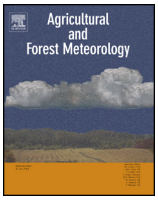
Agricultural and Forest Meteorology 228–229 (2016) 370–383

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Carbon balance of an intensively grazed permanent grassland in southern Belgium

Louis Gourlez de la Motte[a,*], Elisabeth Jérôme[a], Ossénatou Mamadou[a,c], Yves Beckers[b], Bernard Bodson[b], Bernard Heinesch[a], Marc Aubinet[a]

[a] University of Liege—Gembloux Agro-Bio Tech, TERRA, Exchange Ecosystem Atmosphere, Avenue de la Faculté, 8, B-5030 Gembloux, Belgium
[b] University of Liege—Gembloux Agro-Bio Tech, TERRA, Passage des Déportés, 2, B-5030 Gembloux, Belgium
[c] University of Porto-Novo, Institute of Mathematics and Physical Sciences (IMSP), BP 613, Porto-Novo, Benin

ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form 10 June 2016
Accepted 13 June 2016
Available online 30 June 2016

Keywords:
Grassland
Carbon budget
Carbon dioxide flux
Management
Eddy covariance
Uncertainty

ABSTRACT

Grasslands are an important component of the global carbon balance, but their carbon storage potential is still highly uncertain. In particular, the impact of weather variability and management practices on grassland carbon budgets need to be assessed. This study investigated the carbon balance of an intensively managed permanent grassland and its uncertainties by drawing together 5 years of eddy covariance measurements and other organic carbon exchanges estimates. The results showed that, despite the high stocking rate and the old age of the pasture, the site acted as a relatively stable carbon sink from year to year, with a 5-year average net biome productivity of −161 [−134 −180] g C m^{-2} yr^{-1}. Lateral organic carbon fluxes were found to increase the carbon sink because of high carbon imports (organic fertilization, feed complements) and low carbon exports in form of meat compared to dairy pastures. The cattle stocking density was adapted to grass production, which itself depends on weather conditions and photosynthesizing area, in order to maintain a steady meat production. This resulted in a coupling between grazing management and weather conditions. As a consequence, both weather and grazing impacts on net ecosystem exchange were difficult to distinguish. Indeed, no correlation was found between weather variables anomalies and net ecosystem exchange anomalies. This coupling could also partly explain the low C budget inter-annual variability. The findings in this study are in agreement with those reported by other studies that have shown that well-managed grasslands could act as carbon sinks.

1. Introduction

Grasslands cover 40% of the Earth's ice-free land surface (Steinfeld et al., 2006) and are characterized by soils with a high soil carbon (C) content (Conant et al., 2001). They therefore constitute an important component of the global C balance (IPCC, 2007). Studies assessing the C balance under grasslands are relevant because grassland C sequestration can play an important role in mitigating the total greenhouse gas emissions from livestock production systems (Lal, 2004; Soussana et al., 2010). There is a strong need, therefore, to accurately evaluate grassland C sequestration (Herrero et al., 2011).

Grassland C sequestration can be determined directly by measuring changes in soil organic carbon (SOC) stocks or indirectly by measuring the balance of C fluxes at the system boundaries. Contrary to studies based on SOC change measurements (Goidts and van Wesemael, 2007; Lettens et al., 2005a,b; Meersmans et al., 2011, 2009), studies assessing the total C grassland budget by combining eddy covariance measurements with measurements of other C fluxes enable investigations to be made of seasonal, annual and inter-annual C flux dynamics and budgets (Byrne et al., 2007; Gilmanov et al., 2010; Klumpp et al., 2011; Mudge et al., 2011; Peichl et al., 2012, 2011; Soussana et al., 2010; Zeeman et al., 2010). They also enable the impact of specific management practices or weather conditions to be analyzed (Aires et al., 2008; Allard et al., 2007; Ammann et al., 2007; Ciais et al., 2005; Harper et al., 2005; Heimann and Reichstein, 2008; Hussain et al., 2011; Jaksic et al., 2006; Jongen et al., 2011; Klumpp et al., 2011; Peichl et al., 2012; Suyker et al., 2003; Teuling et al., 2010).

The results of these studies reveal strong site-to-site variability because of differences in pedoclimatic conditions and management

---

* Corresponding author.
E-mail addresses: l.gourlezdelamotte@ulg.ac.be (L. Gourlez de la Motte), jerome.elisabeth@gmail.com (E. Jérôme), ossenatou.mamadou@gmail.com (O. Mamadou), yves.beckers@ulg.ac.be (Y. Beckers), b.bodson@ulg.ac.be (B. Bodson), bernard.heinesch@ulg.ac.be (B. Heinesch), marc.aubinet@ulg.ac.be (M. Aubinet).

http://dx.doi.org/10.1016/j.agrformet.2016.06.009
0168-1923/

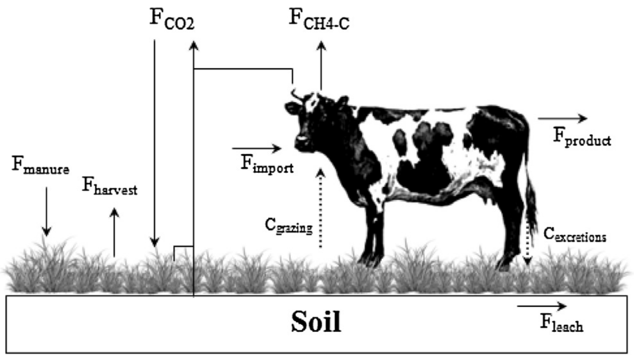


Fig. 1. Carbon (C) cycle of the grazing animal. Solid arrows represent C components of the net biome productivity (see Eq. (1)). Dashed arrows represent internal C fluxes.

practices: they report increases as losses or no change in soil C balances (Soussana et al., 2010). Grassland C balance and the impact of environmental conditions and management practices on this balance are still not well understood (Mudge et al., 2011; Soussana et al., 2010). Grazing is known to directly affect the carbon dioxide (CO_2) net ecosystem exchange (NEE) via livestock respiration and indirectly via biomass consumption, natural fertilization through excreta and soil compaction (Jérôme et al., 2014). A high stocking rate could impact the carbon budget by either reducing growth primary productivity (GPP) through defoliation (Jérôme et al., 2014) but also by stimulating GPP by removing less productive plant material before withering. The land use and the management prior to the study could also affect the carbon budget. Indeed, interventions such as ploughing, reseeding, land use change from a crop field to a grassland and improved management could still increase the CO_2 accumulation many years later before reaching an eventual equilibrium (Smith, 2014).

The main objective of this research was to assess the total C balance of a grazed grassland located in Wallonia (southern Belgium) by measuring all C fluxes exchanged at the system boundaries, using the eddy covariance method, direct measurements made in the field, estimates by the farmer and literature data when no measurements were available. The study site has been a permanent grassland since it was used for grazing (probably more than a century). It has been intensively managed with high stocking rates (around 2 Livestock units (LU) per hectare per year) and the application of mineral and organic fertilization for more than 40 years.

This paper also attempts to answer a few specific questions: (i) is a grassland established for more than a century and intensively managed for more than 40 years with a stocking rate exceeding 2 LU per hectare a C sink or a source? (ii) How do management practices and weather conditions affect the C budget? (iii)What are the main sources of uncertainties and how robust is the methodology used to establish the C budget? The research covered 5 years of measurements, providing an opportunity to assess the grassland C budget on monthly and annual scales, evaluate its uncertainties and identify some drivers linked with weather or grassland management.

2. Material and method

2.1. Carbon balance of the pasture

The net balance of C fluxes exchanged at the system boundaries, commonly known as net biome productivity (NBP, $g\,C\,m^{-2}\,yr^{-1}$), was defined by Soussana et al. (2010) for temperate grazed grassland as (Fig. 1):

$$NBP = F_{CO2} + F_{CH4} + F_{manure} + F_{import} + F_{harvest} + F_{product} + F_{leach} \quad (1)$$

where F_{CO2} is the net ecosystem carbon dioxide (CO_2) exchange, corresponding to the difference between gross CO_2 uptake via photosynthesis (gross primary productivity, GPP) and CO_2 loss via respiration (total ecosystem respiration, TER, including cattle respiration); F_{CH4} is the C lost through methane (CH_4) emissions by grazing cattle (the CH_4 fluxes from the soil were considered as negligible as their magnitude was only 2.5% of the cattle fluxes according to (Dumortier et al., submitted); F_{manure} and F_{import} are the lateral organic C fluxes imported into the system through manure and/or slurry application and supplementary feed, respectively; $F_{harvest}$ and $F_{product}$ are the lateral organic C fluxes exported from the system through mowing and animal products (meat), respectively and F_{leach} represents organic and/or inorganic C losses through leaching. Throughout this paper, we adopt the micrometeorological convention that fluxes from the ecosystem are positive and that fluxes to the ecosystem are negative. A negative NBP therefore corresponds to C uptake.

2.2. Site description

The research was carried out at the Dorinne terrestrial observatory (DTO) (50° 18′ 44″ N; 4° 58′ 07″ E). Dorinne is 18 km south/south-east of Namur, in the Condroz region in Belgium. The Condroz region is characterized by a succession of depressions and crests with soils suitable for arable land use (mainly cereals and sugar beet) and pastures for cattle breeding (Goidts and van Wesemael, 2007). The climate is temperate oceanic. The mean annual air temperature is 10 °C, the annual precipitation is 847 mm and the main wind directions are south-west (IRM, 2011) and north-east. The field is bordered on the south-west by a cultivated field and by pastures on the north-east. The research site is a permanent grassland covering 4.22 ha and dominated by a large colluvial depression exposed south-west/north-east. This depression is situated on a loamy plateau with a calcareous and/or clay substrate. The altitude varies from 240 m (north-east) to 272 m (south). So far as we know, the field has never been cultivated and has been permanent grassland since it started being used for grazing (probably for more than a century). It has been intensively used for cattle grazing, with the application of organic (cattle slurry and manure) and inorganic fertilizers, for about 40 years. The grassland species composition is: 66% grasses, 16% legumes and 18% other species. The dominant species are perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). There has been no renovation of the grass vegetation (ploughing – resowing) for more than 50 years. Flux measurements have been taken since spring 2010. The data given in this study cover 5 full years of measurements from 12 May 2010, when the eddy covariance measurements began, to 12 May 2015.

2.3. Grassland management

The field was intensively managed and grazed during the growing season by Belgian Blue cattle (heifers, suckler cows, breeding bulls, calves). The rotation between stocking (periods with cattle) and recovery periods without cattle (rest periods) depended on herbage growth and its consumption by cattle. In this context, weather conditions limited the grazing pressure, which was adjusted when necessary. Feed (corn silage, hay and a mixture of straw and ProtiWanze®, a by-product of bio-ethanol production) was distributed when necessary to supplement grass shortage (drought or beginning/end of the grazing season). Fertilizers, including mineral and organic fertilizers, were applied at various times to the field throughout the growing season (Table 1). The reference unit used for calculating LU is the grazing equivalent of one 600 kg liveweight (LW) adult dairy cow producing 3000 kg of milk annually, without additional concentrated feed (Eurostat, 2013).

Table 1
List of management activities at the Dorinne Terrestrial Observatory. Weighing values are presented with a 95% confidence interval.

Before the start of the experiment		
10-Mar-10	fertilization: compost (t FM ha^{-1})	11.0
25-Mar-10	fertilization: 10/8/4 + selenstar® (Se) (t ha^{-1})	0.6
2010		
3-Jun–6-Jun-10	cut-harvest (t DM ha^{-1})	2.7
10-Jun-10	fertilization: 24/0/0 + selenstar® (Se) (t ha^{-1})	0.2
20-Jun–11-Jul-10	supplements: corn silage/mixture (t FM ha^{-1})	0.9
Jul-10	scattering of livestock droppings	
31-Jul–21-Aug-10	supplements: mixture (t FM ha^{-1})	1.1
5-Aug-10	heifers weighing (kg animal^{-1})	436 ± 13
7-Sep–22-Nov-10	supplements: mixture (t FM ha^{-1})	3.5
Sep-10	scattering of livestock droppings	
Total fertlization for 2010 (kg N ha^{-1})		164
2011		
26-Jan-11	heifers weighing (kg animal^{-1})	549 ± 20
20-Feb-11	fertilization: compost (t FM ha^{-1})	12.0
9-Mar-11	fertilization: 18/5/5 + Mg (t ha^{-1})	0.4
22-Mar-11	liming: magnesian lime (t ha^{-1})	1.5
9-Apr–23-Apr-11	supplements: mixture (t FM ha^{-1})	0.4
13-May-11	fertilization: 10/8/4 + selenstar® (Se) (t ha^{-1})	0.3
3-Nov–2-Dec-11	supplements: hay (t FM ha^{-1})	0.3
Total fertlization for 2011 (kg N ha^{-1})		162
2012		
19-Mar-12	fertilization: 10/8/4 + selenstar® (Se) (t ha^{-1})	0.4
24-Mar–2-Apr-12	supplements: mixture (t FM ha^{-1})	0.3
30-May-12	fertilization: n27 (t ha^{-1})	0.2
13-Jul-12	fertilization: n27 (t ha^{-1})	0.2
31-Oct-12–14-Nov-12	supplements: hay (t FM ha^{-1})	0.1
Total fertlization for 2012 (kg N ha^{-1})		148
2013		
3-Apr-13	fertilization: 10/8/4 (t ha^{-1})	0.4
3-Apr-13	scattering of livestock droppings	
13-Jul-13	fertilization: n27 (t ha^{-1})	0.2
10-Sep-13	scattering of livestock droppings	
Total fertlization for 2013 (kg N ha^{-1})		94
2015		
11-Mar-15	fertilization: 10/8/4 (t ha^{-1})	0.3
15-Mar-15	scattering of livestock droppings	
Total fertlization for 2015 (kg N ha^{-1})		30

Breeding bulls and suckler cows correspond to 1 LU, and heifers and calves to 0.6 and 0.4 LU, respectively.

2.4. CO_2 flux measurements

The CO_2 flux was measured using the eddy covariance technique. This involved using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Ltd, UK) coupled with a fast CO_2-H_2O non-dispersive infrared gas analyzer (IRGA) (LI-7000, LI-COR Inc., Lincoln, NE, USA) to measure fluxes of CO_2, latent heat, sensible heat and momentum. The system was installed on a mast at a height of 2.6 m above ground in the middle of the field and was surrounded by a secured enclosure. Air was sucked into the IRGA through a tube (6.4 m long; inner diameter 4 mm) by a pump (NO22 AN18, KNF Neuberger, D) with a 12 l min^{-1} flow. Data were sampled at a rate of 10 Hz. Zero and span calibrations were performed for CO_2 and H_2O about once a month. Pure nitrogen (Alphagaz 1, Air Liquide, Liege, Belgium) was used for the zero and 350 μmol mol^{-1} mixture (Chrystal mixture, Air Liquide, Liege, Belgium) for the span.

F_{CO2} was computed half-hourly as the sum of the turbulent flux measured by the eddy covariance system and of the storage term (Foken et al., 2012a). Flux computation was performed using the EDDYSOFT software package (EDDY Software, Jena, Germany, Kolle and Rebmann, 2007) and the 10 Hz time series data. All the computation and correction procedures used were the standard procedures defined within the context of the EUROFLUX – CARBOEUROFLUX – CarboEurope IP networks (Aubinet et al., 2000, 2012a,b). Double rotation was applied to wind velocity in order to align the streamwise velocity component with the direction of the mean velocity vector (Rebmann et al., 2012). Fluxes were corrected for high frequency losses following an original procedure based on the sensible heat cospectra. The complete procedure has been described by Mamadou et al. (2016).

The turbulent fluxes were scrutinized using a stationary test with a selection criterion of 30% according to (Foken et al., 2012b; Foken and Wichura, 1996). Data were separated between night and day using a photosynthetic photon flux density (PPFD) criterion, with a threshold of 5 μmol m^{-2} s^{-1}. In order to avoid night CO_2 flux underestimation, CO_2 fluxes measured under low nighttime turbulence conditions were filtered (Aubinet et al., 2012a,b; Goulden et al., 1996). A critical threshold of u^* was determined at the point where the relationship between u^* and the bin averaged temperature normalized nighttime F_{CO2} flattens. A value of 0.13 m s^{-1} was found and measurements with u^* below this value were systematically discarded.

Net ecosystem exchange (NEE) gaps were filled using the online REddyProc gapfilling and flux partitioning tool (Reichstein et al., 2005). The reference temperatures used to fill the gaps was the soil temperature at a depth of 2 cm. NEE partitioning into GPP and TER was also calculated using the same tool and same reference temperature.

Measurement footprint was calculated using an analytical model following Kormann and Meixner (2001). On average, during instable conditions, 77% of the footprint area was covered by the measured pasture. During stable conditions, this footprint area is much larger. However, most of the fluxes measured during stable conditions were discarded by the u* filtering (Dumortier et al., submitted).

In order to investigate inter-annual variability, flux (NEE, GPP, TER) and weather variable anomalies (temperatures, radiation, soil humidity...) were computed as follows: first, monthly and annual sums (for fluxes and precipitation) or averages (for other weather variables) were calculated. For each variable, a 5-year average was computed and anomalies for a given year were calculated as the difference between the variable (monthly/annual sum or average) for the considered year and its 5-year average.

2.5. Meteorology

Supporting measurements included air temperature and relative humidity (RHT2nl02, Delta-T Devices Ltd, Cambridge, UK), soil temperature (Pt 1000) at depths of 2, 5, 10, 25 and 50 cm and soil moisture (ThetaProbe, Delta-T Devices Ltd, Cambridge, UK) at depths of 5, 25 and 50 cm, gross and net radiation (CNR4, Kipp & Zonen, Delft, The Netherlands), rainfall (tipping bucket rain gauge, 52203, R.M. Young Company, Michigan, USA) and atmospheric pressure (144S BARO, SensorTechnics, Puchheim, Germany). Meteorological data were sampled at a rate of 0.1 Hz and averaged (summed for precipitation) every 30 min. Data were recorded on a data logger (CR3000, Campbell Scientific Ltd, UK). Raw eddy covariance data, sampled at 10 Hz, and half-hourly meteorological data were then stored on a 2 GB compact flash card. Growing degree days (GDD) were computed in order to evaluate the impact of winter temperatures on NEE. GDD was calculated as the sum of daily mean air temperatures above 0 °C from 1 January (Theau and Zerourou, 2008) to 31 March.

2.6. Biomass measurements

2.6.1. Herbage mass

Herbage mass in the field (HM) was deduced from herbage height (h) measurements with a rising plate meter. The mean canopy height was determined manually by measuring the center height of a light-weight plate of 0.25 m^2 dropped onto the canopy at 60 points in the field. This estimation was then converted into HM using allometric relationships fitted on to direct sampling measurements. Samples were taken from the field (nine sample surveys, providing about 20–25 samples per survey) and from three secured enclosures (weekly measurements, see Section 2.6.2) during the stocking periods between 12 May 2010 and 11 May 2012. The samples were mowed at a height of 0.05 m using battery-powered hand clippers and a quadrat (0.5 × 0.5 m). They were then dried at 60 °C in a forced-air oven until constant weight was achieved. A relationship between grass height difference before and after the cut and harvested dry matter was established:

$$\mathrm{HM} = -2.4 \times h^2 + 203.7 \times h \quad \left(R^2 = 0.77; n = 381\right) \qquad (2)$$

where n is the number of samples.

2.6.2. Grass growth under grazing

Three secured enclosures from which animals were excluded were installed in the field to assess grass growth under grazing over a period (R_i). Each enclosure consisted of five strips (0.5 × 2 m). By successively cutting the strips, grazing was simulated and the HM accumulation under grazing was deduced from the canopy height measurements. Measurements were conducted over 5 weeks during the stocking cycle. On week 1, strip 1 was mowed and each week thereafter strip 1 and, successively, strips 2–5 were mowed. A weekly HM accumulation was obtained from the difference between average initial and final grass height of each strip and equation 2 for each secured enclosure. R_i was calculated as the average HM accumulation for the three secured enclosures over a given period.

2.7. Organic carbon exports and imports influencing net biome productivity

F_{CH4} was estimated as a constant fraction of the ingested dry matter (dry matter intake, DMI) by cattle during grazing using the dimensionless methane conversion factor Y_m, which is the methane emitted per kg of DMI. We assumed a typical Y_m value of 6% (Lassey, 2007). The DMI corresponded to the sum of the HM intake by cattle during grazing and the dry matter of supplementary feed imported. F_{manure} and F_{import} were calculated by multiplying the imported mass by its dry matter fraction and its dry matter C content (Table 2). $F_{harvest}$ was estimated by multiplying the HM difference in the field before and after the cut with the grass C content (Table 2). $F_{product}$ was estimated by multiplying the daily cattle LW gain for a growing animal, fixed at 0.647 kg LW $animal^{-1}$ day^{-1} based on *in situ* measurements conducted in Year 1, with a concentration factor of 0.165 ± 0.002 kg C $(kg\,LW)^{-1}$ for Belgian Blue (Mathot et al., 2012). As it was not possible to measure F_{leach} at DTO, it was fixed at 7 ± 7 g C m^{-2} yr^{-1}, based on the work of Schulze et al. (2009).

C content analyses of samples taken *in situ* (herbage, complementary feed, compost) were conducted by the Forest Ecology and Ecophysiology Unit at the Institut National de la Recherche Agronomique (INRA) (UMR 1137 INRA-UHP) using the Dumas method (Dumas, 1831). After drying and grinding (Cyclotec – 1 mm screen), the samples were analyzed using an elemental analyzer (NCS2500, CE instrument Thermo Quest, Italy).

2.8. Other carbon fluxes

In order to analyze in detail all the C fluxes exchanged in this grassland and specifically those linked to grazing, we established the C cycle of the animals. It sought to estimate the components described in the sections below (Fig. 1).

2.8.1. Cattle forage mass consumption and above-ground net primary productivity

For a period of interest (stocking or rest period), HM in the field was measured at the beginning ($HM_{i,beg}$) and end ($HM_{i,end}$) of the period, following the procedure described in Section 2.6.1. During grazing periods, the grass growth under grazing R_i was deduced from secured enclosure measurements, following the procedure described in Section 2.6.2.

From these measurements, we deduced the C intake through HM consumption by cattle during grazing ($C_{grazing,i}$) as (Macoon et al., 2003):

$$C_{grazing,i} = C_{content} \times \left(HM_{i,beg} - HM_{i,end} + R_i\right) \qquad (3)$$

where $C_{content}$ is the grass C content obtained from laboratory measurements.

We also deduced the above-ground net primary productivity ($ANPP_i$). It was computed as:

$$ANPP_i = C_{grazing,i} + C_{content} \times (HM_{t+1} - HM_t) \qquad (4)$$

where ($HM_{t+1} - HM_t$), accounted only when positive, is the un-grazed biomass (biomass refusal because of excretions, trampling...) and $C_{grazingi}$ was zero during rest period. Annual $C_{grazing}$ and ANPP were obtained by summing $C_{grazing,i}$ and $ANPP_i$ for all periods of interest.

Table 2
Dry matter fraction (% DM) and dry matter C content (%C) used to calculate the net biome productivity (NBP) components linked to management practices.

NBP components	Sample taken *in situ*	% DM	Origin	% C	Origin
F_{manure}	Compost	21	Drying: 60 °C in a forced-air oven until constant weight was achieved	36	Grinding: Cyclotec – 1 mm screen Laboratory: Forest Ecology and Ecophysiology Unit, Institut National de la Recherche Agronomique – INRA) (UMR 1137 INRA-UHP). Method: Dumas, 1831. Analyzer: Elemental analyzer (NCS2500, CE instrument Thermo Quest, Italy).
F_{import}	Corn silage	44	Data provided by the farmer	40	
	Straw + ProtiWanze®	45		42	
	Hay	85		42	
$F_{harvest}$	Grass	–	Difference in grass height before and after harvest converted to herbage mass dry matter using equation 2	42	

2.8.2. *Livestock carbon dioxide losses at grazing*

Livestock CO_2 emissions ($F_{CO2,livestock}$) were estimated from the C intake measurements. As most of the C ingested was digestible and therefore respired shortly after intake, we obtained:

$$F_{CO2,livestock} = (OMD \times C_{intake}) - F_{CH4} - F_{product} \quad (5)$$

where OMD (%) is organic matter digestibility and C_{intake} is the sum of $C_{grazing}$ and F_{import}.

In the same way, livestock C excreted ($C_{excretions}$) was estimated as:

$$C_{excretions} = NOMD \times C_{intake} \quad (6)$$

where NOMD (%) is non-organic matter digestibility.

OMD and NOMD values were obtained from the near infrared reflectance spectrometry analyses (NIRS system monochromator 5000–1100 to 2498 nm wavelength by 2 nm steps; Decruyenaere et al., 2009) of samples taken *in situ* (herbage, supplementary feed). After the samples were dried and ground (Cyclotec – 1 mm screen), analyses were conducted at the Walloon agricultural research center (CRA-W).

2.9. *Uncertainty assessments*

Eddy covariance fluxes are affected by uncertainties due to the presence of both random and systematic errors (Baldocchi, 2003; Hollinger and Richardson, 2005; Richardson et al., 2006). Systematic errors are due mainly to the underestimation of night fluxes measured during low turbulent conditions (Ammann et al., 2007; Rutledge et al., 2015) and to high frequency losses. In both cases, a correction procedure was applied, as described in Section 2.4. As these procedures are themselves not exact, however, residual uncertainties remain, mainly because of the choice of the correction parameters (u* threshold for night flux correction, cut-off frequency for high frequency correction).

In order to assess the overall uncertainty of our measurements, we considered four main sources of uncertainty: the random error affecting both measured fluxes and filled data (σ_r) resulting from the random character of turbulence and affecting not only measurements but also gap filled data; an additional systematic error resulting from the procedure used to fill the data (σ_{gf}; i.e., two errors associated with the gap filling) and remaining uncertainties after the application of the night flux (u* threshold chosen to filter the nighttime data [σ_{u*}]); and frequency corrections (cut-off frequency used for the spectral correction [σ_{f_0}]).

2.9.1. *Estimation of the random uncertainty (σ_r)*

The term σ_r combines the random error that affects both measured and filled data. This was calculated adapting a procedure described by Dragoni et al. (2007). The procedure follows three steps. First, the random error for the measured half-hourly flux (ε_m) was computed using the successive days approach developed by Hollinger and Richardson (2005). In this approach, ε_m is estimated as the absolute difference between two valid successive day fluxes at the same hour and during similar weather conditions (maximum PPFD range of 75 µmol m^{-2} s^{-1}, maximum T_s range of 3°, maximum horizontal wind velocity range of 1 ms^{-1}). The standard deviation of this error, $\sigma(\varepsilon_m)$, was then computed for flux classes (same number of observations) and a relationship between $\sigma(\varepsilon_m)$ and flux magnitude was established (Richardson et al., 2006).

This gave at DTO:

$$\sigma(\varepsilon_m) = -0.11 \times F_{CO2} + 147 \quad \text{for } F_{CO2} \le 0 \quad \left(R^2 = 0.90\right) \quad (7a)$$

$$\sigma(\varepsilon_m) = 0.30 \times F_{CO2} + 0.08 \quad \text{for } F_{CO2} > 0 \quad \left(R^2 = 0.97\right) \quad (7b)$$

In the second step, a similar approach was used for the filled data. All valid half-hourly data were marked as artificial gaps and filled using the online REddyProc gapfilling tool (Reichstein et al., 2005). This gave a measured value (F_{CO_2}) and a modelled value (M) for each non-missing NEE value. The standard deviation of the residue ($\sigma(\varepsilon_{gf})$) was calculated as $\sigma(F_{CO2} - M)$ for pre-made flux classes with a same number of observations. A relationship between $\sigma(\varepsilon_{gf})$and the flux magnitude was then established. This gave:

$$\sigma\left(\varepsilon_{gf}\right) = -0.075 \times F_{CO2} + 1.86 \quad \text{for } F_{CO2} \le 0 \quad \left(R^2 = 0.87\right) \quad (8a)$$

$$\sigma\left(\varepsilon_{gf}\right) = 0.15 \times F_{CO2} + 0.9 \quad \text{for } F_{CO2} > 0 \quad \left(R^2 = 0.71\right) \quad (8b)$$

Finally, in the third step, a Monte Carlo simulation was used to estimate the annual random uncertainty. A random error (ε_s) was generated for each half-hourly NEE value assuming a double exponential distribution (Hollinger and Richardson, 2005) with a zero mean, a standard deviation of $\sigma(\varepsilon_m)$ for measured values and $\sigma(\varepsilon_{gf})$ for filled values. Simulated NEE_s values were then calculated as $NEE_s = NEE + \varepsilon_s$and the annual NEE calculated as the sum of NEE_s. This process was repeated 100 times and σ_r was calculated as the standard deviation of the 100 annual NEE_s values.

2.9.2. *Estimation of the gap filling uncertainty (σ_{gf})*

As described above, the gap filling procedure led to a random error that is included in the σ_r term. Another non-random source of uncertainty linked to this procedure was identified, however. The preceding approach supposes that the mean residual gap filling residue ($\hat{\varepsilon}_{gf}$) is zero in each flux class. This was, however, not the case (Fig. 2), as we found that it differed from zero for high absolute fluxes. This would mean that the gap filling procedure underestimates high fluxes both at night and during the day. In order to test the potential influence on annual sums, we conducted another Monte Carlo simulation, but this time used distributions with the corresponding $\hat{\varepsilon}_{gf}$ as means for filled data. σ_{gf} was then calculated

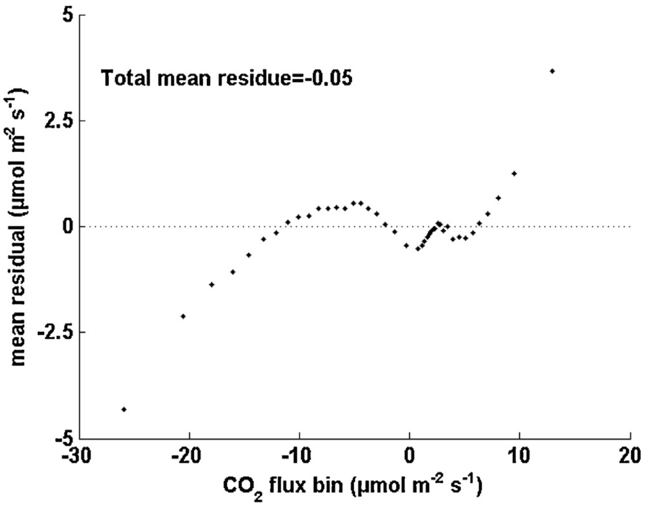


Fig. 2. Relationship between the flux magnitude and the mean residuals for flux classes. Residual values are calculated as the difference between the measured flux and the flux calculated by the gap filling procedure. All values are given in µmol m^{-2} s^{-1}.

as the difference between the average of the 100 annual NEEs and the actual NEE value for each year.

2.9.3. *Estimation of the u* threshold uncertainty (σ_{u*})*

In order to estimateσ_{u*}, annual NEE was calculated by filtering the nighttime data using plausible u* thresholds around 0.13 (0.08–0.18) and filling the data. σ_{u*} was then calculated as half the difference between the annual NEE values calculated using those thresholds (Rutledge et al., 2015).

2.9.4. *Estimation of the cut-off frequency uncertainty (σ_{f_0})*

In order to estimateσ_{f_0}, the standard deviation of the cut-off frequency distribution (0.05 Hz) was calculated. New linear regressions of the correction factor as a function of the wind velocity were established for two new cut-off frequencies 0.37 ± 0.05 Hz for stable and unstable conditions. The fluxes were then corrected using the regression parameters and an annual NEE was calculated for both cut-off frequencies. $\sigma_{f_0}$was then calculated as half the difference between those values.

2.9.5. *Estimation of the total NEE uncertainty (σ_{NEE})*

These sources of NEE uncertainties were combined following the random error propagation rules. σ_{gf} was added as a positive one-sided uncertainty. For the 5-year average uncertainty, σ_{gf}, σ_{u*} and σ_{f_0} were simply averaged while $\sigma_r$was averaged following the random error propagation rule.

2.9.6. *Estimation of the total NBP uncertainty (σ_{NBP})*

In order to estimate uncertainties for C flux other than NEE, we considered that errors associated with data obtained from the farmer amounted to 10% (Ammann et al., 2007) and then randomly cumulated this error with uncertainties associated with laboratory measurements.

By assuming the independence and normality of the different error sources, NBP standard deviation (σ_{NBP}) was calculated by squaring each error term, totaling the resulting values and then taking the square root of the sum (Mudge et al., 2011).

3. Results

3.1. *Meteorological conditions and management practices*

Both air and soil temperatures and PPFD followed a typical seasonal pattern that did not really differ from one year to another. The highest temperature values (around 17 °C) were observed during summer in July and August (Fig. 3a and b), whereas the highest PPFD values (around 450 µmol m^{-2} s^{-1}) were observed from May to July (Fig. 3c). Precipitation was widespread throughout the year. (Fig. 3f). The soil water filled pore (WFP) space at 5 cm, calculated as the ratio of SWC and SWC at saturation, dropped to 32% in May 2011. Low precipitation, high vapor pressure deficit (VPD) values (Fig. 3e) and high temperatures occurred during the same period, suggesting a drought event. The summer of 2013 was also a dry period, with less than average precipitation in July and August, leading to low WFP (38%). At the end of March, GDD was 531 °C day in 2014 (highest value), 426 °C day in 2011, 410 °C day in 2012 and 194 °C day in 2013 (lowest value). The low GDD in 2013 is a result a prolonged snow period and colder temperatures until mid-April.

Over all 5 years of the study, annual averages were within a narrow range for the main environmental variables: air temperature $T_A = 9.6\,°C$ (9.0–10.3), soil temperature at a depth of 2 cm $T_{S2} = 10.1\,°C$ (9.6–10.9), PPFD = 239 µmol m^{-2} s^{-1} (214–249), VPD = 2.00 kPa (1.72–2.29), WFP = 0.82% (72–89) and precipitation PPT = 628 mm (508–672) (Table 3a). The annual averaged air temperatures and cumulated precipitation were significantly lower than the 30-year local normal averages (10 °C and 847 mm, respectively, reported by the Institut Royal Météorologique's Ciney station, 15 km south-east of the site).

Grazing started on different dates, depending on grass availability and technical constraints. It began as early as 24 March in 2012 and as late as 3 May in 2014 because of delay in the experimental set up installation (Fig. 4). In 2010, it began only on 12 June, but was preceded by a harvest on 3 June 2010. In 2013, it started only on 25 April because of low temperatures. The average stocking rate was the lowest in 2010 because a considerable amount of biomass had been harvested in June 2010 and was therefore not available for cattle. On average, cattle grazed for 160 days yr^{-1} (from 134 to 202 days yr^{-1}) and the average stocking density during stocking periods was 5.3 LU ha^{-1} (from 7.5 to 2.2 LU ha^{-1} with four one-day confinement periods around 10–12 LU ha^{-1}). The annual average stocking rate, including stocking and rest periods, was therefore 2.3 LU ha^{-1} year^{-1}.

The average grass height in the field varied from 4 to 10 cm during the grazing season and reached a minimum value of 3 cm in end November (Fig. 4). Every year, the stocking density was always lower at the end of the grazing season when biomass availability was the lowest and the highest from May to mid-September when grass availability was the highest. Rest periods occurred

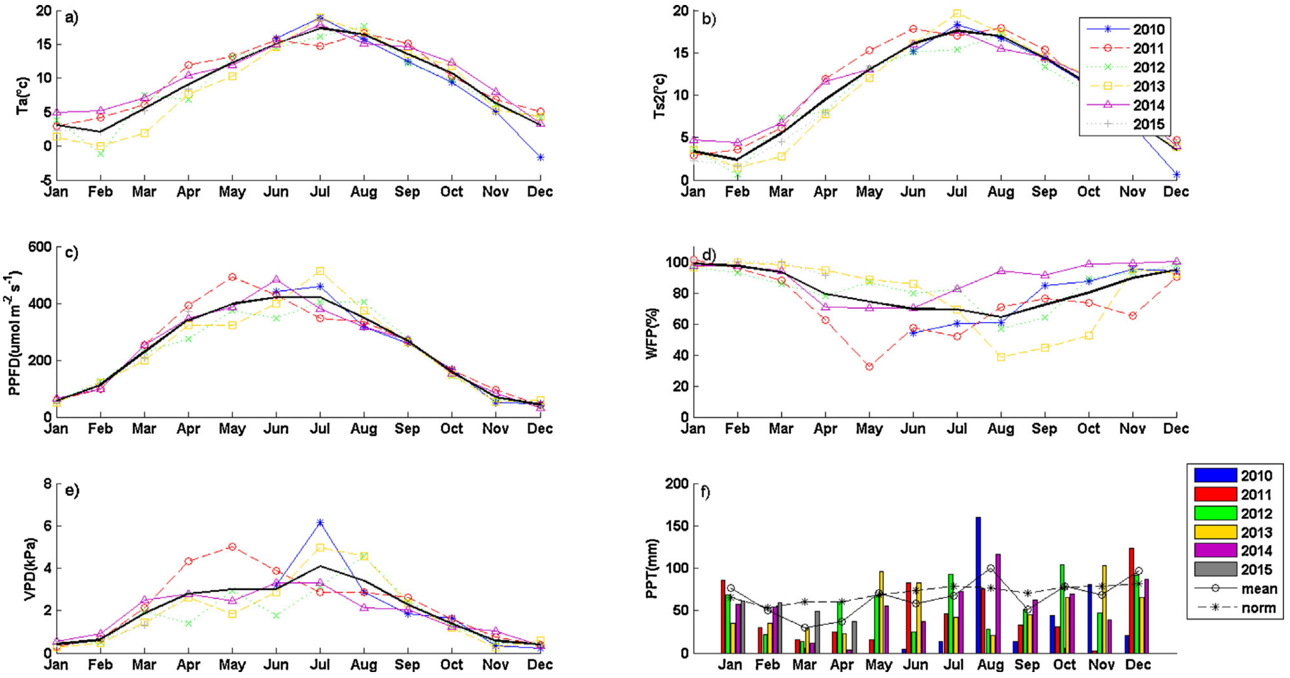


Fig. 3. Monthly means of (a) air temperature (T_A), (b) soil temperature at a depth of 2 cm (T_{S2}), (c) photosynthetic photon flux density (PPFD), (d) soil water filled pore (WFP) space at a depth of 5 cm, (e) vapor pressure deficit (VPD), and (f) monthly precipitation totals (PPT). Circles connected by a continuous line indicate the 5-year averages of monthly total precipitation. Stars connected by an unbroken line represent the last 30-year local normal precipitation averages for the Institut Royal Météorologique's Ciney station, 15 km south-east of the study site.

Table 3

Annual and 5-year averages for the 5 years of measurements made at the Dorinne Terrestrial Observatory. The 5-year averages are calculated from 12 May 2010–12 May 2015. Annual values are given only for the complete years (2011–2014). Consequently, the average given in fifth column *is not* the average of the four first columns. All fluxes and uncertainties were rounded to the unity. An uncertainty of zero means that it is <0.5. Table 3a: Weather variables: air temperature (T_A), soil temperature at a depth of 2 cm (T_{S2}), photosynthetic photon flux density (PPFD), vapor pressure deficit (VPD), soil water filled pore (WFP) space at a depth of 5 cm and yearly cumulated precipitation (PPT). Table 3b: Information on grazing conditions: number of grazing days and average stocking rate (SR). Table 3c: Carbon fluxes included in the net biome productivity (NBP) budget (see equation 1): total ecosystem respiration (TER); gross primary productivity (GPP); net ecosystem exchange (F_{CO2}); C lost through methane emissions by cattle (F_{CH4}); C imported through manure applications (F_{manure}) and through supplementary feed (F_{import}); C exported through harvest ($F_{harvest}$) and as meat ($F_{product}$); organic and/or inorganic C lost through leaching (F_{leach}). Table 3d: Other carbon fluxes of interest: above-ground net primary productivity (ANPP), C intake through grass consumption by cattle ($C_{grazing}$), C intake by cattle (sum of $C_{grazing}$ and F_{import}), livestock CO_2 emissions ($F_{CO2,livestock}$) and livestock C excreted ($C_{excretions}$).

(a) Environmental variables	2011	2012	2013	2014	5-year mean
T_A (°C)	10.3	9.3	9.0	9.4	9.6
T_S (°C)	10.9	9.6	9.9	9.7	10.1
PPFD (μmol m^{-2} s^{-1})	249	228	236	214	239
WFP%	72	84	80	89	82
SWC (m^3 m^{-3})	0.36	0.42	0.37	0.31	0.37
PPT (mm)	568	672	644	508	628
(b) Management					
Total of grazing days	134	157	161	202	160
Average SR (livestock unit ha^{-1})	2.1	2.8	2.3	2.6	2.3
(c) NBP components (g C m^{-2} y^{-1})					
TER	2260	2091	1921	2164	2085
GPP	2313	2250	2024	2357	2226
NEE	−52 [−25 −64]	−159 [−140 −176]	−102 [−85 −111]	−193 [−158 −218]	−141 [−115 −158]
$F_{CH4\text{-}C}$	14 ± 1	12 ± 1	8 ± 1	10 ± 1	12 ± 1
F_{manure}	−111 ± 18	0 ± 0	0 ± 0	0 ± 0	−22 ± 4
F_{import}	−18 ± 1	−11 ± 1	0 ± 0	0 ± 0	−26 ± 2
$F_{harvest}$	0 ± 0	0 ± 0	0 ± 0	0 ± 0	8 ± 1
$F_{product}$	9 ± 0	4 ± 0	0 ± 0	0 ± 0	3 ± 0
F_{leach}	7 ± 7	7 ± 7	7 ± 7	7 ± 7	7 ± 7
NBP	−160 [−127 −183]	−147 [−127 −156]	−87 [−69 −98]	−176 [−141 −200]	−161 [−134 −180]
(d) Others C fluxes (g C m^{-2} y^{-1})					
ANPP	392	385	249	365	355
$C_{grazing}$	372	323	230	286	312
$F_{CO2,livestock}$	273	232	161	204	234
$C_{excretions}$	102	86	61	72	87

generally when grass height went down to 5 cm or below with a notable exception in 2014, when a permanent grazing was organized for experimental purpose. Overall, 19 rotations between rest and stocking periods were observed during grazing seasons from

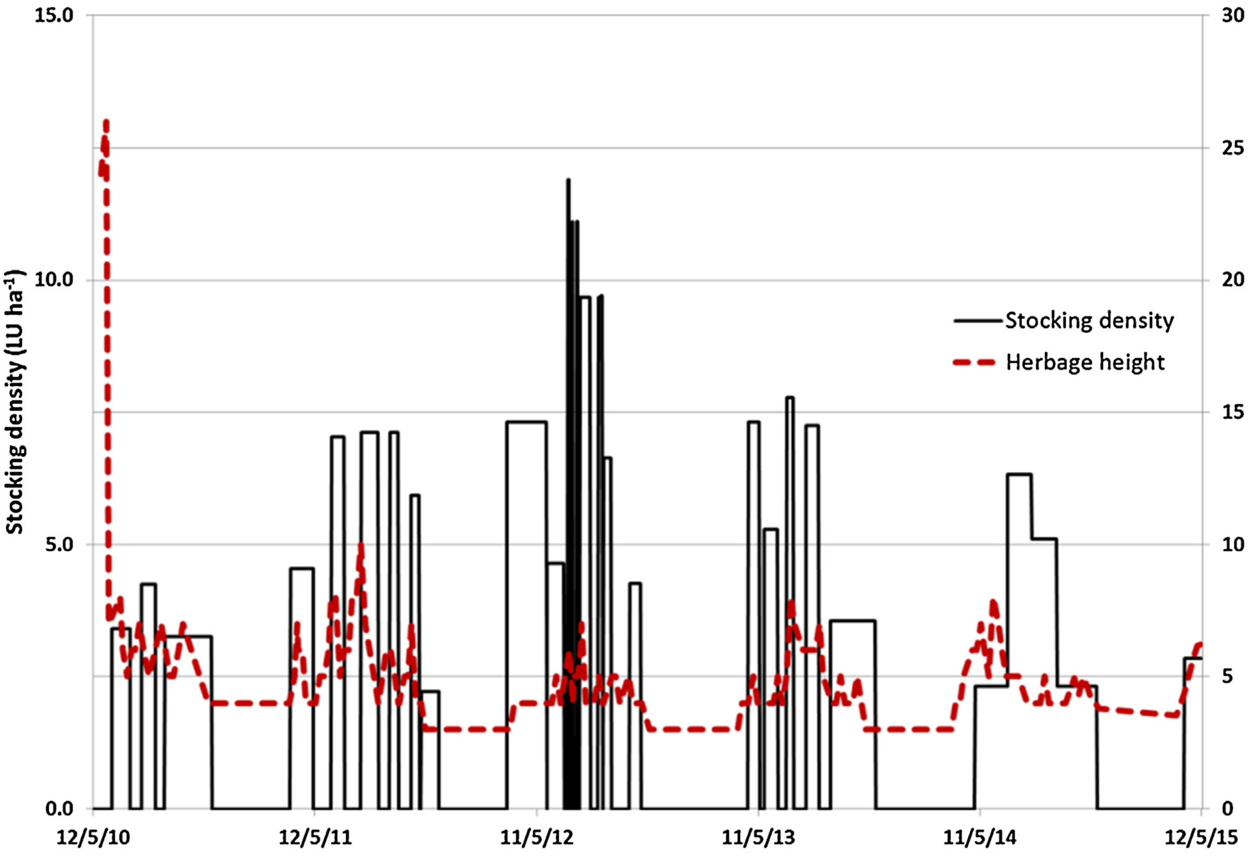


Fig. 4. Cattle stocking rate (LU/ha) throughout the study period and herbage height. A stocking rate of zero designates rest periods.

2010 to 2013. These adaptations of the stocking density and the grazing duration to grass availability, following usual management practices, induces indirectly some link between grazing management and weather conditions as the latter control, at least partly, grass growth.

3.2. Monthly dynamics of NEE, TER and GPP

The 5-year average of monthly TER and GPP values both followed a seasonal cycle, being minimal in winter and maximal in summer, but not at the same time: GPP reached its maximum value (about 310 $\mathrm{gC\,m^{-2}\,month^{-1}}$) between April and June, whereas TER reached it (about 280 $\mathrm{gC\,m^{-2}\,month^{-1}}$) between June and August (Fig. 5). As a result, the monthly 5-year average NEE showed a continuous CO_2 uptake during spring and early summer (March–July), reached its maximum uptake in April, fell to zero around mid-summer (August) and moved to continuous CO_2 emission in autumn and winter. This shift from a CO_2 sink to a source occurred earlier than observed in other temperate ecosystems, such as forests (Aubinet et al., 2002; Falge et al., 2001), probably as the result of grazing that limits vegetation photosynthesizing area and, as a consequence, the GPP.

A highly significant linear relationship was found between monthly TER and GPP (p value < 0.001, $R^2 = 0.84$), (Fig. 6a). The slope of the regression was 0.72. This dependence should be treated with caution however, because self-correlation between TER and GPP could also derive from the partitioning method used to compute these fluxes (Vickers et al., 2009).

In order to assess the impact of meteorological conditions on the C budget inter-annual variability, flux (GPP, TER and NEE) and weather variable (Ts, VPD, WFP, PPFD and precipitation), various anomalies were also investigated. A significant relationship was found between TER and GPP anomalies (p value < 0.001, $R^2 = 0.42$), (Fig. 6b). The slope of the regression was 0.48 (p value < 0.001). NEE anomalies were correlated with GPP anomalies (p value < 0.001, $R^2 = 0.43$) but not with TER anomalies (p value > 0.05, Fig. 6c and d). Monthly GPP and TER anomalies were also both correlated with Ts anomalies (p value < 0.001, data not shown), but no such relationship was found for NEE. Here again, we cannot exclude the dependence partly resulting from the partitioning method used to compute TER and GPP. No other significant relationship was found between monthly CO_2 flux component anomalies (GPP, NEE, TER) and other meteorological variables.

3.3. Carbon budget of the pasture

The 5-year C budget reveals that the pasture behaved each year as a significant C sink (Table 3c). The 5-year average annual NBP was −161 [−134 −180] $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (values in brackets indicate error bounds). This observation is in agreement with most European studies of C fluxes in grasslands, which have found that grasslands generally act as a net C sink (Allard et al., 2007; Ammann et al., 2007; Byrne et al., 2007; Jaksic et al., 2006; Mudge et al., 2011; Peichl et al., 2011; Rutledge et al., 2015; Zeeman et al., 2010). Let's note however, that such agreement was not a priori obvious, in view of the high management intensity and the old age of the pasture. The site has indeed been a grassland for probably more than a century and the average annual stocking rate of 2.3 $\mathrm{LU\,ha^{-1}}$ was more than twice the rate observed for most other intensively grazed European grasslands studied (1 $\mathrm{LU\,ha^{-1}}$ in Klumpp et al., 2011, from 0.12 to 1.32 $\mathrm{LU\,ha^{-1}}$ in Soussana et al., 2007).

Looking to the carbon budget (Table 3c), it appears that the main terms were, in order, NEE, F_{import} and F_{manure} (Table 3c). NEE ranged from −193 $\mathrm{g\,C\,m^{-2}}$ in 2014 to −52 $\mathrm{g\,C\,m^{-2}}$ in 2011. The high 5 years

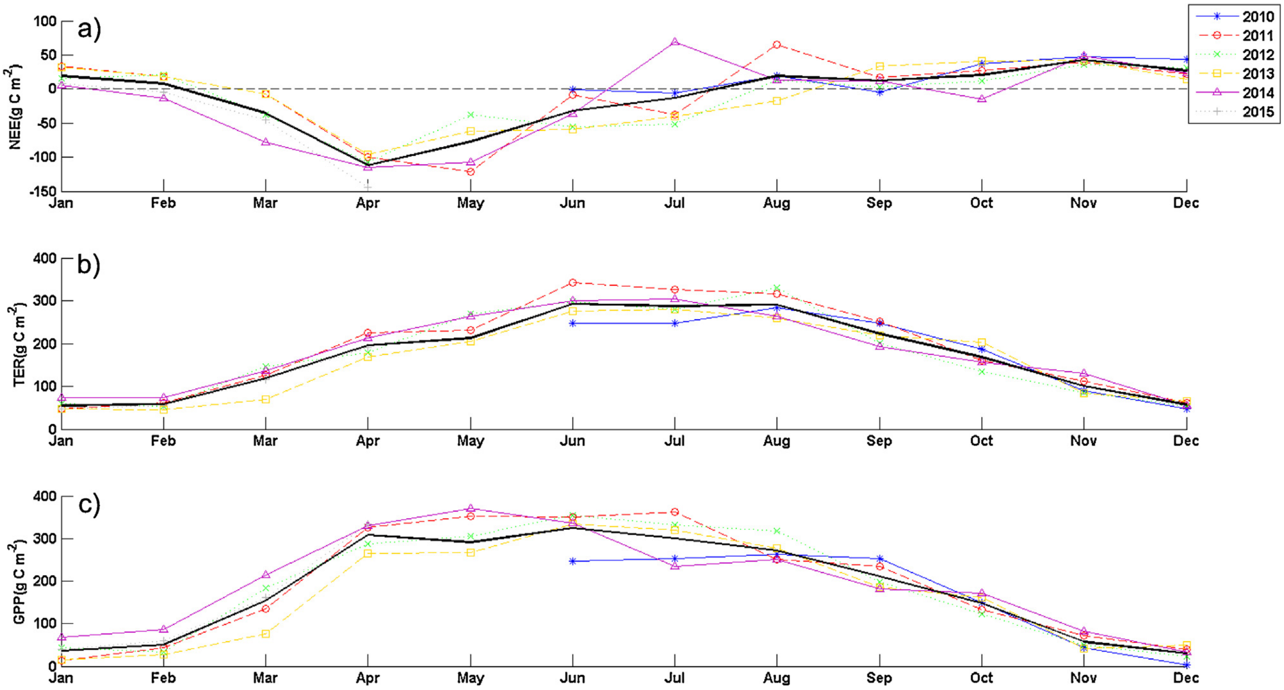


Fig. 5. Monthly totals of the (a) net ecosystem exchange (NEE), (b) total ecosystem respiration (TER) and (c) gross primary productivity (GPP). The dark black continuous line indicates the 5-year average for each month.

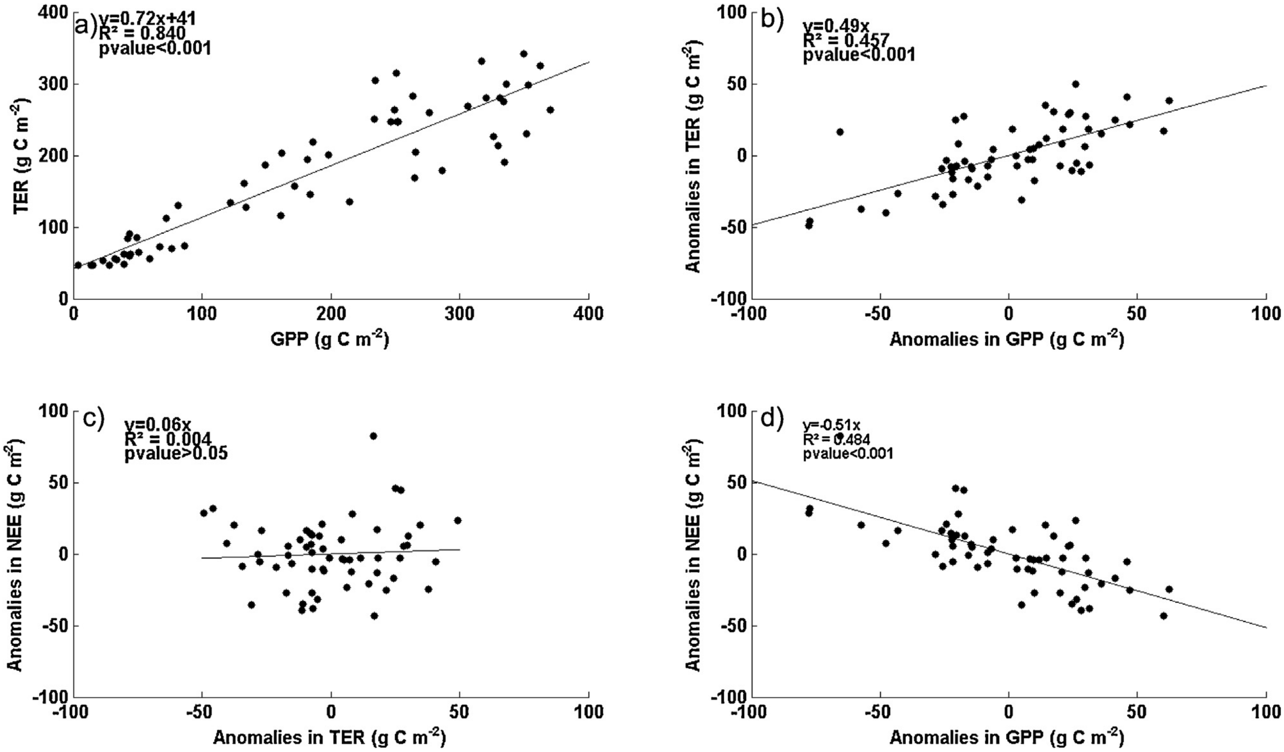


Fig. 6. Correlation between (a) monthly total ecosystem respiration (TER) and monthly gross primary productivity (GPP), (b) anomalies in monthly total ecosystem respiration (TER) and anomalies in monthly gross primary productivity (GPP), (c) anomalies in monthly total ecosystem respiration (TER) and anomalies in net ecosystem exchange (NEE) and (d) anomalies in monthly gross primary productivity (GPP) and anomalies in net ecosystem exchange (NEE).

average F_{import} value is mainly due to the importation in 2010 of an important C amount (about $-100\,g\,C\,m^{-2}$) as a feed supplement (Table 1). This feed was imported to compensate for the harvest in June that year ($40\,g\,C\,m^{-2}$) and the low precipitation from May to July (Fig. 3f), which could have limited grass regrowth. These fluxes affected the 5-year mean budget, but did not appear in the yearly budgets because they occurred in the incomplete year, 2010. Except this contribution, feed supplements remained low compared with NEE. No feed supplements were imported into the field in 2013 and

2014 because the farmer adjusted the stocking rate such that grass regrowth was enough to feed the cattle.

F_{manure} corresponds with the C imported into the field through organic fertilization. It was the most important part of the NBP budget in 2011. As organic fertilization occurred only once during the study period its impact on the average budget was finally small. This is representative of the real management of the pasture as, according to the farmer, organic fertilization frequency is not higher than once every 5 years.

3.4. Inter-annual variability of the carbon budget

Apart from 2013, when it dropped to −87 g C m^{-2}, the NBP did not vary significantly from year to year, remaining at about −161 g C m^{-2}, which indicates a relatively stable annual C budget. These budgets, however, were obtained under contrasting weather conditions and, on a monthly scale, some differences in NEE were notable.

In 2011, a peak emission (NEE anomaly ≈+ 50 g C m^{-2}) was observed in August (Fig. 5), however, an important amount of C had also been imported through organic fertilization (Table 3c) in February in the same year. These two events impacted the annual NBP in opposed ways and compensated each other. In 2014, the first half of the year (February–June) was characterized by an above-average CO_2 uptake (Fig. 5a), due to mild winter conditions. However, later in July, an emission peak occurred (NEE anomaly ≈+ 80 g C m^{-2}), due to below-average GPP (Fig. 5c). Here again, these events, although significant at monthly scale did not affect the annual NBP due to mutual compensation. Finally, in 2013, the beginning of the year was characterized by prolonged cold and snowy conditions, which induced below-average GPP, TER and NEE values, which probably partly explains the lower NEE for this year.

4. Discussion

The effects of weather and management practices on the C budget are not always easy to discern. A major reason for this is that weather and management might be inter-related by several processes. Indeed, as suggested at Section 3.1, a link between grazing management and grass availability and hence, meteorological conditions might exist. Therefore, in order to facilitate the discussion, the effects of climate and management that have been clearly identified will be discussed first separately, after which their combined effects will be assessed when possible.

4.1. Weather impact

The absence of relationship between NEE anomalies and weather variables anomalies (Section 3.2) suggests that, apart from the possible response of TER and GPP to temperature, the inter-annual variability of monthly fluxes could not be explained by any overall response to weather conditions. However, despite this absence of relationship, some weather effects were identified for specific periods without cattle.

The relationship between GPP and GDD was found to be similar for three successive years, from 2012 and 2014 (Fig. 7). As a result, the inter-annual differences between cumulated GPP at the end of March were explained by the GDD. In particular, the high GPP in spring 2014 (375 g C m^{-2}) was explained by the high GDD (about 550 °C day) resulting from mild winter conditions, whereas the low GPP in spring 2013 (125 g C m^{-2}) was explained by a lower GDD (around 190 °C day) indicating colder winter and spring. This resulted in differences in GPP, TER and NEE of, respectively 250, 120 and 130 g C m^{-2} between those years. In 2011, however, the GPP increase with GDD was delayed and slower (cumulative GPP around 100 g C m^{-2} for 300° day and around 180 g C m^{-2} in 2012 and 2014) probably because of the high temperatures (Fig. 3a) and low radiation (Fig. 3c) in February. This led to an early increase in GDD associated with low PPFD, leading to a low GPP/GDD ratio.

The high TER values observed in 2011 could have resulted from either high temperatures or the organic fertilization and liming in February that year. In order to identify the most probable cause, the normalized respiration at 10 °C (R_{10}) was calculated for each year by fitting an exponential relationship onto the valid night fluxes (Lloyd and Taylor, 1994). As no significant difference between R_{10} values in 2011 and in the other years was found we conclude that high TER observed in 2011 resulted more probably from the high temperatures (Fig. 3 a and b) rather than from an increase in emission due to organic fertilization.

4.2. Management impact

The 5-year averaged GPP and TER values reached 2226 and 2085 g C m^{-2} yr^{-1}, respectively, and were larger than all the values obtained by a multi-site analysis (Gilmanov et al., 2007) of 19 European grasslands (maximum values: 1874 and 1621 g C m^{-2} yr^{-1} for GPP and TER, respectively). They were closer to the values observed in an intensive grassland study by Mudge et al. (2011) (2194 and 1999 g C m^{-2} yr^{-1} for GPP and TER, respectively), but lower than those reported by Zeeman et al. (2010) (2647 and 2583 g C m^{-2} yr^{-1} for GPP and TER, respectively). These high values are probably due to a high biomass production, itself resulting from intensive management and fertilization (120 kg N ha^{-1} yr^{-1} on average, Table 1). This was confirmed by the annual ANPP values (Table 3d) that reached 355 g C m^{-2} on average, which is higher than the average production in Wallonia permanent cut grasslands (on average, ≅250 g C m^{-2} for the 2008–2010 period; (SPW, 2010)). In comparison, Klumpp et al. (2011) reported a much lower values of 95 g C m^{-2} ANPP and about 1650 g C m^{-2} TER and GPP.

These results suggest that, even in presence of a very high grazing pressure, high C assimilation could probably be maintained at the DTO thanks to intensive nitrogen fertilization and natural fertilization through excreta. Similar results were found by Allard et al. (2007), who showed that an intensively grassland could maintain a C sink activity over time while an extensively managed one could not.

The lateral fluxes resulting from C import or export as manure, feed supplement, harvest or meat production had clear effects on C balance. On average, lateral organic C fluxes increased the C sink magnitude. This observation differs from the findings reported in other studies (Allard et al., 2007; Ammann et al., 2007; Byrne et al., 2007; Jaksic et al., 2006; Mudge et al., 2011; Peichl et al., 2011; Rutledge et al., 2015; Zeeman et al., 2010) and is because C imports through organic fertilization and feed supplements exceeded C exports. Indeed, C exports were much lower than in those studies as only one harvest occurred during the 5 years and C exports through meat ($F_{product}$) were much lower than C exports in form of milk in dairy pastures (Byrne et al., 2007; Jaksic et al., 2006; Mudge et al., 2011; Rutledge et al., 2015; Zeeman et al., 2010). C exports through meat were low mainly because the field was most of time occupied by fully grown cattle.

Land use and management prior to the study are suspected to affect the carbon assimilation of a pasture for about a century before reaching equilibrium (Smith, 2014). As the pasture was intensively managed for more than 40 years, we can argue that this hypothetic equilibrium was not reached yet a DTO. This observation is therefore in agreement with the assumption made by Smith (2014) that equilibrium should only occur after several decades (and at least more than 40 years) under continuous management.

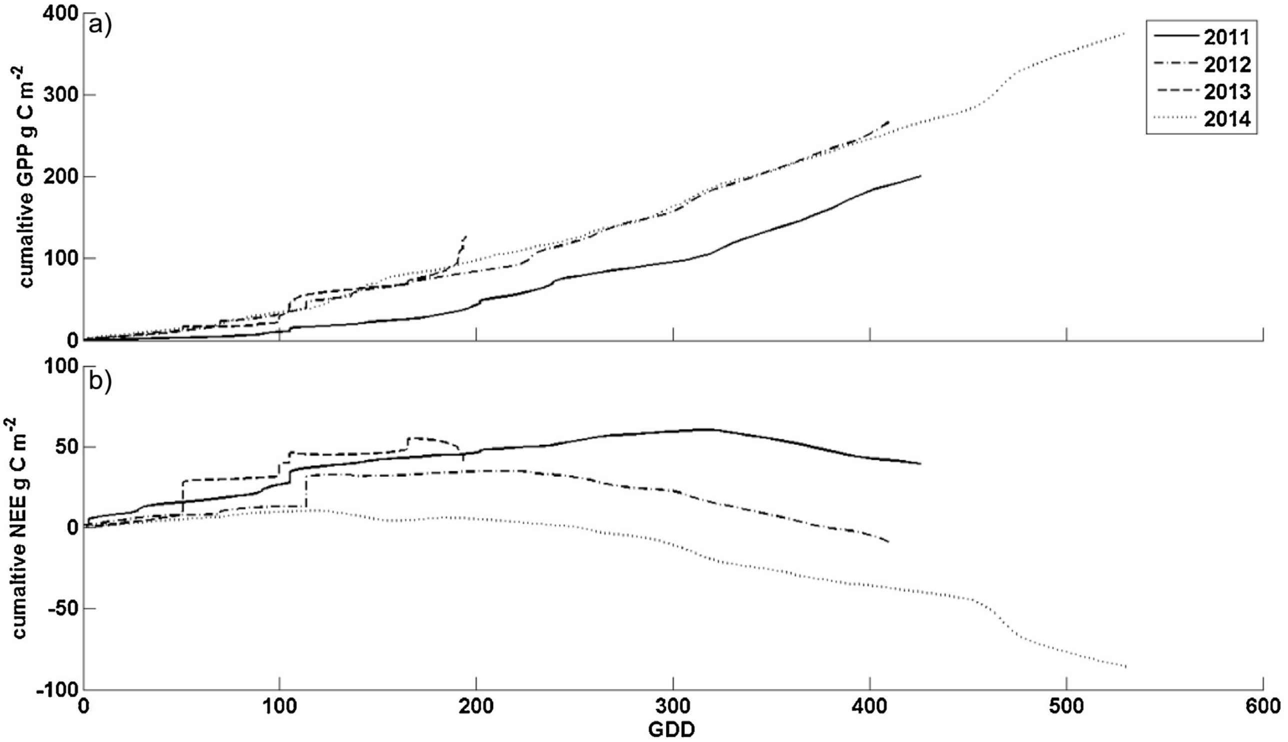


Fig. 7. (a) Evolution of the cumulated gross primary productivity (GPP) and (b) the evolution of the cumulated net ecosystem exchange (NEE) in relationship to the cumulated growing degree days (GDD) from 1 January to 31 March.

4.3. Combined weather and management impact

Maintaining a steady meat production and optimizing grass consumption require a careful herd management from the farmer by continuously adapting stocking density to grass availability. As grass regrowth depends on weather conditions and photosynthesizing area, it is logical to conclude that management is achieved in response to weather conditions. As a result, grass height is subjected to small variations all over the season, being maintained in a range of 5–10 cm (Fig. 4). As a consequence of this link, impacts of climate and management on NEE are difficult to distinguish and sometimes they compensate each other. This could explain why no clear relationship between NEE and weather anomalies was found (Wayne Polley et al., 2008) and, reciprocally, why grazing impact on CO_2 flux dynamics was difficult to discern on both the monthly and seasonal scales (Jérôme et al., 2014).

Possible indirect impacts of grazing are the decrease of GPP because of photosynthesizing area reduction following grass consumption but also a decrease of TER via a decrease in autotrophic respiration. The latter is notably supported by the strong coupling observed between GPP and TER. However, an investigation made at DTO by Jérôme et al. (2014) showed that as the impact of grazing intensity on GPP was observed, no such impact was observed on dark respiration suggesting therefore a larger impact of grazing on GPP than on TER. Indeed TER may not only be impacted negatively through defoliation but also positively trough cattle and feces respiration.

A direct impact of grazing is the increase of TER due to cattle respiration to the TER. This effect is not easy to discern as the number of cattle within the footprint varies and is not known (Felber et al., 2016). To do so, we studied the animal C budget (Fig. 1, Table 3d). It appeared that around 70% of total ingested C ($C_{grazing} + F_{import}$) was lost through cattle respiration ($F_{CO2,livestock}$). Assuming an ideal case where animals are spread evenly over the field at all times so that their respiration signal becomes a constant part of the eddy covariance measurements footprint and considering an average stocking rate of 2.3 LU ha^{-1} yr^{-1}, this represented around 11% of the TER on average.

4.4. Uncertainties

The 5-year average NBP uncertainty was [+27 −19] g C m^{-2} yr^{-1} (Table 3c). The main factor influencing NBP uncertainty was NEE, which itself was affected the choice of the u* threshold and the gap filling (Table 4). A comparison of the u* corrected and uncorrected fluxes in Table 4 suggests that, on average, the night flux underestimation led to an overestimation of the annual sink of about 61 g C m^{-2} yr^{-1}. However, an uncertainty results from this correction. An uncertainty of 0.05 m s^{-1} on the u* threshold led to an uncertainty of 17 g C m^{-2} yr^{-1} for annual sums. The random uncertainty, when important on a half-hourly scale, decreases with time because of the partial compensation when summed. As a result, it did not exceed 6 g C m^{-2} yr^{-1} on an annual scale or 2 g C m^{-2} yr^{-1} on a 5-year scale. The additional uncertainty resulting from the non-annulation of the mean residual error in the gap filling procedure (see Section 2.9), however, led to a systematic flux underestimation estimated to be 19 g C m^{-2} yr^{-1}.

Another critical choice was those of the reference cospectrum used for the spectral correction. The use of a local cospectrum (average sensible heat cospectra) was chosen instead of a theoretical cospectrum (Kansas cospectrum, Kaimal et al., 1972). This methodological choice had a major impact on CO_2 fluxes. Therefore, before presenting this budget, a supplementary validation of the correction procedure had been implemented using *in situ* respiration measurements. Fluxes corrected with the local cospectra were found to be in good agreement with the respiration measurements while fluxes corrected with the Kansas cospectra were found overestimated. The details of the procedure and the validation are presented in a paper by Mamadou et al. (2016). Finally, even by

Table 4
Annual NEE uncertainty components and correction effects. All the values are given in g C m^{-2} yr^{-1}. The 'no spectral' correction value is the NEE value with no spectral correction, but with the u* filter. The 'no filter' value is the value with no filter, but with the spectral correction. The corr. values correspond to the annual NEE values with both u* and spectral corrections.

Year	Spectral correction			U* correction			Gap filling	Random	Total Uncertainty	
	No spectral corr	Corr	σ_{f0}	No filter	Corr.	σ_{u^*}	σ_{gf}	σ_r		
2011	−64	−52	±5	−145	−52	±9	+24	±6	+27	−12
2012	−146	−159	±5	−259	−159	±16	+8	±5	+19	−18
2013	−98	−102	±1	−136	−102	±7	+14	±5	+17	−9
2014	−177	−193	±3	−269	−193	±22	+26	±6	+35	−23
5-year mean	−135	−141	±2	−202	−141	±17	+19	±2	+26	−17

taking all uncertainties into account, the fact that the pasture acts as a significant C sink each year remains a robust finding (Table 3c).

5. Conclusion

This study established and analyzed the total C budget of grassland grazed by Belgian Blue cattle by combining data from CO_2 eddy covariance measurements with other C fluxes and their uncertainties. CO_2 fluxes (NEE) and non CO_2 fluxes in form of manure (F_{manure}) and feed complements ($F_{imports}$) were the main fluxes affecting the C budget, highlighting the need to include them. The results showed that the pasture acted as a relatively stable C sink each year despite the high stocking rate and the old age of the pasture. Both management and weather conditions were found to influence C fluxes. Important C imports through organic fertilization as well as low C exports through meat production helped to maintain a carbon sink. The N fertilization also probably helped to maintain the C sink activity thanks to an improved GPP. However, fertilization could also induce N_2O emissions that could affect the grassland greenhouse gas budgets. These fluxes were not measured. GPP and NEE were affected by low temperatures at the beginning of the year, before the grazing season. Indeed, these weather conditions could have caused a delay in grass growth and GPP that could not always be offset during the rest of the year.

The low inter-annual variability of the C budget and its independence to weather variables anomalies could partially be explained by management practices that adjusted the stocking rate according to grass availability which itself responds to weather conditions. It could also been obtained partly by chance as (i) we did not experience really extreme years and (ii) in some years, compensation between events with high and low accumulation occurred. The findings in this study are in agreement with those reported by other studies that have shown that well-managed grasslands could act as C sinks. Further studies should focus on comparing different grazing management practices in order to better quantify and understand their impact on grassland C storage. Our study also highlighted the need to evaluate the uncertainties linked to flux measurements and to assess the sensitivity of the C budget to methodological choices, such as those linked with spectral correction and the nighttime flux filtering criterion choice, in order to assess how defensible annual C budgets are.

Acknowledgments

This research was funded by the Service public de Wallonie (SPW), Direction Générale Opérationnelle de l'Agriculture, des Ressources naturelles et de l'Environnement, Département du Développement, Direction de la Recherche, Belgium. *Project no. D31-1235,* January 2010 to December 2011. *Project no. D31-1278,* January 2012 to December 2013. *Project no. D31-1327,* January 2014 to December 2015. The authors would like to thank Henri Chopin, Alain Debacq, Frederic Wilmus and Jean Christophe Pector for their technical assistance. They also would also like to thank the farmer, Adrien Paquet, for his collaboration, which was essential to the study.

References

Aires, L.M.I., Pio, C.A., Pereira, J.S., 2008. Carbon dioxide exchange above a Mediterranean C3/C4 grassland during two climatologically contrasting years. Global Change Biol. 14, 539–555, http://dx.doi.org/10.1111/j.1365-2486.2007.01507.x.

Allard, V., Soussana, J.F., Falcimagne, R., Berbigier, P., Bonnefond, J.M., Ceschia, E., D'hour, P., Hénault, C., Laville, P., Martin, C., Pinarès-Patino, C., 2007. The role of grazing management for the net biome productivity and greenhouse gas budget (CO_2, N_2O and CH_4) of semi-natural grassland. Agric. Ecosyst. Environ. 121, 47–58, http://dx.doi.org/10.1016/j.agee.2006.12.004.

Ammann, C., Flechard, C.R., Leifeld, J., Neftel, A., Fuhrer, J., 2007. The carbon budget of newly established temperate grassland depends on management intensity. Agric. Ecosyst. Environ. 121, 5–20, http://dx.doi.org/10.1016/j.agee.2006.12.002.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A., Martin, P., Berbigier, P., Bernhofer, C., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Adv. Ecol. Res. 30, 113–175.

Aubinet, M., Heinesch, B., Longdoz, B., 2002. Estimation of the carbon sequestration by a heterogeneous forest: night flux corrections, heterogeneity of the site and inter-annual variability. Global Change Biol. 8, 1053–1071, http://dx.doi.org/10.1046/j.1365-2486.2002.00529.x.

Aubinet, M., Feigenwinter, C., Heinesch, B., Laffineur, Q., Papale, D., Reichstein, M., Rinne, J., Van Gorsel, E., 2012a. Nighttime flux correction. In: Eddy Covariance: A Practical Guide to Measurements and Data Analysis. Springer Verlag, pp. 133–158.

Aubinet, M., Vesala, T., Papale, D., 2012b. Eddy Covariance: A Practical Guide to Measurements and Data Analysis. Springer Verlag, pp. 438.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biol. 9, 479–492, http://dx.doi.org/10.1046/j.1365-2486.2003.00629.x.

Byrne, K.A., Kiely, G., Leahy, P., 2007. Carbon sequestration determined using farm scale carbon balance and eddy covariance. Agric. Ecosyst. Environ. 121, 357–364, http://dx.doi.org/10.1016/j.agee.2006.11.015.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533, http://dx.doi.org/10.1038/nature03972.

Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol. Appl. 11, 343–355.

Decruyenaere, V., Lecomte, P., Demarquilly, C., Aufrere, J., Dardenne, P., Stilmant, D., Buldgen, A., 2009. Evaluation of green forage intake and digestibility in ruminants using near infrared reflectance spectroscopy (NIRS): developing a global calibration. Anim. Feed Sci. Technol. 148, 138–156, http://dx.doi.org/10.1016/j.anifeedsci.2008.03.007.

Dragoni, D., Schmid, H.P., Grimmond, C.S.B., Loescher, H.W., 2007. Uncertainty of annual net ecosystem productivity estimated using eddy covariance flux measurements. J. Geophys. Res. Atmos. 112, http://dx.doi.org/10.1029/2006JD008149.

Dumas, J., 1831. Procédés de l'analyse organique. Annales de chimie et de physique, Paris.

Dumortier P., Aubinet M., Beckers Y., Chopin H., Debacq A., Gourlez de la Motte, L., Jérôme, E., Wilmus, F., Heinesch, B., 2016. Methane balance of an intensively grazed pasture and estimation of the entheric methane emissions from cattle (Manuscript submitted for publication).

Eurostat, 2013. European Comission Agriculture, Forestry and Fisheries Statistics—2013. Eurostat, pp. 249.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik Ü, Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric. For. Meteorol. 107, 43–69, http://dx.doi.org/10.1016/S0168-1923(00)00225-2.

Felber, R., Neftel, A., Ammann, C., 2016. Discerning the cows from the pasture: quantifying and partitioning the NEE of a grazed pasture using animal position data. Agric. For. Meteorol. 216, 37–47, http://dx.doi.org/10.1016/j.agrformet.2015.09.018.

Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agric. For. Meteorol. 78, 83–105.

Foken, T., Aubinet, M., Leuning, R., 2012a. The eddy covariance method. In: Eddy Covariance: A Practical Guide to Measurements and Data Analysis. Springer Verlag, pp. 1–20.

Foken, T., Leuning, R., Oncley, S., Mauder, M., Aubinet, M., 2012b. Corrections and data quality control. In: Eddy Covariance: A Practical Guide to Measurements and Data Analysis. Springer Verlag, pp. 85–132.

Gilmanov, T., Soussana, J., Aires, L., Allard, V., Ammann, C., Balzarolo, M., Barcza, Z., Bernhofer, C., Campbell, C., Cernusca, A., 2007. Partitioning European grassland net ecosystem CO_2 exchange into gross primary productivity and ecosystem respiration using light response function analysis. Agric. Ecosyst. Environ. 121, 93–120.

Gilmanov, T.G., Aires, L., Barcza, Z., Baron, V.S., Belelli, L., Beringer, J., Billesbach, D., Bonal, D., Bradford, J., Ceschia, E., Cook, D., Corradi, C., Frank, A., Gianelle, D., Gimeno, C., Gruenwald, T., Guo, H., Hanan, N., Haszpra, L., Heilman, J., Jacobs, A., Jones, M.B., Johnson, D.A., Kiely, G., Li, S., Magliulo, V., Moors, E., Nagy, Z., Nasyrov, M., Owensby, C., Pinter, K., Pio, C., Reichstein, M., Sanz, M.J., Scott, R., Soussana, J.F., Stoy, P.C., Svejcar, T., Tuba, Z., Zhou, G., 2010. Productivity, respiration, and light-response parameters of world grassland and agroecosystems derived from flux-tower measurements. Rangel. Ecol. Manage. 63, 16–39, http://dx.doi.org/10.2111/REM-D-09-00072.1.

Goidts, E., van Wesemael, B., 2007. Regional assessment of soil organic carbon changes under agriculture in Southern Belgium (1955–2005). Geoderma 141, 341–354, http://dx.doi.org/10.1016/j.geoderma.2007.06.013.

Goulden, M.L., Munger, J.W., Song-Miao, F., Daube, B.C., Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Global Change Biol. 2, 169–182.

Harper, C.W., Blair, J.M., Fay, P.A., Knapp, A.K., Carlisle, J.D., 2005. Increased rainfall variability and reduced rainfall amount decreases soil CO_2 flux in a grassland ecosystem. Global Change Biol. 11, 322–334, http://dx.doi.org/10.1111/j.1365-2486.2005.00899.x.

Heimann, M., Reichstein, M., 2008. Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature 451, 289–292, http://dx.doi.org/10.1038/nature06591.

Herrero, M., Gerber, P., Vellinga, T., Garnett, T., Leip, A., Opio, C., Westhoek, H.J., Thornton, P.K., Olesen, J., Hutchings, N., Montgomery, H., Soussana, J.F., Steinfeld, H., McAllister, T.A., 2011. Livestock and greenhouse gas emissions: the importance of getting the numbers right. Anim. Feed Sci. Technol. 166–167, 779–782.

Hollinger, D.Y., Richardson, A.D., 2005. Uncertainty in eddy covariance measurements and its application to physiological models. Tree Physiol. 25, 873–885.

Hussain, M., Grünwald, T., Tenhunen, J., Li, Y., Mirzae, H., Bernhofer, C., Otieno, D., Dinh, N., Schmidt, M., Wartinger, M., 2011. Summer drought influence on CO_2 and water fluxes of extensively managed grassland in Germany. Agric. Ecosyst. Environ. 141, 67–76.

IPCC, 2007. Climate Change 2007: The Scientific Basis (Contribution of Working Group I to the Fourth Assessment Report of the IPCC).

IRM, 2011. Le Climat. Publ. L'Institut R. Météorologique IRM.

Jérôme, E., Beckers, Y., Bodson, B., Heinesch, B., Moureaux, C., Aubinet, M., 2014. Impact of grazing on carbon dioxide exchanges in an intensively managed Belgian grassland. Agric. Ecosyst. Environ. 194, 7–16.

Jaksic, V., Kiely, G., Albertson, J., Oren, R., Katul, G., Leahy, P., Byrne, K.A., 2006. Net ecosystem exchange of grassland in contrasting wet and dry years. Agric. For. Meteorol. 139, 323–334, http://dx.doi.org/10.1016/j.agrformet.2006.07.009.

Jongen, M., Pereira, J.S., Aires, L.M.I., Pio, C.A., 2011. The effects of drought and timing of precipitation on the inter-annual variation in ecosystem-atmosphere exchange in a Mediterranean grassland. Agric. For. Meteorol. 151, 595–606, http://dx.doi.org/10.1016/j.agrformet.2011.01.008.

Kaimal, J.C., Wyngaard, J.C., Izumi, Y., Coté, O.R., 1972. Spectral characteristics of surface-layer turbulence. Q. J. R. Meteorol. Soc. 98, 563–589, http://dx.doi.org/10.1002/qj.49709841707.

Klumpp, K., Tallec, T., Guix, N., Soussana, J.F., 2011. Long-term impacts of agricultural practices and climatic variability on carbon storage in a permanent pasture. Glob. Change Biol. 17, 3534–3545.

Kolle, O., Rebmann, C., 2007. EddySoft Documentation of a Software Package to Acquire and Process Eddy Covariance Data. MPI-BGC.

Kormann, R., Meixner, F.X., 2001. An analytical footprint model for non-neutral stratification. Bound.-Layer Meteorol. 99, 207–224, http://dx.doi.org/10.1023/A:1018991015119.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627, http://dx.doi.org/10.1126/science.1097396.

Lassey, K.R., 2007. Livestock methane emission: from the individual grazing animal through national inventories to the global methane cycle. Agric. For. Meteorol. 142, 120–132, http://dx.doi.org/10.1016/j.agrformet.2006.03.028.

Lettens, S., Van Orshoven, J., Van Wesemael, B., De Vos, B., Muys, B., 2005a. Stocks and fluxes of soil organic carbon for landscape units in Belgium derived from heterogeneous data sets for 1990 and 2000. Geoderma 127, 11–23, http://dx.doi.org/10.1016/j.geoderma.2004.11.001.

Lettens, S., Van Orshoven, J., Van Wesemael, B., Muys, B., Perrin, D., 2005b. Soil organic carbon changes in landscape units of Belgium between 1960 and 2000 with reference to 1990. Global Change Biol. 11, 2128–2140, http://dx.doi.org/10.1111/j.1365-2486.2005.001074.x.

Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315, http://dx.doi.org/10.2307/2389824.

Macoon, B., Sollenberger, L.E., Moore, J.E., Staples, C.R., Fike, J.H., Portier, K.M., 2003. Comparison of three techniques for estimating the forage intake of lactating dairy cows on pasture. J. Anim. Sci. 81, 2357–2366.

Mamadou O., Gourlez de la Motte, L., De Ligne, A., Heinesch, B., Aubinet, M., 2016. Sensitivity of the annual net ecosystem exchange to the cospectral model used for high frequency loss corrections at a grazed grassland site.

Mathot, M., Decruyenaere, V., Stilmant, D., Lambert, R., 2012. Effect of cattle diet and manure storage conditions on carbon dioxide, methane and nitrous oxide emissions from tie-stall barns and stored solid manure. Agric. Ecosyst. Environ. 148, 134–144, http://dx.doi.org/10.1016/j.agee.2011.11.012.

Meersmans, J., Van Wesemael, B., De Ridder, F., Dotti, M.F., De Baets, S., Van Molle, M., 2009. Changes in organic carbon distribution with depth in agricultural soils in northern Belgium, 1960–2006. Global Change Biol. 15, 2739–2750, http://dx.doi.org/10.1111/j.1365-2486.2009.01855.x.

Meersmans, J., Van Wesemael, B., Goidts, E., Van Molle, M., De Baets, S., De Ridder, F., 2011. Spatial analysis of soil organic carbon evolution in Belgian croplands and grasslands, 1960–2006. Global Change Biol. 17, 466–479, http://dx.doi.org/10.1111/j.1365-2486.2010.02183.x.

Mudge, P.L., Wallace, D.F., Rutledge, S., Campbell, D.I., Schipper, L.A., Hosking, C., 2011. Carbon balance of an intensively grazed temperate pasture in two climatically contrasting years. Agric. Ecosyst. Environ. 144, 271–280.

Peichl, M., Leahy, P., Kiely, G., 2011. Six-year stable annual uptake of carbon dioxide in intensively managed humid temperate grassland. Ecosystems 14, 112–126.

Peichl, M., Carton, O., Kiely, G., 2012. Management and climate effects on carbon dioxide and energy exchanges in a maritime grassland. Agric. Ecosyst. Environ. 158, 132–146.

Rebmann, C., Kolle, O., Heinesch, B., Queck, R., Ibrom, A., Aubinet, M., 2012. Data acquisition and flux calculations. In: Eddy Covariance: A Practical Guide to Measurements and Data Analysis. Springer Verlag, 59-84.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biol. 11, 1424–1439.

Richardson, A.D., Hollinger, D.Y., Burba, G.G., Davis, K.J., Flanagan, L.B., Katul, G.G., William Munger, J., Ricciuto, D.M., Stoy, P.C., Suyker, A.E., Verma, S.B., Wofsy, S.C., 2006. A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes. Agric. For. Meteorol. 136, 1–18, http://dx.doi.org/10.1016/j.agrformet.2006.01.007.

Rutledge, S., Mudge, P.L., Campbell, D.I., Woodward, S.L., Goodrich, J.P., Wall, A.M., Kirschbaum, M.U.F., Schipper, L.A., 2015. Carbon balance of an intensively grazed temperate dairy pasture over four years. Agric. Ecosyst. Environ. 206, 10–20, http://dx.doi.org/10.1016/j.agee.2015.03.011.

SPW, 2010. Evolution de l'économie agricole et horticole de la Wallonie 2009–2010.

Schulze, E.D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I.A., Soussana, J.F., Smith, P., Grace, J., Levin, I., Thiruchittampalam, B., Heimann, M., Dolman, A.J., Valentini, R., Bousquet, P., Peylin, P., Peters, W., Rödenbeck, C., Etiope, G., Vuichard, N., Wattenbach, M., Nabuurs, G.J., Poussi, Z., Nieschulze, J., Gash, J.H., 2009. Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. Nat. Geosci. 2, 842–850, http://dx.doi.org/10.1038/ngeo686.

Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? Global Change Biol. 20, 2708–2711, http://dx.doi.org/10.1111/gcb.12561.

Soussana, J., Allard, V., Pilegaard, K., Ambus, P., Amman, C., Campbell, C., Ceschia, E., Clifton-Brown, J., Czóbel, S., Domingues, R., 2007. Full accounting of the greenhouse gas (CO2, N2O, CH4) budget of nine European grassland sites. Agric. Ecosyst. Environ. 121, 121–134.

Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4, 334–350.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., De Haan, C., 2006. Livestock's Long Shadow: Environmental Issues and Options. Food and Agriculture Organisation of the United Nations, Rome.

Suyker, A.E., Verma, S.B., Burba, G.G., 2003. Interannual variability in net CO_2 exchange of a native tallgrass prairie. Global Change Biol. 9, 255–265.

Teuling, A.J., Seneviratne, S.I., Stöckli, R., Reichstein, M., Moors, E., Ciais, P., Luyssaert, S., Van Den Hurk, B., Ammann, C., Bernhofer, C., Dellwik, E., Gianelle, D., Gielen, B., Grünwald, T., Klumpp, K., Montagnani, L., Moureaux, C., Sottocornola, M., Wohlfahrt, G., 2010. Contrasting response of European forest and grassland energy exchange to heatwaves. Nat. Geosci. 3, 722–727, http://dx.doi.org/10.1038/ngeo950.

Theau, J., Zerourou, A., 2008. Herbage, une méthode de calcul des sommes de températures pour la gestion des prairies. Presented at the Symposium Internationnal Vista-WP5, Outils Pour la Gestion des Prairies Naturelles, 91–102.

Vickers, D., Thomas, C.K., Martin, J.G., Law, B., 2009. Self-correlation between assimilation and respiration resulting from flux partitioning of eddy-covariance CO2 fluxes. Agric. For. Meteorol. 149, 1552–1555, http://dx.doi.org/10.1016/j.agrformet.2009.03.009.

Wayne Polley, H., Frank, A.B., Sanabria, J., Phillips, R.L., 2008. Interannual variability in carbon dioxide fluxes and flux–climate relationships on grazed and ungrazed northern mixed grass prairie. Global Change Biol. 14, 1620–1632.

Zeeman, M.J., Hiller, R., Gilgen, A.K., Michna, P., Plüss, P., Buchmann, N., Eugster, W., 2010. Management and climate impacts on net CO_2 fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland. Agric. For. Meteorol. 150, 519–530, http://dx.doi.org/10.1016/j.agrformet.2010.01.011.