sowed + rolled	Harrowed + kale seed	Harrowed + kale seed				
June		Grazing			4–10.6	4–10.6	16–25.6	16–25.6
July		Grazing			1–6.7	1–6.7	11–15.7	11–15.7
August		Grazing			25–31.7	25–31.7		
August 27	239	Subsoiled + rolled			Subsoiled	Subsoiled	8–18.8	8–18.8
August 28	240	Harrowed + rolled			Harrowed	Harrowed		
August 29	241	Sowed + rolled			Grass seed	Grass seed		
September/October		Grazing					18.9–5.10	18.9–5.10
November		Grazing			2–7.11	2–7.11	17–29.11	17–19.11
December		Grazing (kale)	3–31.12	3–31.12				
Date	DOY	Management activity	Field codes + annual management regime <sup>a</sup> + management events <sup>b</sup>					
			Field A S2	Field B S2	Field C S2	Field D S2	Field E S2'	Field F S2
<b>2008</b>								
		Grazing + harvest	No detailed information available <sup>c</sup>					
		Grazing + harvest	No detailed information available <sup>c</sup>					

<sup>a</sup> Annual management regime codes: G, grazing; S1, one silage cut per year; S2, two silage cuts per year; K, kale planting for winter forage production; RS, re-seeded with grass.

<sup>b</sup> Grazing periods are indicated with start–end date (day/month); dates for harvest, kale planting, re-seeding and soil work events are presented in the left column entitled 'Date'.

<sup>c</sup> Grazing and harvest practices occurred, however, details on the timing, frequency and intensity of the management events at the individual fields were not available for the years 2008 and 2009.

vegetation re-growth and reduced transpiration due to relatively shorter vegetation in grazed grassland.

We further conclude that periodic winter kale planting and grass re-seeding during spring/summer decreased the annual net CO<sub>2</sub> uptake and resulted in an annual net CO<sub>2</sub> emission while simultaneously increasing  $H$  and  $\beta$ . The removal of photosynthesizing and transpiring vegetation during the peak growing season (late spring and early summer), enhanced decomposition of soil organic matter following scarification and bare soil exposure associated with kale planting and re-seeding events are the likely causes for these observed effects. In the absence of such activities, this maritime grassland supported substantial uptake of atmospheric CO<sub>2</sub>.

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## Appendix A

### Table A1.

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