1 **Title: Herd position habits can bias net CO_2 ecosystem exchange estimates in free range**
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3 Running head: Herd position habits can bias net CO_2 ecosystem exchange estimates in free

4 range grazed pastures.

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Highlights

- Grazing animals influence eddy covariance NEE measurements through their respiration

- A methodology is proposed to assess if this respiration is effectively included in NEE estimates

- CH_4 fluxes and GPS trackers were used to detect cow presence in the footprint

- Biased annual NEE were found because of herd location habits

- Cow respiration rates were corrected to obtain unbiased annual NEE

Abstract

28 The eddy covariance (EC) technique has been widely used to quantify the net CO_2 ecosystem

29 exchange (NEE) of grasslands, which is an important component of grassland carbon and greenhouse

30 gas budgets. In free range grazed pastures, NEE estimations are supposed to also include cattle

31 respiration. However, cattle respiration measurement by an EC system is challenging as animals act as

32 moving points emitting CO_2 that are more or less captured by the EC tower depending on their

33 presence in the footprint. Often it is supposed that, over the long term, cattle distribution in the pasture

34 is homogeneous so that fluctuations due to moving sources are averaged and NEE estimates are

35 reasonably representative of cattle respiration.

36 In this study, we test this hypothesis by comparing daily cow respiration rate per livestock unit (LU)

37 estimated by postulating a homogeneous cow repartition over the whole pasture with three other

38 estimates based on animal localization data, animal scale carbon budget and confinement experiments.

39 We applied these methods to an intensively managed free range grassland and showed that the NEE

40 estimate based on a homogeneous cow repartition was systematically lower than the three other

41 estimates. The bias was about 60 g C m^{-2} yr^{-1}, which corresponded to around 40% of the annual NEE.

42 The sign and the importance of this bias is site specific, as it depends on cow location habits in relation

43 to the footprint of the EC measurements which highlight the importance of testing the hypothesis of

44 homogeneity of cattle distribution on each site.

45 Consequently, in order to allow estimating the validity of this hypothesis but also to improve inter site

46 comparisons, we advocate to compute separately pasture NEE and grazer's respiration. For the former

47 we propose a method based on cattle presence detection using CH_4 fluxes, elimination of data with

48 cattle and gap filling on the basis of data without cattle. For the second we present and discuss three

49 independent methods (animal localization with GPS, animal scale carbon budget, confinement

50 experiments) to estimate the cattle respiration rate.

1 Introduction

Grasslands cover around 40% of Earth's land area (Steinfeld et al., 2006) and are therefore one of the most important ecosystems on earth. More specifically, pasturelands are dedicated to the production of forage for harvest by grazing, cutting, or both. These lands constitute important carbon (C) stocks estimated at 343 Pg C, which is nearly 50% more than the carbon stored in worldwide forest soils (Conant et al., 2017). They can therefore act as important carbon sinks that can play an important role in mitigating livestock production-related GHG emissions (Hörtnagl et al., 2018; Soussana et al., 2007). There is therefore a strong need to accurately quantify grassland C sequestration.

The most used technique to quantify CO_2 exchanges between grasslands and the atmosphere is the Eddy Covariance (EC) technique (Aubinet et al., 2012). In addition, by combining net CO_2 ecosystem exchanges (NEE) obtained with this technique with other non-CO_2 carbon export and import measurements, a complete ecosystem carbon budget (net biome productivity, NBP) can be obtained (Soussana et al., 2007). Studies measuring NBP showed that pastures could act as important C sinks that could at least partially offset the CH_4 and N_2O emitted in the pasture, depending on management and pedoclimatic conditions. Study sites were either grazed (Allard et al., 2007; Felber et al., 2016a; Gourlez de la Motte et al., 2016; Klumpp et al., 2011; Nieveen et al., 2005; Rutledge et al., 2017a, 2017b, 2015; Wayne Polley et al., 2008), mown (Ammann et al., 2007; Merbold et al., 2014; Wohlfahrt et al., 2008), or both (Jones et al., 2017; Mudge et al., 2011; Skinner, 2008; Skinner and Dell, 2015; Zeeman et al., 2010).

Flux measurements over grazed pastures are especially challenging. In the presence of cattle, the total net ecosystem exchange (NEE_{tot}) of a pasture can be partitioned between the net ecosystem exchange without grazing animals (NEE_{past}) and the total respiration of the animals on the field (R_{cows}) (Felber et al., 2016b):

$$NEE_{tot} = NEE_{past} + R_{cows} \qquad (1)$$

which can further be combined with other C exports and C imports to obtain the NBP of a pasture :

$$NBP = NEE_{tot} - C_{exports} + C_{imports} \qquad (2)$$

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77   However, as cattle act as moving CO_2 sources their emissions either will or won't be captured by the

78   measuring system, depending on the presence of the cattle in the footprint area. Although R_{cows} is a

79   small flux compared to gross primary productivity (GPP) and the total ecosystem respiration (TER), it

80   can be of the same order of magnitude as NEE_{tot}. Even if its magnitude may vary from site to site,

81   R_{cows} around 200 g C m^{-2} yr^{-1} may be expected in pastures with a high stocking rate (Jérôme et al.,

82   2014). Therefore, an under- or overestimation of this flux could lead to a non-negligible systematic

83   bias in annual NEE_{tot} values and therefore in annual NBP.

84   Historically, most of the studies on grazed sites assumed (explicitly or not) that, averaged over a

85   grazing season, cattle were spread evenly over the field so that their respiration signals become a part

86   of NEE_{tot} and are correctly estimated by EC. Although most often not verified, this hypothesis was

87   commonly (sometimes implicitly) used for free range grazed pastures where the presence or not of

88   cattle within the footprint at a given time is not easy to assess (Byrne et al., 2007; Gourlez de la Motte

89   et al., 2016; Jaksic et al., 2006; Klumpp et al., 2011; Zeeman et al., 2010).

90   When the pasture is divided into several paddocks for rotational grazing this hypothesis is not met, but

91   the presence of cattle in the footprint is much easier to assess so that the computation of NEE_{past} is

92   possible by filtering fluxes affected by cattle respiration. In an intensively rotationally grazed site with

93   multiple paddocks, Skinner (2008) advocated that fluxes affected by cattle respiration should be

94   removed as CO_2 fluxes were very erratic in the presence of a high stocking density within the

95   footprint. He proposed to filter out the fluxes from paddocks affected by cattle respiration, compute

96   NEE_{past}, and account for the biomass ingested by the animals as C exports and the animal excretions as

97   C imports, thereby considering cattle to be external to the system. More recently, several studies also

98   identified this problem and adapted their methodology to exclude grazer respiration and thus, compute

99   NEE_{past} (Felber et al., 2016a; Hunt et al., 2016; Rutledge et al., 2017a, 2017b). Kirschbaum et al.,

100   (2015) also highlighted the need to filter fluxes in the presence of high stocking density in the

101   footprint in order to obtain good agreement between modelled and measured CO_2 fluxes in a

102   rotationally grazed pasture.

103   Alternatively, Felber et al. (2016b) used GPS trackers on cows in combination with a footprint model

104   to separate fluxes with and without cattle respiration. Animal positions were then used to estimate a

105   reference respiration rate per animal. In order to verify the hypothesis that NEE_{tot} includes R_{cows} in a

106   representative way, they compared this respiration rate value to the respiration rate calculated

107   considering a homogeneous cattle distribution on the pasture. For their site, a rotationally grazed

108   multi-paddock pasture, they found that on a yearly basis animal respiration was included in NEE_{tot} in a

109   representative way suggesting that there were no correlations between the animal positions and the

110   wind direction. However, this result is site specific and such observations has yet to be verified for

111   continuously grazed pastures (Felber et al., 2016a). In those sites the animals are allowed to move

112   freely in the pasture so that, if cattle are more likely to remain grouped in specific areas of the pasture

113   such as shade areas or near water/feed supplies, which is very probable, NEE_{tot} would be biased in a

114   way and to an extent that depends on the position of these specific areas relative to the footprint.

115   The aim of the present study is to test different methods to verify if the contribution of grazing animal

116   respiration is adequately represented in the NEE measured in a continuously grazed pasture. The

117   methods were applied at the Dorinne Terrestrial Observatory (DTO), an intensively managed pasture

118   with a high annual stocking rate (>2 livestock units (LU) per hectare). A solution is also proposed to

119   correct cow respiration values if not estimated properly. Conclusions and consequences regarding the

120   computation of the carbon budget of the pasture are also discussed. Advantages and drawbacks of the

121   different methods proposed in the paper are discussed and more general guidelines are provided for

122   researchers who aim to measure consistent NEE and cow respiration rates in grazed pastures.

2 Materials and methods

2.1 Site description and grassland management

The method was tested at the Dorinne Terrestrial Observatory (DTO) (50° 18' 44''N; 4° 58' 07'' E) in southern Belgium. The site consists of a 4.2 ha intensively managed permanent pasture grazed by Belgian Blue beef cattle with an average stocking rate of about 2.3 LU ha^{-1} yr^{-1}. Cattle are usually on the field from April to mid-November and are free to graze throughout the whole pasture at all times. The pasture is fertilized with an annual nitrogen fertilization of around 120 kg N ha^{-1} (excluding cow excreta). The main wind directions are South-West and North-East during anticyclonic weather conditions. The locations of the flux tower, water trough, hedges, feeding place, and fences are described in Figure 1 and have not changed since the start of the measurements in 2010. The carbon (Gourlez de la Motte et al., 2016) and the methane (Dumortier et al., 2017) budgets of the site have been presented in previous studies. The vegetation is mainly composed of ryegrass (*Lolium perenne L.*) and white clover (*Trifolium repens L.*). The site is a commercial farm with management that is, as much as possible, representative of the common practices on beef cattle farms around the region. Breeding bulls and suckler cows correspond to 1 LU, heifers and calves to 0.6 and 0.4 LU, respectively.

2.2 Flux measurements and processing

The CO_2 flux was measured with an eddy covariance setup using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Ltd, UK) coupled with a closed path CO2/H2O gas analyzer IRGA (LI-7000, LI-COR Inc., Lincoln, NE, USA). The system was installed at a height of 2.6 m in the middle of the field. Air was pumped into the analyzer through a polyurethane tube (6.45 m long; 4 mm inner diameter) by a pump (NO22 AN18, KNF Neuberger, D) with a flow of 12 l min^{-1}. A more detailed description of the CO_2 set up can be found in (Gourlez de la Motte et al., 2016).

The CH_4 flux was measured using the same anemometer on the same mast coupled with a fast CH_4 analyzer (PICARRO G2311-f, PICARRO Inc, USA). Air was pumped into the analyzer using a heated

149 tube (6.85 m long, 6 mm inner diameter). A more detailed description can be found in Dumortier et al.

150 (2017).

151 Half hourly CO_2 and CH_4 fluxes were computed following the standard procedure defined by the

152 CarboEurope IP network (Aubinet et al., 2012, 2000). CO_2 fluxes were calculated as the sum of the

153 turbulent flux and of the storage term (Foken et al., 2012a) using the EDDYSOFT software package

154 (EDDY Software, Jena, Germany, (Kolle and Rebmann, 2007)). They were corrected for high

155 frequency loss following the procedure proposed by Mamadou et al. (2016). They were later filtered

156 for stationarity using a selection criteria of 30%, according to Foken et al. (2012b). CH_4 fluxes were

157 calculated using the EddyPro® (LI-COR Inc, Lincoln, NE, USE) open source software (Version 6). A

158 double rotation was applied to wind velocity for both fluxes (Rebmann et al., 2012). Both CO_2 and

159 CH_4 fluxes were filtered for low turbulence using a friction velocity (u*) threshold of 0.13 m s^{-1}. This

160 threshold was determined as the u* value where the relationship between u* and the temperature

161 normalized nighttime CO_2 flux flattens. A more detailed description of CO_2 and CH_4 flux computation

162 can be found in Gourlez de la Motte et al. (2016) and Dumortier et al. (2017), respectively. Note that,

163 in this study, the requirement for the CH_4 flux quality is low as the fluxes are only used as a tool to

164 assess the presence or absence of cows in the footprint (binary test).

165 ## 2.3 Meteorological measurements

166 Meteorological measurements included air temperature and relative humidity (RHT2nl02, Delta-T

167 Devices Ltd, Cambridge, UK), soil temperature and soil moisture (ThetaProbe, Delta-T Devices Ltd,

168 Cambridge, UK), global and net radiation (CNR4, Kipp & Zonen, Delft, The Netherlands), rainfall

169 (tipping bucket rain gauge, 52203, R.M. Young Company, Michigan, USA), and atmospheric pressure

170 (144S BARO, SensorTechnics, Puchheim, Germany).

171 ## 2.4 General description of the methodology

172 A methodology was developed to assess if cow respiration is included in a representative way in

173 annual NEE$_{tot}$ estimates and, if needed, to make the necessary corrections. The main steps of this

174 methodology are:

175   -   First (homogeneous approach), average cattle respiration rates per LU were computed postulating a homogeneous cow repartition over the whole pasture on an annual timescale. For this, CH_4 fluxes were used as a tool to detect the presence of cattle in the footprint and filter NEE_{tot} to compute the net ecosystem exchange of the pasture without cow respiration (NEE_{past}) for extensive data sets. Both NEE_{tot} and NEE_{past} data sets were gap filled and total annual R_{cows} values were then computed by subtraction of these two estimates. The average annual cattle respiration rates per LU (E_{cow}) was then deduced by dividing R_{cows} by the average stocking density on the pasture (SD_p).

183   -   Secondly, as a tool of comparison, three reference cow respiration rates per LU were computed. The first (GPS approach) consists in localizing the animals with GPS trackers during several measurement campaigns in order to compute the stocking density in the footprint (SD_f) as proposed by Felber et al. (2016b, 2015). The second (confinements approach) consists in constraining the movement of the animals on the pasture by confining them to a small part of the field in the main wind direction and for a short period in order to compare fluxes during this period with fluxes during animal-free periods, just before and after the confinement (Gourlez de la Motte et al., 2018; Jérôme et al., 2014). The third method (animal C budget approach) consists in building a complete carbon budget at the animal scale by estimating the ingested biomass and measuring its carbon content and digestibility (Gourlez de la Motte et al., 2018, 2016).

194   -   Finally, the respiration rates obtained considering a homogenous stocking density on the field at the annual scale were compared to reference respiration rates in order to verify if animal respiration was measured in a representative way. A significantly lower value would indicate a lower than average cow presence in the footprint, while a higher value would indicate the opposite. A procedure is also proposed to correct the fluxes in case cow respiration would not be measured in a representative way.

200   **2.5   Stocking density in the footprint and on the pasture**

201　Both the homogeneous and the GPS approaches rely on stocking density estimates. The homogeneous

202　approach (average stocking density, SD_p) rely on the average number of LU on the whole field (n_{avg}),

203　which was carefully monitored by the farmer during the whole grazing season, and corrected (factor φ)

204　to take into account the average pasture contribution to the footprint:

205　$$SD_p = \frac{n_{avg} \times \varphi}{A} \qquad (3),$$

206　where A is the total pasture area. The average pasture contribution to the footprint φ was computed for

207　every half hour, using an analytical footprint model (Kormann and Meixner, 2001) designated

208　hereafter as the KM model. This correction was necessary as, very often, the footprint area was bigger

209　than the pasture. It supposes there are no cattle in the footprint area outside of the experimental area,

210　which is the case in the main wind direction (SW) where the pasture is bordered by a crop field. In the

211　other directions, the pasture is surrounded by other pastures where some cows may be present from

212　time to time. As a result, around 80% of the cumulated footprint is coming from the pasture and from

213　the crop. The remaining contribution is coming from pastures that may, sporadically, be polluted by

214　other cows. To take this into account, an uncertainty of 10% was accounted for SD_p.

215　The second estimate (geolocation-based stocking density, SD_f) is based on geolocation tracking. The

216　individual contribution of each animal was estimated half-hourly using the KM model and was

217　summed as (Felber et al., 2016b):

218　$$SD_f = \sum_i \sum_j n_{ij} \phi_{ij} \frac{n_{avg}}{n_{detected}} \qquad (4),$$

219　where i and j represent the position of each cell on a 2D grid, n_{ij} is the number of animals in the cell ij,

220　ϕ_{ij} is the value of the footprint function in the cell ij (m^{-2}) and $n_{detected}$ the number of LU detected for a

221　specific half hour. For each half hour, the position of some animals was unknown (calves were not

222　tracked and not all geolocation devices were always operational), the calculated SD_f was thus

223　corrected in order to also include undetected or unaccounted animals. The resulting average correction

224　factor ($\frac{n_{avg}}{n_{detected}}$) was of 1.47.

225   Both SD_p and SD_f depend on the model used to compute the footprint function and its associated

226   uncertainties. The footprint model used in this study was thus carefully selected through an artificial

227   source experiment run by (Dumortier et al., 2019) at the same site.

228   2.6   Homogeneous approach for E_{cow}

229   In the homogeneous approach (Figure 2), annual R_{cows} were computed using equation 1. For the

230   determination of NEE_{past}, CH_4 fluxes were used as a cow detection tool, considering that CH_4 fluxes

231   emitted by the cattle were much higher than those exchanged by the soil and the vegetation (Dumortier

232   et al., 2017). The advantage of this CH_4 flux filtering approach is that it can be used throughout the

233   year, even outside GPS tracking campaigns. Annual CO_2 flux data series were filtered in order to only

234   keep data when net ecosystem exchange was unaffected by cow respiration (NEE_{past}).

235   The CH_4 flux threshold used for filtering was calibrated during the GPS tracker campaigns: cows were

236   considered to be absent when SD_f was lower than 2×10^{-5} LU m^{-2}. The CH_4 flux threshold was then

237   fixed in order to keep a maximum of events without cows and a minimum of events with cows. The

238   best compromise (>85% of events without; <10% of events with cows) was obtained for a value of

239   25 nmol CH_4 m^{-2} s^{-1}.

240   Missing NEE data were filled for both NEE_{past} and total NEE_{tot} data sets using the online REddyProc

241   gap   filling   and   flux   partitioning   tool   (https://www.bgc-

242   jena.mpg.de/bgi/index.php/Services/REddyProcWeb, (Reichstein et al., 2005)). This algorithm uses

243   time-moving look up tables and finds fluxes measured in similar meteorological conditions to fill the

244   data. Meteorological variables used by the algorithm are the air temperature (T_{air}), the vapor pressure

245   deficit (VPD), and the global radiation (R_g). R_{cows} was then obtained by subtracting filled NEE_{tot} and

246   NEE_{past} data series, and average monthly/annual respiration rates per LU ($E_{cow,hom}$) were obtained by

247   dividing this result by monthly/annual average SD_p.

248   The uncertainties on $E_{cow,hom}$, besides those affecting SD_p, are due to uncertainties affecting R_{cows}

249   estimation, which itself depends on NEE_{tot} and NEE_{past} estimates during grazing periods. To be

250 complete, the uncertainties on NEE_{tot} and NEE_{past} were computed for the whole year but were

251 combined only during grazing periods to estimate uncertainties on R_{cows}.

252 Annual NEE estimates are typically affected by different sources of random and systematic errors:

253 1) Random errors affecting both the measured fluxes and the gap filling procedure (Dragoni et

254 al., 2007; Richardson et al., 2006).

255 2) Error associated with the additional gaps in NEE_{past} due to cow presence.

256 3) A residual uncertainty associated with the choice of the u* threshold used to filter fluxes under

257 low turbulence conditions (Aubinet et al., 2018).

258 4) A residual uncertainty associated with the choice of the cut-off frequency for the high

259 frequency loss corrections (Gourlez de la Motte et al., 2016; Mamadou et al., 2016).

260 Each sources of error were computed separately:

261 (1) The random error on half-hourly fluxes was computed using the successive days approach

262 developed by Hollinger and Richardson, (2007). In this approach, half hourly errors on measured

263 fluxes (ε_m) were computed as the absolute difference between two valid successive day fluxes with

264 similar weather. A regression between bin-averaged NEE (same number of observations per bin) and

265 the standard deviation of the error ($\sigma(\varepsilon_m)$) was established separately for positive and negative flux

266 values for NEE_{tot} (Felber et al., 2016b; Gourlez de la Motte et al., 2016) :

$$267 \quad \begin{cases} \sigma(\varepsilon_m) = -0.11 \times NEE + 1.47 & \text{for } NEE \leq 0 \quad (R^2 = 0.90) \\ \sigma(\varepsilon_m) = 0.30 \times NEE + 0.08 & \text{for } NEE > 0 \quad (R^2 = 0.97) \end{cases} \tag{5},$$

268 and for NEE_{past} :

$$269 \quad \begin{cases} \sigma(\varepsilon_m) = -0.1 \times NEE + 1.02 & \text{for } NEE \leq 0 \quad (R^2 = 0.84) \\ \sigma(\varepsilon_m) = 0.21 \times NEE + 0.22 & \text{for } NEE > 0 \quad (R^2 = 0.94) \end{cases} \tag{6}$$

270 For both data sets, random noise was then added to half-hourly NEE assuming an exponential

271 distribution (Richardson and Hollinger, 2007) with zero mean and a standard deviation $\sigma(\varepsilon_m)$ (Monte

272 Carlo simulation (Dragoni et al., 2007)). Data were then filled and annual NEE values were computed.

273   The operation was repeated 100 times and the random error was computed as 2σ (standard deviation)

274   of the 100 annual NEE values.

275   (2) The error due to additional gaps in NEE_{past} was estimated using the following procedure. First,

276   missing data in the NEE_{past} data set were filled. Then, gaps initially present in NEE_{past} except those due

277   to cow presence were re-added. Noise was also added to the gap filled data using equation 6. By

278   doing so, we obtain a data set without cow respiration influence but with the same number of gaps as

279   the NEE_{tot} data set. Then, a number of gaps corresponding to the amount of additional gaps due to cow

280   presence in the footprint were randomly added to the data set only during grazing periods. The

281   operation was repeated 100 times and the annual NEE_{past} were computed. The error was computed as

282   2σ of the 100 annual NEE values.

283   (3) The uncertainty associated with the choice of the u* threshold was estimated by computing annual

284   NEE values by varying the u* threshold within a plausible range of 0.13 ± 0.5 m s^{-1} (Gourlez de la

285   Motte et al., 2016). The error was computed as 2σ of the computed values.

286   (4) The uncertainty associated with the choice of the cut-off frequency amounted to only 2 g C m^{-2} yr^{-1}

287   on average at our site and was therefore neglected (Gourlez de la Motte et al., 2016).

288   The different sources of uncertainties were combined following Gaussian propagation rules to estimate

289   annual uncertainties on NEE_{tot} and NEE_{past}.

290   Finally the uncertainty on R_{cows} was computed. As R_{cows} is computed as the difference between NEE_{tot}

291   and NEE_{past} which are computed from the same data sets (with additional gaps for NEE_{past}), the last

292   two sources of errors nullify. The error on R_{cows} is therefore the combination of (1) the random error

293   affecting both NEE_{tot} and NEE_{past} during grazing events only and (2) the error due the presence of

294   additional gaps in NEE_{past} (also only during grazing events). The resulting uncertainty on R_{cows} was

295   computed by combining these terms following Gaussian error propagation rules. The magnitude of

296   each error term during grazing periods is computed for both years in Table 1. The uncertainty on $E_{cow,}$

297    $_{hom}$ was computed by adding the relative errors on R_{cows} with the relative error of 10% on SD_p.

2.7 Heterogeneous approaches for Ecow

2.7.1 GPS approach

Four cattle geolocalization campaigns were organized (Table 2). During each campaign adult cattle positions and behavior were recorded using lab-made geopositioning trackers attached to the cows' necks. The trackers included a GPS module (FASTRAX, UP501), 4 batteries (3.8 V, 2000 mAH) and a communication antenna which allowed distant detection of malfunctions. In order to reach one month of autonomy, the devices only turned on once every 5 minutes, waited for the acquisition of at least 3 satellite signals (which typically took about 30 s), and recorded the position before turning off. Although the devices' autonomy was approximately one month, some batteries had to be replaced during the measurements, leading to some data loss. The GPS module precision was assessed by leaving the device motionless at a known position for 41 days. During this test, 50% of the points were found within 3 m, 76% within 5 m, and 95% within 11 m.

The GPS approach uses a partly similar procedure to the homogeneous approach, differing only by three steps. First, the criterion used to filter the data with the presence of cows and compute NEE_{past} is based on SD_f instead of the CH_4 flux. The filtering used a threshold of $SD_f > 2 \times 10^{-5}$ LU ha^{-1}. Secondly, only the NEE_{past} data set was gap filled. As result, a valid R_{cows} value is computed to be the difference between a valid NEE_{tot} measurement and a filled NEE_{past}. Finally, the cattle respiration rate per LU ($E_{cow,GPS}$) was deduced as the slope of the linear regression between R_{cows} and SD_f (Felber et al., 2016b). Only the best gap filling quality NEE_{past} values were kept for the regression (time window used by the gap filling routine lower than 15 days and all meteorological variables available (Reichstein et al., 2005)).

The uncertainty on $E_{cow,GPS}$ was computed as 2 times the standard error associated to the slope of the regression. This random error on the slope of the regression is the result of errors affecting booth R_{cows} (section 2.6) and SD_f estimates. The random uncertainty associated with the computation of SD_f include three main sources of uncertainties which are the random error on GPS measurements, the fact that the position of some cows (calves and instrument failures) was unknown for certain periods as

324 well as the use of the KM footprint function to weight the animals' contribution. It however does not

325 include uncertainties associated with the choice of the footprint model as stated at section 2.5.

2.7.2 Confinements approach

327 Confinement experiments specifically designed to estimate the cattle respiration rate per LU were

328 carried out at DTO. The methodology and the results are fully described and discussed in a previous

329 paper (Jérôme et al., 2014). Briefly, the method consists of confining the entire herd for one day on a

330 small part of the pasture located in the main wind direction. By confining the cows in the main wind

331 direction area (Figure 1) and by filtering the fluxes according to wind direction, the probability that the

332 cows are in the footprint area is greatly increased. The designated paddock was not grazed the day

333 before or the day after the confinement. Fluxes measured during the confinement periods were then

334 compared to the fluxes measured one day before and after:

335 $$R_{cows,conf} = \frac{\sum (NEE_i - NEE_{,i\pm24h})}{n_{obs}} \tag{7}$$

336 Where $R_{cows,conf}$ is the average respiration of all the cows in the confinement area, NEE_i is the NEE at a

337 given hour during the confinement, $NEE_{i\pm24h}$ is the NEE at the same hour 24 h before and after the

338 confinement, and n_{obs} the number of valid paired NEE observations. To make sure that these

339 differences were due to cow respiration and not to micrometeorological variability, only data pairs

340 with similar conditions were kept (soil and air temperature within 3°C, wind speed 3 m s^{-1} and photon

341 photosynthetic flux density (PPFD) within 75 µmol m^{-2} s^{-1}). The experiment was repeated four times.

342 The average livestock respiration rate ($E_{cow,conf}$) during the confinement was then obtained by

343 converting the average difference in terms of kg C LU^{-1} d^{-1} by dividing $R_{cows,conf}$ by SD_c (stocking

344 density during confinements), computed using Equation 3 considering φ as the average contribution of

345 the confinement area to the footprint, A the confinement area and n_{avg} the number of animals in this

346 area. By doing so, we consider a homogeneous repartition of the cows in the confinement area which

347 is more realistic as cattle are confined in a smaller area that is within the footprint extent, ensuring that

348 cows are contributing to the measured flux. In the present study, the results obtained from this former

349   study were used but note that this latter footprint correction was not implemented in Jérôme et al.

350   (2014) (i.e. φ was considered equal to 1).

351   The uncertainty on $E_{cow,conf}$ was computed as 2 times standard error of the average $E_{cow,conf}$. Note that,

352   again, this uncertainty estimate does not account for uncertainties associated with the choice of the

353   footprint model.

354   ### 2.7.3   Animal carbon budget approach

355   Another possibility to estimate the cow respiration rate per LU is to compute a complete carbon

356   budget at the animal scale when the animal is on the pasture (C fluxes at the barn are not included).

357   This carbon budget was computed from ingested biomass estimates, combined with their C content

358   and digestibility. The methodology and the results are fully described and discussed in a former paper

359   (Gourlez de la Motte et al., 2016). Figure 3 describes the C fluxes involved in the C budget of an

360   animal. Briefly, to build this C budget, the C ingested in dry matter (C_{intake}) was estimated using

361   biomass measurements combined with laboratory dry matter C content measurements.

362   To do so, herbage heights were measured almost once a week during the grazing season using a 0.25

363   m^2 rising plate herbometer over 60 points covering the whole field. Previously, an allometric equation

364   between the herbage height and the herbage mass (HM, dry matter) was calibrated in order to convert

365   herbage heights into HM (Gourlez de la Motte et al., 2016). For this, samples were directly harvested

366   in the field and protected enclosures with a 0.25 m^2 quadrat. Herbage heights were measured right

367   before and after being sampled. The samples were then dried using a forced-air oven to obtain their

368   dry matter content. A relationship between grass height differences and harvested dry matter content

369   was then established. Biomass C content was determined by laboratory measurements of samples

370   following the dumas method (Dumas, 1831). Three secured enclosures were used to obtain grass

371   growth rates during grazing periods ($HM_{gr,i}$). Cattle C intake through biomass consumption for a given

372   period i was computed as:

373    $$C_{intake,i} = C_{content,grass}(HM_{beg,i} - HM_{end,i} + HM_{gr,i}) + C_{content,feeds}F_{import,i} \qquad (8)$$

374   where $HM_{beg,i}$ and $HM_{end,i}$ are the herbage mass at the beginning and at the end of the period i

375 (weekly), $C_{content,grass}$ the C content of grass in the field, $C_{content,feeds}$ the C content of feeds supplements

376 and $F_{import,i}$ the dry matter ingested in form of feed supplements. This equation was used on a weekly

377 basis and the annual C_{intake} was computed by summing all the periods. Note that, when

378 $HM_{beg,i} > HM_{end,I}$, this biomass is accounted negatively and is therefore considered uneaten.

379 The C lost by the animal through excretions ($C_{excretions}$) was computed as the fraction of non-digestible

380 ingested carbon. Digestible and non-digestible organic matter contents were obtained by analyzing the

381 biomass samples collected almost every week in the field using near infrared reflectance spectrometry

382 analysis (Decruyenaere et al., 2009). Cow CH_4-C emissions were estimated using a constant fraction

383 of the ingested biomass, which was 6% (Lassey, 2007). The meat production term ($F_{product}$) was

384 estimated from live weight gain measurements but was negligible compared to other fluxes. Finally

385 the CO_2 cow respiration ($E_{cow,budg}$) was computed by closing the C budget of the animal. The results

386 obtained from this former study were directly used in the present paper.

387 In lack of a suitable method to evaluate the uncertainty associated with this method, no error bound

388 was computed for $E_{cow,budg}$. Note that the main factor influencing $E_{cow,budg}$ uncertainty should be the

389 uncertainty on dry biomass intake which is especially challenging to estimate in continuously grazed

390 pastures.

391 ## 2.8 Alternative NEE_{tot} determination

392 As direct NEE_{tot} estimates rely on the homogeneity hypothesis assuming an even distribution of the

393 grazing animals, significant biases may appear if this hypothesis is not met. An alternative annual

394 NEE_{tot} may then be provided by computing NEE_{past} (using CH_4 filter, see section 2.6) and R_{cows}

395 independently and by summing them using equation 1. R_{cows} can be obtained by combining the cow

396 respiration rate per LU obtained by one of the three methods detailed above (Section 2.7) with the

397 average stocking density (SD_p). The uncertainty on the up scaled R_{cows} was computed by adding the

398 relative errors on both the concerned E_{cow} and SD_p. The choice of the used respiration rate depends on

399 the available data and the site configuration and is fully discussed in Section 4.

3   Results

3.1   Animal positions on the pasture and footprint area

Cow positions were recorded every 5 minutes during the GPS campaigns. From these position measurements, cow distribution maps were computed for both daytime (global radiation >2.5 W m^{-2}) (Figure 4, a) and nighttime (Figure 4, b). Typical annual wind roses (year 2015) are presented for these conditions. The maps show that, during the day, cattle visited the whole pasture with a slightly more important presence in the south-west direction. They also tend to cluster near the water trough and near the border with an adjacent pasture in the north-west. During the night, the cows tend to cluster in the north-east part of the pasture near the hedge. Consequently, during the nights, an important part of the pasture (essentially the south-western part), which is under the main wind direction, is not visited at all. Therefore, this observation suggests that the night stocking density in the footprint (SD_f) should be quite low when the wind is blowing from the south-west, which would imply an underestimation of cow respiration during these periods. This statement was confirmed when comparing SD_f to SD_p during the GPS campaigns (Table 3). When the wind was coming from the south (campaigns n°2 to 4) SD_f observed during the nights were much lower than SD_p, while being much closer to SD_p when observed during the day. This behavior was much less visible during campaign n°1 when the wind was mainly blowing from the north-east.

In addition, in regard to the shape of the footprint function (Kormann and Meixner, 2001), the contribution of the animals to the footprint also depends on their distance from the tower. Given the clustering of the cattle, particularly at night, their contribution could be low if clustered far away from the flux tower. This was investigated by comparing the average SD_f to SD_p during the night when the wind was blowing from the north-east (campaign n°1). On average, during these periods, SD_f (6.9 LU ha^{-1}) was higher than SD_p (4.9 LU ha^{-1}). This observation show that, at our site, the low SD_f observed at night were due to low cow presence in the footprint and not that much to their distance from the tower.

425   On average, SD_f was 25% lower than SD_p during the campaigns. This result however cannot be

426   directly extrapolated to the entire year in terms of cow respiration, as the north-east wind conditions

427   were over represented in the data when compared to yearly wind direction statistics (data not shown).

428   Nevertheless, the cow distribution maps clearly show that the cows are not evenly distributed on the

429   pasture, especially during the night.

430   ### 3.2   Cow respiration rate per LU considering a homogeneous cow repartition

431   #### 3.2.1   Validation of the CH_4 flux filtering approach

432   In order to validate the CH_4 flux filtering approach, NEE_{past} was computed during GPS tracking

433   campaigns by using both the CH_4 and the cow presence (GPS) criterion. The results show that, after

434   gap filling, very similar NEE_{past} were obtained when using both partitioning methods for each

435   campaign (Table 4) with differences in NEE_{past} that varied only from 0 to 4 g C m^{-2}. Identical

436   differences between R_{cows} were observed, as they were computed as the difference between NEE_{tot}

437   (which was the same for both methods) and NEE_{past}.

438   #### 3.2.2   Discriminating NEE_{tot} into NEE_{past} and R_{cows}

439   The CH_4 flux filtering approach was then applied to two years of measurements. After filtering, the

440   NEE_{tot} data set consisted of 8579 (49%) and 8432 (48%) valid fluxes (Table 5) in 2013 and 2015

441   respectively, while the NEE_{past} data set consisted of 6911 (39%) and 6325 (36%) valid fluxes.

442   Cumulative NEE_{tot}, NEE_{past}, R_{cows} and stocking densities are shown in Figure 5 for 2013 and 2015. The

443   same trend can be observed for both years. At the beginning of the year, NEE_{tot} and NEE_{past} were

444   identical as there were no animals on the pasture. Then, the curves start to deviate from each other

445   because of the animal. At the end of the year, when no animals were on the pasture, the curves evolve

446   again in parallel. The total annual R_{cows} amounted to very similar values of 112 ± 20 and 111 ± 24

447   g C m^{-2} yr^{-1} in 2013 and 2015 respectively.

3.2.3 Cow respiration rate per LU ($E_{cow,hom}$)

Cow respiration rates could be computed monthly and annually from R_{cows} data sets assuming a homogeneous cow distribution on the pasture. The annual SD_p were very similar and amounted to 1.4 and 1.5 LU ha^{-1} in 2013 and 2015 respectively. As a result, the average annual $E_{cow,hom}$ amounted to 2.0 ± 0.6 and 2.0 ± 0.6 kg C LU^{-1} d^{-1} for both years (Figure 6, a, Table 6) with relatively consistent values every month except in November. During this month, SD_p was very low making R_{cows} difficult to compute. To check if $E_{cow,hom}$ was the same during the day and during the night, $E_{cow,hom}$ was calculated separately from day (Figure 6, b) and from night fluxes (Figure 6, c). The $E_{cow,hom}$ value was much higher when calculated from daylight fluxes (2.4 and 2.6 kg C LU^{-1} d^{-1} in 2013 and 2015) than from night fluxes (1.4 and 1.0 kg C LU^{-1} d^{-1} in 2013 and 2015), confirming that the cow presence in the footprint is much higher during the day than during the night, as already suggested by the cow repartition maps.

3.3 Cow respiration rate per LU with considering heterogeneous cow repartition

3.3.1 GPS trackers ($E_{cow,GPS}$)

A linear regression between the stocking density in the footprint (SD_f) and the total cow respiration R_{cows} was carried out on a half hourly basis in order to compute $E_{cow,GPS}$ (Figure 7). All GPS tracker campaigns were grouped together for a total of 803 data points available for the regression. The slope of the regression was 3160 ± 491 µmol CO_2 LU^{-1} s^{-1} (p value < 0.001, $R^2 = 0.1$) which corresponds to an average $E_{cow,GPS}$ of 3.2 ± 0.5 kg C LU^{-1} d^{-1}. The intercept of the regression was forced to zero as it was not significantly different from zero (p value $= 0.96$).

The linear regression is affected by important random noise. This uncertainty results in a relatively low R^2 and rather large error bounds on $E_{cow,GPS}$. Such a large dispersion was expected in view of the random error at the half hourly scale when computing R_{cows} as described at section 2.6 as well as in view of the uncertainties associated with the use GPS combined to the KM footprint function to compute SD_f (section 2.7.1).

3.3.2 Confinement experiments ($E_{cow,conf}$)

A total of 4 confinement experiments were carried out in 2012 as detailed in Jérôme et al. (2014). After applying all selection criteria, 44 pairs of NEE data were available for the analysis. The data from two of the experiments could not be used because of inappropriate wind direction. Before footprint correction, Jérôme et al. (2014) found a cow respiration rate of 2.59 ± 0.58 kg C LU^{-1} d^{-1}. On average the contribution of the confinement area to the footprint was 71% during the experiments. As a result, after the footprint correction, $E_{cow,conf}$ was found to be 3.6 ± 0.8 kg C LU^{-1} d^{-1}, which is within the error bounds of $E_{cow,GPS}$.

3.3.3 Animal scale carbon budget ($E_{cow,budg}$)

The daily carbon budget of an animal on the pasture was computed (Figure 8). The results correspond to the average C budget for 5 years (2010-2014) of grazing at DTO. All the results are detailed in Gourlez de la Motte et al. (2016) but with different units (g C m^{-2} yr^{-1}). On average, cows ingested 9.5 kg of dry matter per day (8.9 kg from grazing and 0.6 from feeds). Around 87% of total above ground net primary productivity was eaten by the cows. The measured forage and feeds digestibility amounted to around 70% which corresponded to a daily cow respiration rate $E_{cow,budg}$ of 2.9 kg C LU^{-1} d^{-1}. This value is in the error bounds of both $E_{cow,GPS}$ and $E_{cow,conf}$. However, it's important to note that this budget varied from one year to another. In 2013, the productivity of the pasture was the lowest, so that the estimated C_{intake} of the cattle amounted to only 2.9 kg C LU^{-1} d^{-1} (6.8 kg of dry matter) with a cow respiration rate of only 2.0 kg C LU^{-1} d^{-1}, which is much lower than the 5-year average value. According to the farmer, such a low dry matter intake is not realistic and would have resulted in supplementary feeds given to the cows (which was not the case in 2013). It is therefore very likely that this respiration rate is under-estimated. Contrastingly, the highest C_{intake} was observed in 2011 with value as high as 5.1 kg C LU^{-1} d^{-1} resulting in a respiration rate per LU as high as 3.5 kg C LU^{-1} d^{-1}. These unexpected variations highlight the difficulty to obtain robust C_{intake} estimates in continuously grazed pastures as discussed at section 4.3. For these reasons, only the 5-years averaged $E_{cow,budg}$ value was used as a tool of rough comparison.

3.4 **Bias induced by a non-homogeneous cow distribution**

As shown in Table 6, $E_{cow,hom}$ was significantly (non-overlapping uncertainty bounds) than the cow respiration rate per LU estimated using either the GPS (37% lower) or the confinement (45% lower). It was also much lower than the value estimated from the carbon budget method (31% lower). This was even more true during the night when $E_{cow,hom}$ was on average 65% lower than during the day. These results suggest a low presence of the cows in the footprint, especially during the night, as illustrated by the cow repartition maps (Figure 4). Despite the different methods were applied at different periods (GPS campaigns were carried out in 2014-2015, confinement experiments were carried out in 2012 and $E_{cow,hom}$ were measured in 2010-2014), which could have induced variations in cow respiration rates, we expect these variations to be limited as the herd characteristics and management remained the same during the whole experiment.

In order to assess the magnitude of the bias due to low cow presence in the footprint during the night, annual reference R_{cows} could be computed by scaling up the obtained reference E_{cow} value to the entire year. This can be done by using the E_{cow} values with one of the three methods previously proposed. For illustration purposes, $E_{cow,GPS}$ was used to quantify and correct the systematic error made at DTO. This method was chosen as it seemed to be the most suitable for free range pastures as discusses at section 4.3. Nevertheless, similar conclusions would have been met using other methods. When scaled up, $R_{cows,GPS}$ amounted to 164 ± 41 and 175 ± 44 g C m^{-2} in 2013 and 2015 respectively (Table 6), which suggests a systematic underestimation of R_{cows} and thus an overestimation of NEE_{tot} of 52 and 64 g C m^{-2} yr^{-1} (51% and 34% of NEE_{tot},) in 2013 and 2015. As a result, new NEE_{tot} (computed as $NEE_{past} + R_{cows,GPS}$) values were -50 ± 48 and -122 ± 55 g C m^{-2} yr^{-1} (the error bounds were computed by quadratically adding errors on annual NEE_{past} and $R_{cows,GPS}$).

4 Discussion

4.1 Using methane fluxes as a NEE$_{tot}$ partition tool

The CH$_4$ flux filtering approach has proven to be a useful tool to partition NEE$_{tot}$ and disentangle the net ecosystem exchange of the soil and the vegetation (NEE$_{past}$) from the respiration of the cows. The results at DTO showed that similar NEE$_{past}$ values were obtained using this method and the GPS tracker method.

Compared to the GPS method, the main advantage of the CH$_4$ flux filtering approach is that it can be more easily used routinely, whereas the use of GPS trackers requires specific instrumentation that is not commercially available, and is man-power consuming. The use of the CH$_4$ flux filtering approach was also supported by Felber et al., (2016b, Figure 13) who found a good correlation between measured CH$_4$ fluxes and cow respiration in the EC footprint. To do so, CH$_4$ fluxes must be available, but these are more and more frequently measured at grazed sites (Coates et al., 2018; Dengel et al., 2011; Dumortier et al., 2017; Felber et al., 2015; Jones et al., 2017) thanks to the increasing availability of fast and precise CH$_4$ sensors. This method can therefore be used on larger data sets as long as CH$_4$ fluxes are measured (which we advocate).

The method cannot be used to estimate consistent cow respiration rates per LU when the cows are not evenly distributed on the pasture, but is promising as a partitioning tool of NEE$_{tot}$ into NEE$_{past}$ and R$_{cows}$, which is the first step needed to check if R$_{cows}$ is measured in a representative way and to correct NEE$_{tot}$ estimates if this is not the case. The successful application of the partitioning method in the present study overrules the statement by Felber et al. (2016a) that the computation of NEE$_{past}$ would not be possible for continuously grazed pastures as no sufficient and defined periods without cows in the footprint would be available.

4.2 Biased NEE estimates because of a non-homogeneous cow repartition

The application of the methodology at the DTO site showed that NEE$_{tot}$ estimates based on direct EC measurements were subject to a non-negligible bias of about $60 \, \mathrm{g\,C\,m^{-2}\,yr^{-1}}$ because of non-homogeneous cow repartition resulting in an underestimation of R$_{cows}$. This underestimation implies

548   that the carbon sink activity of the pasture was considerably overestimated when using NEE_{tot} values

549   to compute its net biome productivity. The NBP (including cow respiration, equation 2) of the pasture

550   was computed for 5 years (2010-2014) in a previously published paper using NEE_{tot} estimates and

551   other non CO_2 carbon fluxes (Gourlez de la Motte et al., 2016). Those results showed that the pasture

552   acted as a C sink every year with an average NBP value of -161 g C m^{-2} yr^{-1} (lowest absolute in 2013:

553   -87 g C m^{-2}, highest absolute value in 2014: -176 g C m^{-2}) and an average annual stocking rate of

554   2.3 LU ha^{-1}. If we assume that the NBP was affected by the same bias of ≈ 60 g C m^{-2} yr^{-1} (around

555   37% of NBP) every year because of cow respiration underestimation, the corrected average NBP is

556   reduced (in absolute values) to ≈ -100 g C m^{-2} yr^{-1}. The magnitude and sign of this bias is of course

557   site specific so that, depending on the site configuration, the wind direction, and the gregarious

558   behavior of the animals, it can lead to either positive or negative systematic errors. This must therefore

559   be verified on a case by case basis. It is important to highlight the fact that gregarious behaviors of the

560   animals on free range pastures are expected, at least for cows (Hassoun, 2002) and sheeps (Dumont

561   and Boissy, 2000). The methodology presented in this paper may be used at each site to detect and, if

562   necessary, estimate this bias and correct C budgets accordingly.

563   4.3   **Method to measure a reference cow respiration rate per LU**

564   In this paper, three methods were proposed and tested at DTO to estimate a reference E_{cow} that does

565   not assume a homogeneous cow repartition in the pasture and that can be used as a basis of

566   comparison to check if R_{cows} is measured in a representative way. This respiration rate per LU can also

567   be used to correct R_{cows} if necessary.

568   The GPS tracker method appeared to be very useful as it provided an improved understanding of

569   animal location habits. The distribution maps have proven to be a useful tool to detect heterogeneous

570   cattle distributions. The use of GPS devices combined with footprint models also provides a more

571   realistic stocking density in the footprint (Felber et al., 2016b, 2015). This footprint function is

572   however also the subject of several uncertainties (Dumortier et al., 2019). Finally, the GPS tracking

573   method has the advantage of not disturbing the behavior of the cows when compared, for example, to

574   confinement experiments.

The confinement method gave consistent results when compared to the other methods. This method is less time consuming than the use of GPS trackers and doesn't require any specific equipment. This is true especially in intensive rotationally grazed pastures where confinement is expected (Gourlez de la Motte et al., 2018). Confinement in rotational grazing systems can be exploited to compute $E_{cow,conf}$ as shown by Gourlez de la Motte et al. (2018). If the rotations are longer than one day, an adapted procedure is proposed in the cited paper. However, confinement also has several drawbacks. First, very similar weather conditions and wind direction during and after the confinement must be met in order to compare the fluxes from the same area. Secondly, the respiration may also be modified (especially for free range pastures) as confinements may alter the cow's feeding behavior and activity. In addition, confinement experiments are based on the hypothesis of a homogeneous cow repartition. This is more realistic as confinement is exerted in a smaller area that is within the footprint extent, ensuring that cows are contributing to the measured flux. However, it cannot be determined to what extent. This source of uncertainty should however be lowered when replicating confinement experiments and when using daily fluxes as cows tend to spread more evenly during the day. Finally, as stated above, cow contribution cannot be weighted by using a footprint model which may lead to other biases.

The animal carbon budget approach requires an estimation of the C_{intake} of the cows which requires reliable biomass growth measurements as well as forage digestibility measurements for the whole grazing season. These types of measurement are time consuming but are often carried out at grazed EC sites (Gourlez de la Motte et al., 2016; Klumpp et al., 2011; Rutledge et al., 2017b; Skinner, 2008; Skinner and Dell, 2015). Estimating the C_{intake} of cows is especially difficult in continuously grazed sites where grass growth during grazing must be estimated. This was done at the DTO by simulating grazing using protected enclosures. However, it is not easy to ensure that grass growth observed in these protected enclosures is representative of the whole pasture. In short rotation grazing sites, the regrowth can be considered negligible, making the computation of C_{intake} easier and more reliable (Skinner, 2008). Another option to compute C_{intake} is to estimate the energy requirements of the animals for maintenance, activity, and grazing and convert this energy into dry matter intake (and then

602   C_{intake}) (IPCC, 2006) or, for dairy cows, using equations based on milk yields and the lactation week of

603   the cows, as proposed by Felber et al. (2016a).

5   Conclusions and recommendations

The results of this study highlight the necessity to carefully check if cow respiration is measured in a representative way by the EC system when dealing with grazed pastures. To do so, monitoring the presence and number of cows on the field is highly advised (Figure 5, c). For beef cattle, monitoring the presence of the cattle on the field is easier as off pasture times are greatly reduced. For dairy cattle, the task is a bit more difficult as the cows often leave the pasture for milking. These milking periods must therefore be accounted for as well. Measuring the CH_4 fluxes is also highly advisable as it allows the computation of NEE_{past} which is the first step of the proposed methodology and can be used for any kind of pasture (i.e., continuous grazing, rotational grazing, etc.) grazed by ruminants. Finally, estimating a reliable cow respiration rate as a reference is also required. For this last step, three methods are proposed and the choice of the method can differ depending on the available data and the configuration of the site. As a general rule, combining two or three methods is always better as their comparison gives the most defensible results.

For a continuously grazed site, the GPS campaigns are very useful as they allow the habits of the herd to be assessed without disturbing their behavior. However, organizing these campaigns can be time consuming and requires expensive equipment. As an alternative, the use of digital camera combined with an animal detection software have also proven to be a valuable tool to detect the presence of cows in the EC footprint (Baldocchi et al., 2012). If GPS (or any other localization devices) monitoring is not available, repeated confinement experiments are cheap, relatively easy to implement, and also provide consistent results. Combining these confinement experiments with animal C budget estimates is advised in order to check the consistency of the results. Using only the animal C budget is less advisable as C_{intake} estimates may be uncertain for continuously grazed pastures.

For rotationally grazed sites composed of several paddocks, GPS trackers may be avoided. In these sites, the cows are constrained to a relatively small paddock so that their location is known. Combining a footprint model (or simply wind direction) with a precise grazing schedule allows correct assessment of the presence of cows in the footprint in order to compute NEE_{past}, as shown by Felber et al. (2016b). If available, CH_4 fluxes can still be used as a partitioning tool. For these sites, the

confinement method should be preferred as cattle are already expected to be confined (Gourlez de la Motte et al., 2018). Again, it's advisable to combine the confinement experiments with an animal carbon budget in order to constrain the $E_{cow,conf}$ value to obtain more defensible estimates. For rotationally grazed sites, another solution would consist in computing NEE_{past} and excluding the grazers from the ecosystem. When computing NBP, the grazers are therefore considered to be an agent of C export (by grazing) and import (by excretions) (Felber et al., 2016a; Rutledge et al., 2017a, 2017b; Skinner, 2008). This solution requires reliable biomass measurements and/or animal performance data in order to compute C_{intake} and $C_{excretions}$. For this reason, using this solution for continuously grazed sites is less advisable. Note that, if the estimation of E_{cow} and $C_{excretions}$ are estimated from the animal C budget, both methods are equivalent and give the same results.

Finally, the results of this study highlighted how grazers can significantly affect NEE values reported in grazed grassland studies. Therefore, a consistent approach to report CO_2 fluxes derived from eddy covariance in grazed ecosystems is needed in order to allow better NEE inter-site comparisons. In this line of thought, we advocate that, when possible, NEE_{past} and grazers respiration should be computed separately in both continuously and rotationally grazed systems. By excluding grazer's respiration, the reported NEE_{past}, which correspond to the NEE of the vegetation and soil only, would be more comparable to the values reported by other grazed grassland studies as well as those reported by mown meadows. This would also help modelers as it would allow the computation of both fluxes separately (Kirschbaum et al., 2015). In this sense, continuously measuring CH_4 fluxes in grazed ecosystems has proven to be very useful to obtain consistent NEE_{past} values.

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8 Tables

Table 1: Sources of uncertainties for annual R_{cows} values. Values are provided in g C m^{-2} yr^{-1} but are accounted only during grazing period. Random error (2σ) on NEE_{past} and NEE_{tot} were computed by adding some random noise in the data during grazing periods only. The error due to the additional gaps in NEE_{past} was computed by randomly adding gaps in NEE_{past} data set. The uncertainty or R_{cows} (2σ) was computed by combining the different error terms following Gaussian error propagation.

	Random NEE_{past}	Random NEE_{tot}	Gap filling NEE_{past}	R_{cows}
2013	14	12	8	20
2015	17	15	9	24

Table 2: Description of the GPS campaigns.

Period	Time frame	Duration (days)	Number of cows/calves	Main wind direction
n°1 Spring 2014	27 May 2014 - 25 Jun 2014	30	17-19/17-19	N-E
n°2 Spring 2015	14 Apr 2015 - 7 May 2015	24	12/0	S-W
n°3 Summer 2015	14 Aug 2015 - 2 Sep 2015	20	12/10	S-W
n°4 Fall 2015	19 Oct 2015 - 2 Nov 2015	15	8/0	S-E

Table 3: Comparison of the average stocking densities on the pasture (SD_p) with the average stocking density in the footprint (SD_f) for the GPS measurement campaigns. The averages calculated are for all data from all campaigns combined.

Campaign n°	Main wind direction	SD_p (LU ha^{-1})	Day SD_f (LU ha^{-1})	Night SD_f (LU ha^{-1})	SD_f (LU ha^{-1})	SD_f/SD_p
1	N-E	4.9	2.7	3.9	3.1	0.64
2	S-W	1.9	1.2	1.1	1.1	0.59
3	S-W	2.7	3.2	1.0	2.3	0.85
4	S-E	1.3	1.4	0.5	0.9	0.70
Average	–	**2.7**	**2.2**	**1.7**	**2.0**	**0.75**

845　　Table 4: Gap filled net ecosystem exchange of the pasture without cow influence (NEE$_{past}$) using the

846　　CH4 cow presence filtering criterion and the GPS criterion for each GPS campaign.

Campaign n°	CH$_4$ filter NEE$_{past}$ (g C m^{-2})	GPS filter NEE$_{past}$ (g C m^{-2})
1	−68	−68
2	−98	−98
3	23	22
4	17	13

847　　Table 5: Number of valid net ecosystem exchange measurements, including the cow respiration rate

848　　(NEE$_{tot}$) and excluding it (NEE$_{past}$), annual gap filled sums of both net ecosystem exchange and the

849　　total gap filled annual respiration R$_{cows}$ for both 2013 and 2015. Note that error bar on R$_{cows}$ are not the

850　　combination of the error bars on annual NEE$_{tot}$ and NEE$_{past}$ (see section 2.6).

Year	valid NEE$_{tot}$	valid NEE$_{past}$	NEE$_{tot}$ (g C m^{-2})	NEE$_{past}$ (g C m^{-2})	R$_{cows}$ (g C m^{-2})
2013	8579	6911	−102 ± 22	−214 ± 24	112±20
2015	8432	6325	−188 ± 31	−299 ± 32	111±24

851

852

853 Table 6: Average footprint contribution of the pasture and stocking density on the pasture (SD_p), daily

854 average cow respiration rates per livestock unit (LU) computed from a) annual gap filled data sets

855 assuming a homogeneous cow repartition on the field from day (global radiation > 2.5 W m^{-2},

856 $E_{cow,hom,day}$), night ($E_{cow,hom,night}$), and all the data ($E_{cow,hom}$) and b) without assuming this cow repartition

857 and using GPS trackers ($E_{cow,GPS}$), confinement experiments ($E_{cow,conf}$), and the carbon budget of the

858 animal ($E_{cow, budg}$). Field scale cow respiration rates are also given when computed from the CH$_4$

859 partitioning (R_{cows}) and when upscaled using $E_{cow,GPS}$ ($R_{cows,GPS}$). The footprint is expressed as the

860 percentage of the flux that comes from the field on average for each year according to the KM model.

	2013	2015
Footprint %	68%	69%
SD_p (LU ha^{-1})	1.4	1.5
Animal scale fluxes (kg C LU^{-1} d^{-1})		
a) Homogeneous cow repartition hypothesis		
$E_{cow,hom}$	2.0 ± 0.6	2.0 ± 0.6
$E_{cow,hom,day}$	2.4	2.6
$E_{cow,hom,night}$	1.4	1.0
b) No homogeneous cow repartition hypothesis		
$E_{cow,GPS}$	3.2 ± 0.5	
$E_{cow,conf}$	3.6 ± 0.6	
$E_{cow,budg}$	2.9	
Field scale fluxes (g C m^{-2} yr^{-1})		
$R_{cows,hom}$	112 ± 20	111 ± 28
$R_{cows,GPS}$	164 ± 41	175 ± 44
Bias (absolute value)	52	64

861

862   **9   Figures**

863   Figure 1: Schematic map of the site. During confinements, internal fences were closed and the cattle

864   were confined in the south-west part of the pasture. Figure taken from Dumortier et al., 2017.

865   Figure 2: Flow chart of the procedure used to estimate cow respiration rates per livestock unit (E_{cow})

866   using either GPS campaigns or assuming a homogeneous cow repartition in the field (CH_4 approach).

867   Both procedures are similar, differing in their way of assessing the presence of cows in the footprint

868   (FP) and of assessing the stocking density (stocking density in the pasture (SD_P) for the CH_4 filtering

869   approach, or stocking density in the footprint (SD_f) for the GPS method). Gaps in total net ecosystem

870   exchange (NEEtot) were filled only for the CH_4 approach. Gaps in pasture net ecosystem exchange

871   (NEE_{past}) were filled for both approaches. Figure modified after Felber et al., (2016b).

872   Figure 3: Illustration of the fluxes involved in the carbon (C) budget of a cow. $E_{cow,budg}$ corresponds to

873   the respiration of a cow estimated from the carbon budget, FCH_4-C the methane emitted by the cow,

874    $C_{excretions}$ the C lost in excretions, and C_{intake} the C ingested through biomass consumption.

875   Figure 4: Cow distribution maps during the GPS campaigns for both days (a) and nights (b). The same

876   scale is used for both maps. The numeric scale of the color map is given for a comparison purpose.

877   One unit corresponds to the presence of one animal in a pixel of $5 \times 5m^{-2}$ during 5 minutes. Areas

878   colored in white are areas that are never visited by the herd. The average wind rose for the year 2015 is

879   also presented both during the day (c) and during the night (d). For interpretation of the colors in this

880   figure, the reader is referred to the electronic version of this article.

881   Figure 5: Evolution of the gap filled total cow respiration (R_{cows}), the net ecosystem exchange

882   including cow respiration (NEE_{tot}) and the net ecosystem exchange excluding cow respiration NEE_{past}

883   for both 2013 (a) and 2015 (b). Grazing periods are indicated in grey. (c) Evolution of stocking

884   densities on the field for both years.

885   Figure 6: Mean cow respiration rates per LU in 2013 and 2015 computed from (a) all the data

886   ($E_{cow,hom}$), (b) daylight data ($E_{cow,hom,day}$, global radiation >2.5 W m^{-2}), and (c) night data ($E_{cow,hom,night}$)

887   considering a homogeneous cow repartition. Average monthly/annual respiration rates per LU were

888   obtained by dividing total annual/monthly cow respiration (R_{cows}) by monthly/annual average SD_p.

889   Annual values are marked by lines while circle markers correspond to the monthly values.

890   Figure 7: Linear regression between the total respiration of the cows in the footprint (R_{cows}) on a half-

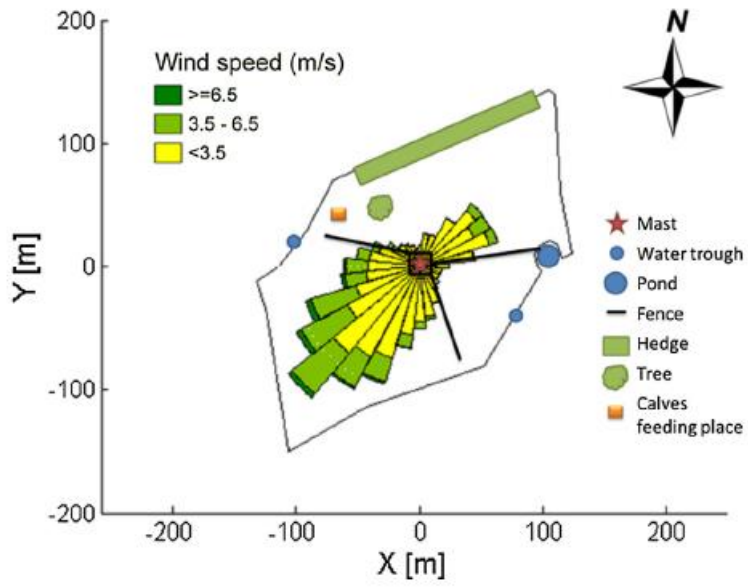891   hourly time scale and the weighted stocking density in the footprint (SD_f). The fitted line (y = 3160x

892   SE = 245, R^2 = 0.1) corresponds to a daily cow respiration rate of 3.2 ± 0.5 kg C LU^{-1} d^{-1}. The

893   uncertainty bound is given as 2SE.

894   Figure 8: Average daily carbon budget of a Belgian Blue beef cow.

895

896
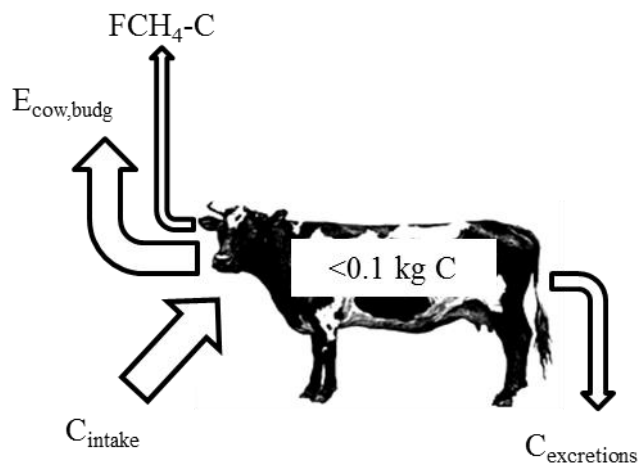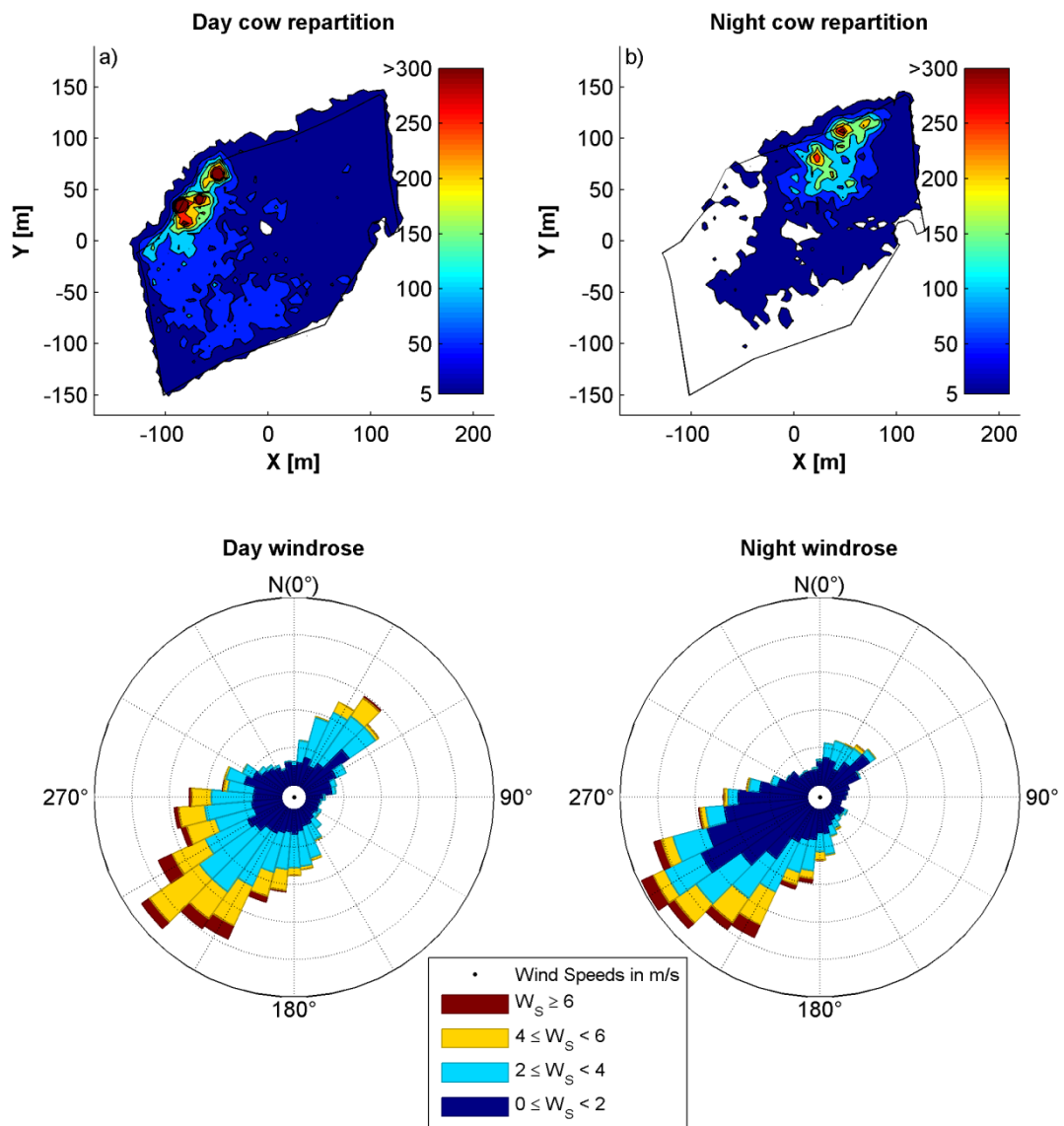
897 **Figure 1**

898

899

900   **Figure 2**

FCH$_4$-C

E$_{cow,budg}$

<0.1 kg C

C$_{intake}$

C$_{excretions}$

901

902   **Figure 3**

Day cow repartition

Night cow repartition

Day windrose

Night windrose

Wind Speeds in m/s
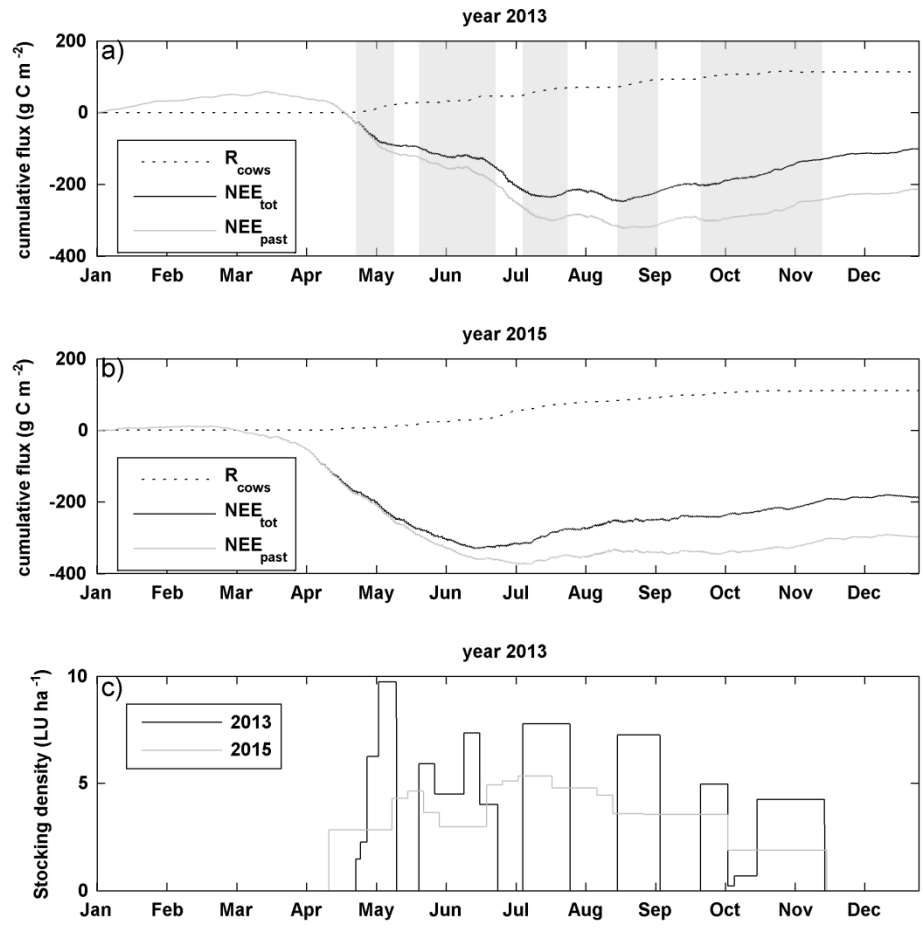
$W_S \geq 6$

$4 \leq W_S < 6$

$2 \leq W_S < 4$
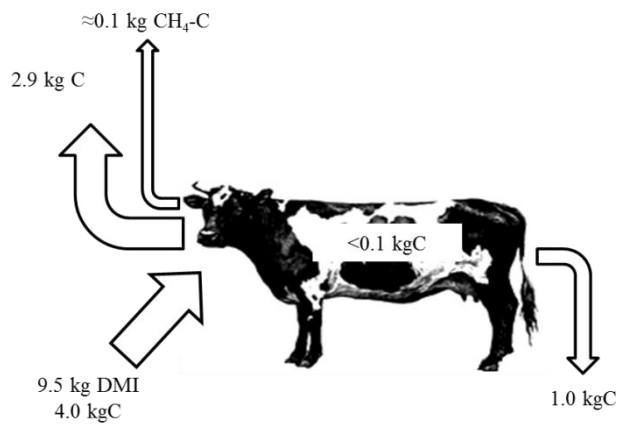
$0 \leq W_S < 2$
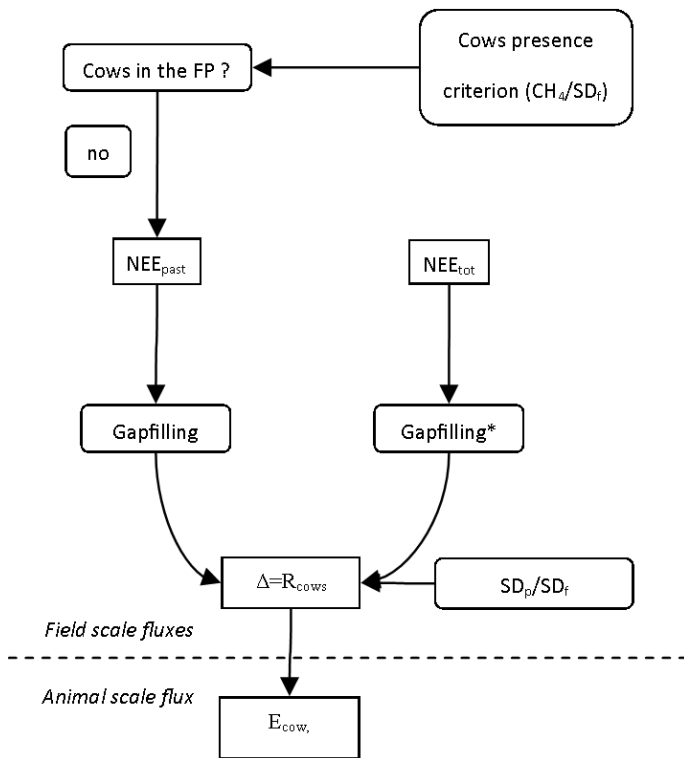
903

904 **Figure 4**

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906

907 **Figure 5**
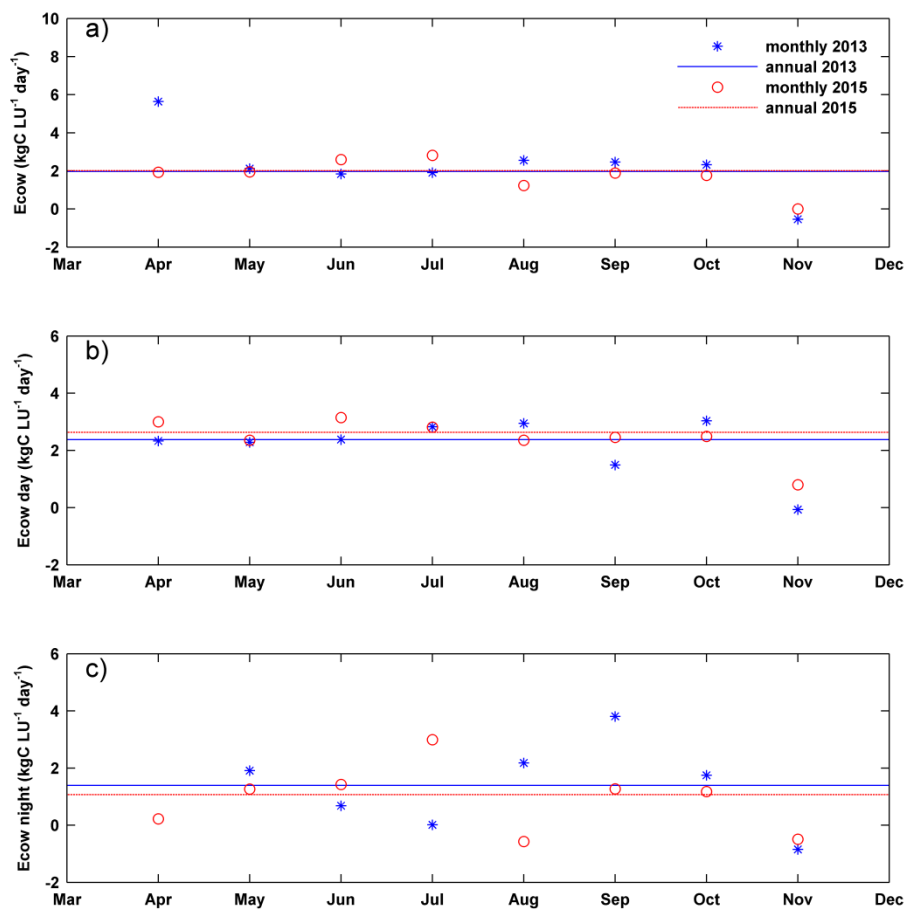
908 _____

909 **Figure 6**

910

911

912 **Figure 7**

≈0.1 kg CH₄-C

2.9 kg C

<0.1 kgC

9.5 kg DMI
4.0 kgC

1.0 kgC

913

914 **Figure 8**

915