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Research Paper

Rotational and continuous grazing does not affect the total net ecosystem exchange of a pasture grazed by cattle but modifies CO_2 exchange dynamics

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ABSTRACT

Grassland carbon budgets are known to be greatly dependent on management. In particular, grazing is known to directly affect CO_2 exchange through consumption by plants, cattle respiration, natural fertilisation through excreta, and soil compaction. This study investigates the impact of two grazing methods on the net ecosystem exchange (NEE) dynamics and carbon balance, by measuring CO_2 fluxes using eddy covariance in two adjacent pastures located in southern Belgium during a complete grazing season. Rotational (RG) grazing consists of an alternation of rest periods and short high stock density grazing periods. Continuous grazing (CG) consists of uninterrupted grazing with variable stocking rates. To our knowledge, this is the first study to assess the impact of these grazing methods on total net ecosystem exchange and CO_2 exchange dynamics using eddy covariance. The results showed that NEE dynamics were greatly impacted by the grazing method. Following grazing events on the RG parcel, net CO_2 uptake on the RG parcel was reduced compared to the CG parcel. During the following rest periods, this phenomenon progressively shifted towards a higher assimilation for the RG treatment. This behaviour was attributed to sharp biomass changes in the RG treatment and therefore sharp changes in plant photosynthetic capacity. We found that differences in gross primary productivity at high radiation were strongly correlated to differences in standing biomass. In terms of carbon budgets, no significant difference was observed between the two treatments, neither in cumulative NEE, or in terms of estimated biomass production. The results of our study suggest that we should not expect major benefits in terms of CO_2 uptake from rotational grazing management when compared to continuous grazing management in intensively managed temperate pastures.

1. Introduction

Livestock total greenhouse gas (GHG) emissions represent 14.5% of all anthropogenic GHG emissions (IPCC, 2014), among which cattle production represents 41% of the sector's emissions (Gerber et al., 2013). Therefore, there is a strong need to find and evaluate levers to mitigate these GHG emissions. During the last decade, several studies suggested that grasslands could act as important carbon (C) sinks (Klumpp et al., 2011; Mudge et al., 2011; Peichl et al., 2011; Rutledge et al., 2015; Soussana et al., 2007, 2010) with a notable site to site variability depending on several factors, such as pedoclimatic conditions and management practices. Maintaining and increasing the C sink activity of grasslands by improving their management has been identified as a lever to reduce the sector's GHG emissions (Pellerin et al., 2013; Soussana and Lemaire, 2014).

Grassland C balance and net ecosystem exchange are known to be greatly impacted by management (Smith, 2014; Soussana and Lemaire, 2014). The annual net carbon dioxide ecosystem exchange (annual NEE) is known to be directly impacted by grazing intensity through cattle respiration and indirectly through biomass consumption, natural fertilisation in the form of excreta, and soil compaction (Felber et al., 2016b, 2016a; JérÔme et al., 2014; Rong et al., 2017). The fertilisation rate also affects grassland carbon balance and carbon dioxide (CO_2) flux dynamics (Allard et al., 2007; Ammann et al., 2007; Klumpp et al., 2011; Skinner, 2013). Several studies assessing CO_2 fluxes and total C balance in rotational grazing (Campbell et al., 2015; Felber et al., 2016b; Mudge et al., 2011; Peichl et al., 2011; Rutledge et al., 2015), continuous grazing systems (Allard et al., 2007; Gourlez de la Motte et al., 2016; Klumpp et al., 2011) or both (Soussana et al., 2007) have been carried out. In those studies, grazing impacts on CO_2 exchanges

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were not easy to discern as they were blurred by CO2 flux responses to meteorological variables. Studies comparing CO_2 and C exchanges of both grazing methods in similar pedoclimatic conditions are very scarce (Chan et al., 2010; Cowie et al., 2013; Sanderman et al., 2015). These cited studies investigated the impact of rotational and continuous grazing by comparing direct soil organic carbon (SOC) measurements in different pastures. However, the lack of exactly similar management (stocking rates, fertilization etc.), pedoclimatic conditions and inherent SOC random variability between the investigated farms made differences difficult to analyze.

This research investigates the impact of two conventional cattle grazing methods on the CO_2 flux dynamics and its implication for the C balance. The first method, continuous grazing (CG), consists of uninterrupted grazing with variable stocking rates. It favours the ingestion of growing biomass thereby maintaining a relatively low standing biomass on the field during the whole grazing season. When well managed this method maintains a relatively stable grass height in the field by adjusting the stocking density to forage mass. This common system is not labour intensive and is well adapted to humid grasslands where grass production remains steady. The second method, rotational grazing (RG, also known as multi paddock grazing), consists of an alternation of short grazing periods (around 5 days) with high stocking densities and rest periods. During grazing periods, the forage mass accumulated during the preceding rest period is quickly eaten by the cattle leading to a rapid grass height shortening. This grazing system is commonly used in cattle production and has several advantages. First, it is very easy to keep an ungrazed paddock for harvest and therefore reduce forage loss. It is also easier to adapt the rotations to grass growth and maintain high productivity as well as good animal nutrition. It also facilitates operations such as fertilisation after grazing, scattering of livestock droppings, and the harvest of uneaten biomass because of cattle rejections, flowering etc. On the other hand, rotational grazing requires more workforce than continuous grazing, a good soil carrying capacity, and more drinking infrastructure across paddocks.

The main objectives of this study are to assess the impact of these two grazing methods on CO_2 flux dynamics as well as implications for the C balances. For this, a full grazing season (14th April to 17th November) monitoring of CO_2 turbulent fluxes using the eddy covariance (EC) method was performed simultaneously over two adjacent pastures managed according to these two grazing methods.

2. Material and methods

2.1. Site description and grassland management

This research was performed at the Dorinne Terrestrial Observatory (DTO) (50° 18′ 44″ N; 4° 58′ 07″ E) in southern Belgium. The mean air temperature is 10 °C and annual precipitation is 847 mm. Briefly, the site consists of two adjacent intensive permanent grasslands both similarly managed by the same farmer before the experiment (Fig. 1). The carbon balance and management of one of the pastures has been described in detail in a preceding paper (Gourlez de la Motte et al. (2016)), the second one has been added and fully equipped for the present experiment. Both pastures have been grazed by Belgian Blue cattle and fertilised using organic and mineral fertilisers for more than 40 years. According to the farmer there has been no vegetation restoration for more than 40 years. The grassland species composition is mainly grasses, with legumes and other species. The dominant species are perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). The main wind directions are south-west and north-east. The site used for this study is part of a commercial farm so that stocking rates, fertilization rates and other management practices are, as much as possible, representative of the common practices in beef cattle farms around the region.

The continuous grazing treatment (labelled "CG") was operated on a 4.2 ha pasture. The pasture was fertilised in March 2015 with 7 kg N ha^{-1} just before the beginning of the experiment. The field was continuously grazed from 14th April 2015 to 17th November 2015 (220 days) with a varying stocking rate depending on forage availability and weather conditions (Fig. 2). The annual stocking rate was 2.1 LU ha^{-1}.

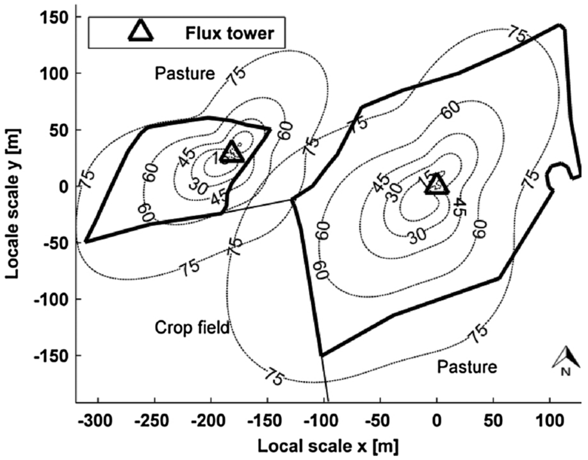

Fig. 1. Plan of the measurement site with both the rotational grazing parcel (RG) and the continuous grazing parcel (CG). Cumulative footprint contributions for the whole measurement season are illustrated by the dashed lines. Contribution levels are given in the labels for each line.

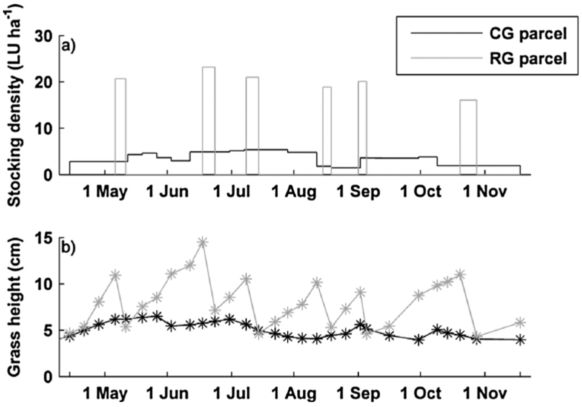

Fig. 2. Cattle stocking density (a) and herbage height (b) throughout the grazing season in the CG and RG parcels. A stocking density of zero designates rest periods.

In order to simulate rotational grazing (labelled "RG"), a plot of 1 ha was delimited within a bigger pasture for the purpose of the experiment (Fig. 1). The field was grazed with an alternation of high stocking density periods and rest periods (Fig. 2). A total of six grazing periods, each an average of six days with a stocking density of 19.3 LU ha^{-1} were carried out, leading to 36 days of grazing and an average annual stocking rate of 1.9 LU ha^{-1}. The cattle were confined in the parcel when grass height was between 10 and 15 cm. The stocking densities and grazing duration were adapted, so that similar stocking rates were obtained for both treatments with stocking densities and grazing durations in agreement with common practices in the region.

Throughout the paper, all variables labelled "RG" concern the rotational grazing treatment and all variables labelled "CG" concern the continuous grazing. Differences between the two treatments are always calculated as RG–CG and labelled using the symbol "Δ". 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). Breeding bulls and suckler cows correspond to 1 LU, and heifers and calves to 0.6 and 0.4 LU, respectively.

2.2. Instruments and setup

2.2.1. CO_2 flux measurements

The CO_2 fluxes were measured simultaneously on both fields with two eddy covariance setups each using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Ltd, UK) coupled with a closed-path CO_2/H_2O gas analyser IRGA (LI-7000, LI-COR Inc., Lincoln, NE, USA). On the CG parcel, the system was installed at 2.6 m height on a mast in the middle of the field. Air was pumped into the analyser through a polyurethane tube (6.45 m long; 4 mm inner diameter) by a pump (NO22 AN18, KNF Neuberger, D) at a 12 l min^{-1}. A more detailed description of the CG set up can be found in (Gourlez de la Motte et al., 2016). The system was identical for the RG parcel and was installed at 1.92 m height on a mast on the border of the parcel. This disposition and height was chosen in order to optimise the footprint under south-west wind direction (Fig. 1).

2.2.2. Ancillary measurements

Meteorological sensors were installed on the CG mast and are described in Gourlez de la Motte et al. (2016). Measurements included air temperature and relative humidity (RHT2nl02, Delta-T Devices Ltd, Cambridge, UK), soil temperature and soil moisture (ThetaProbe, Delta-T Devices Ltd, Cambridge, UK), global 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).

The herbage height was measured with a rising plate meter of 0.25 m^2 at 60 equidistant points in each field. Measurements on the field were taken once a week during the grazing season in the CG parcel and just before and after cattle confinements in the RG parcel. Previously (Gourlez de la Motte et al., 2016), an allometric relationship was established for the site to convert herbage height to herbage mass (HM). To establish this, direct samples were taken from the field underneath secured enclosures. Then, the relationship between grass height and harvest dry matter (DM) was computed. Samples were clipped from within0.5 × 0.5 m quadrats. DM was obtained by drying the samples at 60 °C using a forced air-oven. Biomass carbon content ($C_{content}$) was measured from laboratory measurements using the Dumas method (Dumas, 1831). The analyses were conducted by the Forest and Ecophysiology unit at the Institut National de la Recherche Agronommique (INRA).

Three secured enclosures were also used to obtain grass growth (HM_{gr}) under grazing for the CG treatment.

Cattle C intake through biomass consumption was deduced from biomass measurements for a given period using:

$$C_{intake} = C_{content}(HM_{beg} - HM_{end} + HM_{gr}) \quad (1)$$

where HM_{beg} and HM_{end} are the herbage mass at the beginning and at the end of the period.

2.3. Eddy flux computation and data processing

Half hourly CO_2 fluxes were computed following the procedure defined by the EUROFLUX-CARBOEUROFLUX-CarboEurope IP networks (Aubinet et al., 2000, 2012) and were fully described in Gourlez de la Motte et al. (2016). Briefly, CO_2 fluxes were calculated as the sum of the turbulent flux and of the storage term (Foken et al., 2012a) using EDDYSOFT software package (EDDY Software, Jena, Germany, Kolle and Rebmann (2007)). A double rotation was applied to wind velocity (Rebmann et al., 2012). Fluxes were corrected for high frequency loss on both masts following the procedure proposed by Mamadou et al. (2016). They were later filtered using a stationarity criterion according to Foken et al. (2012b) and low friction velocity (u*) (Aubinet et al., 2012). The u* threshold value was 0.13 m s^{-1} for the CG set up and 0.10 m s^{-1} for the RG set up. These thresholds were determined at the u* value where the relationship between u* and bin averaged temperature nighttime NEE flattens.

The complete CG dataset from 14th April to 17th November consists of 10608 30-min flux measurements. After filtering, the data consisted of 5276 30-min flux measurements corresponding to a data coverage of around 50%. Because of the limited RG parcel size, some fluxes had to be discarded when the parcel contribution to the footprint was not sufficient. To do that, we used the footprint evaluation tool proposed by Neftel et al. (2008). This tool calculates the contribution of a delimited surface (φ, in%) to the flux footprint relying on an analytical model (Kormann and Meixner, 2001) for the footprint function evaluation. Cumulative footprint contributions for the whole grazing season are illustrated in Fig. 1. The fluxes within the RG data set were automatically discarded when the contribution of the parcel to the footprint was less than 65%. As a result, fluxes measured under north-east wind conditions were automatically discarded. We tried, if possible, to confine the cattle when the parcel was within the measurement footprint. Confinements were advanced or delayed only when weather forecasts indicated a favorable wind direction change within a few days. Otherwise, confinements were done regardless of wind direction. After filtering, the RG data consisted of 3490 30-min fluxes corresponding to a data coverage of 33%.

Missing NEE data were filled following Reichstein et al. (2005). This algorithm fills the gaps using time-moving look up tables with data from time periods with similar environmental conditions. We adapted those look up tables so that data gaps occurring during confinements were not filled using rest periods data and vice versa. Filtering the data with too low footprint contribution and adding this condition should ensure that grass height is relatively steady during the time window used to fill the data in order to limit possible biases (Merbold et al., 2014).

2.4. Instruments validation before the experiment

In order to make sure that both eddy covariance systems measured fluxes identically, an instrument validation was carried out before the start of the experiment during 11–17th June 2014. To do so, both eddy covariance systems were placed next to each other in the CG parcel at the same heights (2.62 m). All the needed corrections described above were made and a regression between fluxes measured by both systems was computed. The slope of the regression was not significantly different than one ($R^2 = 0.97$, no intercept) indicating that both systems effectively measured identical fluxes.

2.5. Regression and data analysis

In order to remove the influence of the most important meteorological variables controlling NEE (radiation and temperature), a function describing NEE response to those variables was fitted on seven days times series and relevant physiological parameters were deduced from these. The objective was to assess how the variation of those parameters was affected by the grazing method. To do so, both data sets were divided into grazing and rest periods according to the RG treatment's grazing schedule so that a grazing period corresponds to a period when both parcels were grazed, while rest periods correspond to periods when only the CG parcel was grazed. A total of six grazing periods and seven rest periods were identified. Each of the rest periods were divided into seven day windows and a daytime NEE light response curve was fitted for each window. Grazing periods were not divided as their duration was mostly less than seven days. We used a modified *Michaelis Menten* light response curve (Falge et al., 2001; Lasslop et al., 2010) including temperature sensitivity to respiration (Lloyd and Taylor, 1994; Reichstein et al., 2005):

$$\mathrm{NEE_{day}} = -\frac{\alpha\times \mathrm{PPFD}\times \mathrm{G_{PPFD_{ref}}}}{\alpha\times\mathrm{PPFD} + \mathrm{G_{PPFD_{ref}}}(1-\frac{\mathrm{PPFD}}{\mathrm{PPFD_{ref}}})} + \mathrm{Rd_{10}}\times \exp\left\{\mathrm{E_0}(\frac{1}{\mathrm{T_{ref}}-\mathrm{T_0}} - \frac{1}{\mathrm{T_s}-\mathrm{T_0}})\right\} \tag{2}$$

where G_{ref} is the gross primary productivity at a reference photon flux density ($PPFD_{ref}$). $PPFD_{ref}$ was fixed at 1500 µmol m^{-2} s^{-1} and $G_{PPFDref}$ was therefore named G_{1500} throughout the paper. The traditional *Michaelis Menten* equation was modified in order to obtain G_{1500} instead of gross primary productivity at light saturation because light saturation was not reached at the end of the season. Rd_{10} (µmol m^{-2} s^{-1}) is the dark respiration normalised at reference temperature (T_{ref}) set at 10 °C. The other parameters are α, the quantum light efficiency (µmol CO_2 μmol^{-1} photons), T_0 which was set at −46.02 °C (Reichstein et al., 2005) and the respiration sensitivity to temperature E_0. T_s (°C) is the averaged soil temperature at 2 cm for the time window. A fixed long term E_0 value deduced from the annual response of nighttime u*-filtered NEE to soil temperature was used for each regression. The standard errors (ε) of the coefficients were also computed.

In order to compare the regression coefficients, normalised differences (u_{obs}) between two parameters (c) of the same time window were computed as follows:

$$u_{obs} = \frac{c_{RG} - c_{CG}}{\sqrt{\varepsilon_{RG}^2 + \varepsilon_{CG}^2}} \tag{3}$$

Differences between two coefficients were considered significant ($\alpha = 0.05$) when $|u_{obs}| > 1.96$.

2.6. Cattle respiration

2.6.1. Estimation of cattle respiration from eddy covariance fluxes

The net ecosystem exchange (NEE) measured by eddy covariance is the sum of cow respiration (R_{cows}) and soil and vegetation net exchange (Felber et al., 2016a, 2016b). The procedure used to estimate R_{cows} is described in Fig. 3. First, we selected valid nighttime fluxes in the RG data set. Then, the data set was divided into periods with cows in the field (total ecosystem respiration, TER) and periods without cows (ecosystem respiration, ER) according to the grazing schedule. Then, as ER is sensitive to soil temperature, a two parameter exponential equation (Lloyd and Taylor, 1994) was fitted on the ER data set (see Eq. (1)) and a modelled ecosystem respiration (ER_m) was computed using this equation. As ER_m is representative of the average respiration response to soil temperature without cows, the average R_{cows} can be computed as:

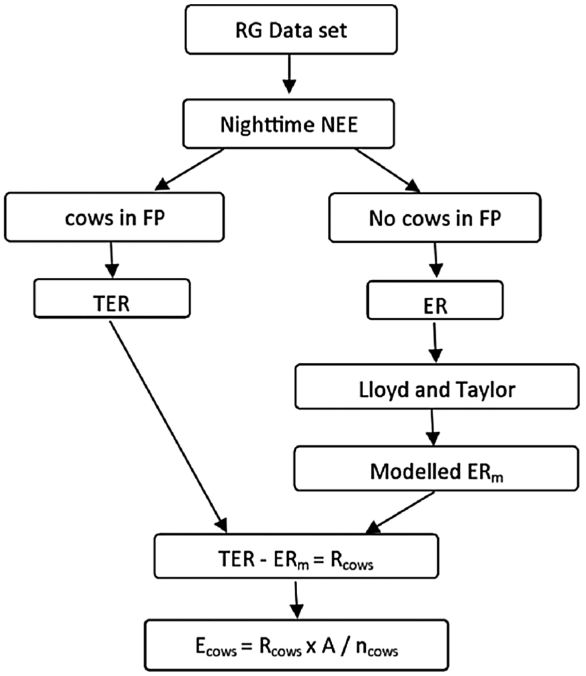

Fig. 3. Flowchart of the cattle respiration calculation.

$$\sum(\mathrm{TER} - \mathrm{ER_m})/\mathrm{n_{obs}} = \widehat{\mathrm{R}}_{\mathrm{cows}} \tag{4}$$

where n_{obs} is the number of valid TER observations. Then the average estimated respiration for one livestock unit ($\hat{E}_{cow}$) was calculated as

$$\hat{\mathrm{E}}_{\mathrm{cow}} = \frac{\widehat{\mathrm{R}}_{\mathrm{cows}}\mathrm{A}}{\hat{\mathrm{n}}_{\mathrm{LU}}} \tag{5}$$

where $\hat{n}_{LU}$ is the average number of livestock units in the field and A the surface of the field.

2.6.2. Estimation of cattle respiration from ingested biomass

Cattle respiration was also estimated from ingested biomass by assuming that only a fraction of the ingested C is re-emitted in the form of CO_2 as described by Gourlez de la Motte et al. (2016). During a grazing event, cattle respiration was estimated as follows:

$$\mathrm{E_{cow}} = \frac{((\mathrm{OM\ D}\times \mathrm{C_{intake}}) - \mathrm{F_{CH4-C}})}{\hat{\mathrm{n}}_{\mathrm{LU}}} \tag{6}$$

where OMD (%) is the digestible organic matter and C_{intake} the ingested C during grazing. OMD was obtained from near infrared reflectance spectrometry analysis (Decruyenaere et al., 2009) of samples taken *in situ*. $F_{CH4\text{-}C}$ was estimated as a fraction of ingested DM using a constant methane emission factor fixed at 6% of DM intake (Lassey, 2007).

3. Results and discussion

3.1. Grazing method impact on carbon dioxide flux dynamics

Daily averaged NEE_{CG} and NEE_{RG} showed different patterns during the grazing season. Daily averaged NEE_{CG} showed mostly net CO_2 uptakes from the start of the grazing season until late June and then shifted to mostly net CO_2 emissions for the rest of the year (Fig. 4a). This early shift was previously observed at the same site by Gourlez de la Motte et al. (2016) and was attributed to grazing that limits gross primary productivity by limiting photosynthetic capacity. In contrast, NEE_{RG} showed different dynamics (Fig. 4b). Considerable CO_2 emission peaks were observed during grazing events predominantly because of cattle respiration followed by a progressive shift towards CO_2 uptake during rest periods. Prolonged CO_2 uptake events were observed in August and October at the end of the rest periods. This led to more pronounced CO_2 emissions on the RG treatment during cattle confinement compared to the CG treatment, and more pronounced CO_2 uptake after several days of recovery (Fig. 4c). Similar switches from a source to a sink were previously observed after grazing or cutting because of rapid changes in standing biomass (Nieveen et al., 2005; Peichl et al., 2012; Rogiers et al., 2008; Rutledge et al., 2015; Wohlfahrt et al., 2008). It is noted that a long gap between the 5th and 6th confinements could not be filled because of prolonged north-west wind direction conditions.

Herbage heights in RG were similar at the beginning of each rest period. However, the height was mostly stable in the CG parcel due to continuous grazing, while grass grew quickly in the RG parcel during rest periods (Fig. 2). These differences in standing biomass caused by the grazing method could have impacted gross primary productivity as well as the total ecosystem respiration and therefore NEE dynamics. In order to identify which processes were responsible for the observed differences in NEE dynamics a regression analysis was carried out to compute G_{1500}, the gross primary productivity at high radiation, and Rd_{10}, the dark respiration normalised at 10 °C.

During each rest period, notable differences in G_{1500} dynamics could

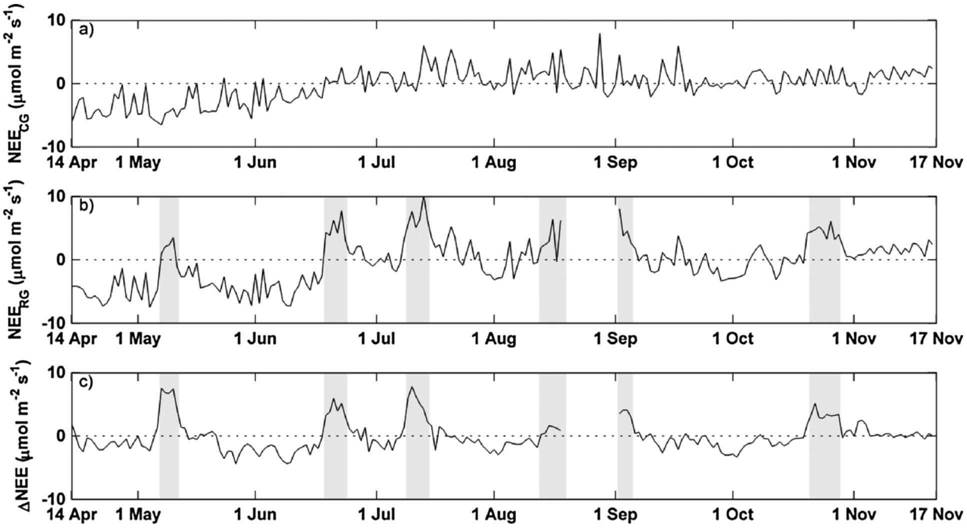

Fig. 4. Daily means of (a) net ecosystem exchange of the CG parcel (NEE_{CG}), (b) net ecosystem exchange of the RG parcel (NEE_{RG}) and (c) differences between NEE_{RG} and NEE_{CG} ($\Delta NEE = NEE_{RG}–NEE_{CG}$). Confinement periods on the RG parcel are coloured grey.

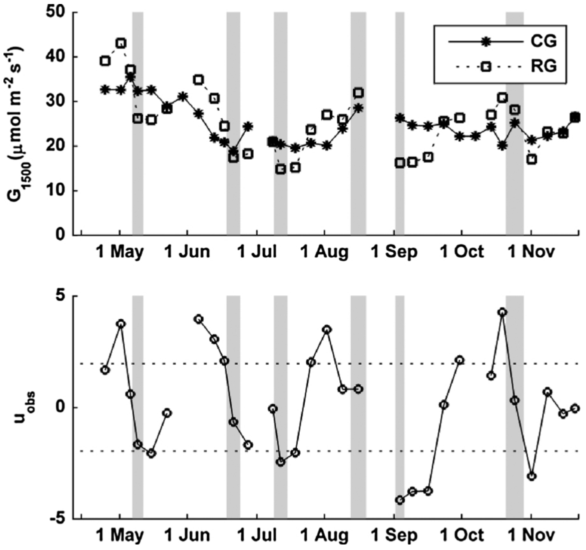

Fig. 5. Evolution of (a) gross primary productivity at high radiation (G_{1500}) and (b) normalised differences between the two coefficients (u_{obs}). Confinement periods on the RG parcel are coloured grey. Horizontal dashed lines correspond to the 95% level of confidence (± 1.96).

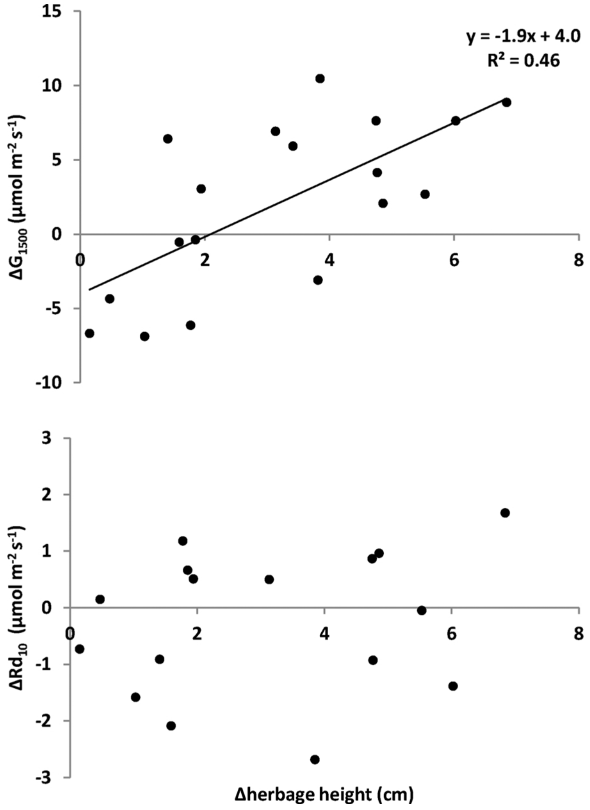

Fig. 6. Relationship between differences in herbage height and (a) differences in dark respiration normalised at 10 °C (ΔRd_{10}) and (b) differences in gross primary productivity at high radiation (ΔG_{1500}).

be observed (Fig. 5). At the beginning of each rest period, just after the cattle confinement, G_{1500} was lower on the RG parcel. This difference progressively shifted towards a higher G_{1500} at the end of the rest period. This behaviour was less visible for the last rest period at the end of the growing season when grazing intensity was very low on the CG parcel because of low biomass production. As a result, ΔG_{1500} was significantly correlated (p value < 0.05) to the difference of herbage height between the two parcels (confinement periods excluded, Fig. 6). This correlation illustrates the influence of grass height on gross primary productivity (GPP) and the plant's photosynthetic capacity. The impact of fast changes in vegetation heights due to rotational grazing on gross primary productivity at high radiation was also observed by Felber et al. (2016b) using a similar approach and by Campbell et al. (2015) using an automated phytomass index analysis (Lohila et al., 2004).

It is also notable that G_{1500} was systematically lower (less assimilation) on the RG parcel following the confinements even when grass heights were similar on both parcels. This may be due to a reduced regrowth rate after intensive grazing. Indeed, following intensive grazing, the ratio of leaf area per plant weight is reduced thereby limiting its regrowth rate (Oesterheld and McNaughton, 1991).

No similar impact of grazing on Rd_{10} dynamics was observed. No significant correlation (p value > 0.05) was found between ΔRd_{10} and the difference of herbage height between the two parcels (Fig. 6). These results are in agreement with another investigation made at the same site (JérÔme et al., 2014) that found a decrease in gross primary productivity at light saturation during grazing periods and an increase during rest periods, but no impact of grazing intensity on normalised respiration at 10 °C, probably due to opposing effects of grazing on the total ecosystem respiration. Therefore, in our study, the observed switch from a CO_2 source to a CO_2 sink after a grazing event on the RG parcel was more likely to be due to changes in photosynthetic capacity rather than processes influencing the total ecosystem. Other studies have also shown that changes in NEE after grazing or cutting were more driven by changes in GPP rather than changes in ER (Rogiers et al., 2008; Wohlfahrt et al., 2008).

During confinements, NEE_{RG} was found to be greatly affected by cattle respiration. Indeed, cattle respiration was estimated at 3.0 ± 0.8 kg C LU^{-1} d^{-1} (see Section 3.3). The average stocking density during cattle confinement was 19.3 LU ha^{-1} while it was 3.5 LU ha^{-1} on average in the CG parcel. Therefore, this difference of stocking densities should have led to a contribution of 4.5 ± 1.2 µmol m^{-2} s^{-1} to ΔNEE on average. Nighttime NEE_{RG} was 3.4 µmol m^{-2} s^{-1} higher on average than NEE_{CG} during confinement, which is within the error bound of the estimated cattle respiration. Therefore, it is more likely that differences in total ecosystem respiration during confinements were mostly due to cattle respiration (Felber et al., 2016b; JérÔme et al., 2014). The higher difference observed during the daytime (5.7 µmol m^{-2} s^{-1}) can be explained by the gross primary productivity reduction in the RG parcel because of defoliation during confinement.

Cattle respiration could also have had an impact on measured NEE_{CG} dynamics. However, on short term measurements (daily to monthly), the contribution of moving emissions spots like cattle are highly uncertain and variable because of uneven spatial and temporal cattle distribution within the footprint (Dumortier et al., 2017; Felber et al., 2016b). This probably explains why no clear impact of cattle respiration could be observed on short term NEE_{CG} dynamics.

3.2. Biomass production and consumption

A total production of 6270 kg DM ha^{-1} and from 6470 to 7420 kg DM ha^{-1} were estimated on the CG parcel and the RG parcel respectively leading to a rather small difference between the two treatments. For the RG treatment, the lower value is obtained by considering zero growth during confinements while the higher value is obtained by using the same grass growth as the CG treatment (around 950 kg DM ha^{-1}). Considering a zero growth might underestimate the annual grass production regarding the length of those events (a total 36 days). However, assuming identical growth rate is also unlikely as growth should have been highly constrained once trampled and grazed. We note that similar forage production between rotational and continuous grazing has previously been observed (Briske et al., 2008; Popp et al., 1997) but under very different climatic conditions and farm management than in our study.

3.3. Estimation of cattle respiration

Cattle respiration was estimated from eddy covariance measurements following the procedure described in Section 2.6.1. A R_{10} value of 5.6 µmol m^{-2} s^{-1} and a E_0 value of 238.4 K were obtained from the fit of the exponential equation on nighttime fluxes without cows. $\widehat{R}_{cows}$on the RG parcel was 6.1 ± 1.6 µmol m^{-2} s^{-1} leading to an $\hat{E}_{cow}$value of 3.0 ± 0.8 kg C LU^{-1} d^{-1}. Values are presented with their 95% confidence intervals. Cattle respiration was also independently estimated from ingested biomass. A value of 2.5 kg C LU^{-1} d^{-1} was estimated which is within the uncertainty of the estimated value using eddy covariance.

The cattle respiration value estimated from eddy covariance was not significantly different from the value of 2.59 ± 0.58 kg C LU^{-1} d^{-1} obtained from eddy covariance at the same site and from the value obtained from ingested biomass by JérÔme et al. (2014). JérÔme et al. (2014) also used confinement experiments to estimate cattle respiration but followed a different methodology. In that experiment, cattle respiration was estimated by calculating the average difference between fluxes just before and after the confinement experiment under similar environmental conditions. A different method was proposed in this study because the confinement periods were longer (average 6 days vs. 1 day) and the changes in standing biomass were very different leading to non-similar conditions before and after confinement. Other limitations of confinement experiments to estimate cattle respiration were widely discussed by JérÔme et al. (2014). In a similar way, Felber et al. (2016b) estimated a cattle respiration value of 4.6 kg C $head^{-1}$ d^{-1} for dairy cows using either a precise grazing schedule or animal positioning system and eddy covariance.

The total contribution of cattle respiration to NEE (R_{cows}) could also be estimated by upscaling E_{cow} to the entire year using the grazing schedule for both parcels. The total R_{cows} was 230 ± 61 g C m^{-2} yr^{-1} for the CG parcel and 208 ± 55 g C m^{-2} yr^{-1} for the RG. The difference of contribution of cattle respiration to ΔNEE is therefore around 22 g C m^{-2} yr^{-1}. This scaling up assumes spatially homogenous cattle distribution over time so that their respiration signal becomes a constant part of the eddy covariance measurements signal. This hypothesis is more likely to be met for the RG treatment as fluxes are discarded when the measurement footprint is outside the parcel increasing the probability that the herd is in the system footprint (JérÔme et al., 2014). For the CG parcel, this hypothesis is less likely to be met (Felber et al., 2016b) as herds can or cannot contribute to the CO_2 flux depending on wind direction and herd position in the field. However, as suggested by Dumortier et al. (2017) for methane flux measurements at DTO, this hypothesis is more likely to be reached when integrating fluxes over long periods.

3.4. Impact of grazing method on cumulative net ecosystem exchange

In order to assess the impact of the grazing method on the cumulative NEE, the data sets were divided into seven periods. The first period started at the beginning of the grazing season and ended at the beginning of the first confinement (Table 1, Fig. 7). Then, each rotation corresponds to the cattle confinement and its resting period until the start of the next rotation. For each rotation cumulative NEE_{RG} increased during confinement leading to a positive difference between cumulative NEE_{RG} and NEE_{CG} (ΔNEE). Then, cumulative ΔNEE stagnated for a few days and eventually started to decrease if the rest period was long enough. After the last confinement, cumulative ΔNEE stagnated because of very limited photosynthetic activity at the end of the grazing season. Cumulative ΔNEE could therefore be negative ($NEE_{RG} < NEE_{CG}$) or positive depending on the length of the rest period and when it occurred in the grazing season. ΔNEE ranged from −30 to 41 g C m^{-2} (Table 1). It was negative for the two rotations with the longest rest periods. For these two rotations, neutrality ($NEE_{RG} = NEE_{CG}$) was obtained after a recovery period of 31 and 27 days. We also noticed that the 4th rotation's recovery period lasted for 28 days leading to a budget close to neutrality (ΔNEE = +8 g C m^{-2}). Although these observations lack replicates, we can argue that the time needed to reach neutrality should be around four weeks depending on weather conditions and stocking densities. It is also important to note that rest period fluxes were similar at the end of the season when grass growth was practically zero.

When accounting only for periods that could be completely filled, NEE_{RG} was −88 g C m^{-2} and NEE_{CG} was −74 g C m^{-2} leading to a ΔNEE of −14 g C m^{-2}. Accounting for the difference in cattle respiration due to a difference in stocking densities shifts NEE_{RG} to −66 g C m^{-2} which leads to a cumulative ΔNEE of +8 g C m^{-2}. At DTO, for the CG parcel, an average uncertainty for the annual cumulative NEE of +26 (upper range) and −17 (lower range) g C m^{-2} yr^{-1} were estimated by Gourlez de la Motte et al. (2016). When considering both the lower data coverage and the fast changes in standing biomass in the RG treatment, we can presume that the uncertainty in RG treatment is even greater. Therefore, this very small difference in NEE is not likely to be significant. It may also be noted that no significant difference in terms of annual productivity and ingested biomass was observed between the two treatments. This leads to the conclusion that, in our study, no significant difference in total NEE could be observed

Table 1
Starting and ending dates (in year 2015), cumulative net ecosystem exchange for the continuous grazing (NEE_{CG}), rotational (NEE_{RG}) grazing treatments, difference in net ecosystem exchange between those treatments ($\Delta NEE = NEE_{RG}–NEE_{CG}$), stocking densities and grazing durations for each period. The first period starts at the beginning of the grazing season (14th April 2015) and ends at the beginning of the first confinement. Next periods correspond each to a confinement followed by its restoration period. The 5th period marked with * is incomplete because of too low data coverage.

			Continuous grazing		Rotational grazing				
Period n°	Dates	Duration (days)	Stocking density (LU ha^{-1})	NEE_{CG} (gC m^{-2})	Confinement duration (days)	Rest periods (days)	Stocking density (LU ha^{-1})	NEE_{RG} (g C m^{-2})	ΔNEE (gC m^{-2})
1	14/Apr-6/May	23	2.8	−92	–	23	0	−119	−27
2	6/May-17/Jun	42	3.6	−123	5	37	20.7	−153	−30
3	17/Jun-8/Jul	21	4.5	13	6	15	23.3	32	19
4	8/Jul-11/Aug	34	5	49	6	28	21.1	57	8
5*	11/Aug-31/Aug	20	3.9	17	7	13	18.9	22	5
6	31/Aug-19/Oct	49	3.2	26	4	45	20.1	−4	−30
7	19/Oct-20/Nov	32	1.9	36	8	24	16.1	77	41
Total/average		221	3.5	−74	36	162	19.3	−88	−14

between the two grazing methods assuming similar stocking rates. Similar conclusions have been observed using direct soil organic carbon measurements comparing rotationally grazed and continuously grazed grasslands with similar management for at least a decade (Chan et al., 2010; Cowie et al., 2013; Sanderman et al., 2015). It is more likely that grassland carbon budgets depend more on the stocking and fertilisation rates than the grazing method (Allard et al., 2007; Klumpp et al., 2011; Soussana and Lemaire, 2014).

The absence of significant difference between the two treatments assumes no inherent variability in terms of annual NEE between the two parcels. Although this hypothesis is widely used by other studies using paired eddy covariance measurements to study management impact on CO_2 fluxes (eg. Allard et al., 2007; Cowan et al., 2016; Klumpp et al., 2011; Skinner, 2013), Rutledge et al. (2017) found that this strong assumption was not always met. Indeed, by measuring C fluxes in each block during one complete year before the experiment, they found significant differences between the blocks that could not easily be attributed to large pre-treatment differences in term of management, soil types and site history. In this experiment, we tried to limit those possible biases as much as possible by choosing two adjacent pastures with very similar soil, site history and management.

4. Conclusion

To our knowledge, this study is the first to compare the impact of rotational and continuous grazing in terms of CO_2 flux dynamics and C budget measured by eddy covariance. It was carried out in an intensively managed pasture grazed by Belgian Blue suckler cows located in southern Belgium. The results showed that despite CO_2 fluxes showing very different dynamics between the two grazing management systems, overall NEE sums were very similar. Although no significant differences in term of cumulative NEE was observed, it is important to emphasise that this result is highly dependent on the stocking rates and the length of the rest periods. Shorter rest periods (with similar stocking densities) on the RG treatment could have led to an overall reduced photosynthetic capacity of the pasture, thereby emphasising the need to maintain a suitable stocking rate. The strong link between gross primary productivity at high radiation and herbage height also highlights the strong need to account for continuous biomass changes when modelling or studying the relationship of NEE to other environmental variables (Campbell et al., 2015; Lohila et al., 2004).

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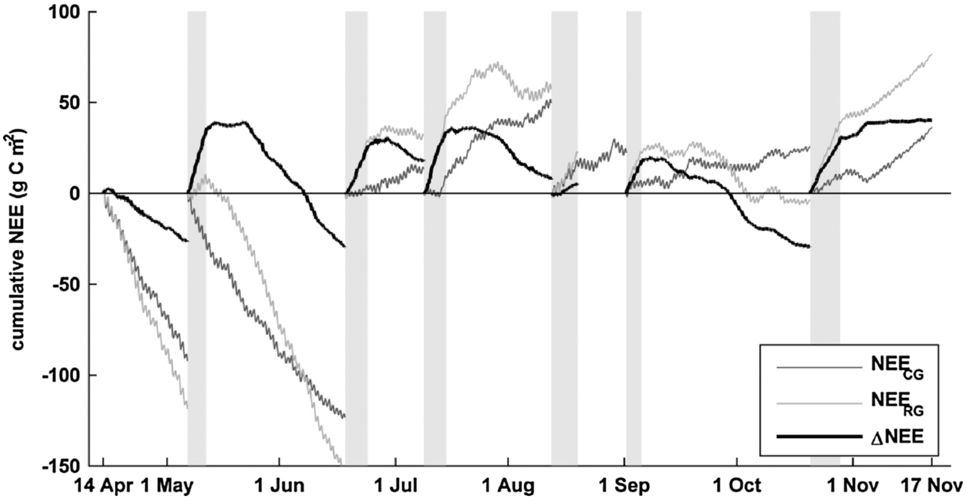

Fig. 7. Evolution of cumulative NEE and ΔNEE ($\Delta NEE = NEE_{RG}–NEE_{CG}$). The data set is divided into 7 periods indicated by vertical dashed lines. Confinement periods on the RG parcel are coloured grey.

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