CAN EDDY-COVARIANCE BE USED ON A PASTURE?

ESTIMATION OF CATTLE AND SOIL - PLANT METHANE EMISSIONS AND TRANSFER TO OTHER GREENHOUSE GASES

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Abstract

Much debate has arisen as to the contribution of natural and anthropized ecosystems to the global production of greenhouse gases (GHG), ways to limit this contribution or how to use ecosystems as carbon sinks. To provide solid ground for this debate, reliable data is required. Eddy-covariance (EC) is commonly used to measure gaseous exchanges from homogeneous ecosystems (crops, forests…). However, in its standard form, it may be biased when working with heterogeneous ecosystems, especially grazed pastures where cattle is an important, but also moving and intermittent GHG source. In this thesis, using data from the Dorinne ecosystem station, a Belgian pasture grazed by Belgian Blue beef, we disentangled cattle methane (CH_4) and carbon dioxide (CO_2) exchanges from soil-plant exchanges. This work allowed us estimate cattle CH_4 and CO_2 emissions and compute an un-biased pasture GHG budget. Our work therefore opens the door to a wider use of EC on grazed pastures and thus the monitoring of this important ecosystem.

In practice, EC measures gaseous exchanges from an area upwind from the measurement mast. Each area contribution to the measured flux can be computed using a mathematical model (footprint model). We combined this footprint model with cattle positions on the pasture, obtained using GPS-collars, and EC in order to estimate cattle CH_4 emissions. The proposed method was validated through an artificial tracer experiment where source recovery rates were between 90 and 113% and no bias was associated with atmospheric conditions or the distance between the source and the measurement mast. Applying this validated method on grazing Belgian Blue cows led to estimated CH_4 emissions of 220 ± 35 gCH_4 head^{-1} day^{-1}. Cow's behavior was also monitored and presented a clear daily pattern of activity with more intense grazing just after sunrise and right before sunset. However, no significant CH_4 emission pattern could be associated with it, indicating that the diurnal emission variation might be lower than the measurement uncertainty range.

We extended our method to cattle CO_2 emissions. To avoid the need for cattle geolocation, we used CH_4 fluxes as an indicator of cattle presence in the footprint. This allowed us by-passing labor intensive handling of cattle, thus making our method easier to use on a large number of test sites. Using this method, estimated cow CO_2 emissions were of 3.2 ± 0.5 kgC head^{-1} day^{-1}. Moreover, we computed a pasture GHG emission (CO_2, CH_4 and N_2O) of 629 ± 296 gCO_{2eq} m^{-2} yr^{-1}. This figure should be handled with some precautions as it is site specific, dependent on budget boundaries and subject to annual variations.

Key words: Methane, Carbon dioxide, Pasture, Eddy covariance, Cattle, Footprint, Geolocation.

Résumé

La contribution des écosystèmes naturels et anthropisés à la production mondiale de gaz à effet de serre (GES), les façons de limiter cette contribution et l'utilisation des écosystèmes comme puits de carbone fait l'objet de nombreux débats. Pour fournir une base solide à ce débat, des données fiables sont nécessaires. La covariance des turbulences (CT) est couramment utilisée pour mesurer les échanges gazeux provenant d'écosystèmes homogènes (cultures, forêts…). Cependant, dans sa forme standard, elle peut être biaisée lorsque l'on travaille avec des écosystèmes hétérogènes, en particulier les pâturages où le bétail est une source de GES importante, mais aussi une source mobile et intermittente. Dans cette thèse, en utilisant les données de la station écosystème de Dorinne, un prairie belge pâturée par du bétail blanc bleu belge, nous avons séparés les échanges de méthane (CH_4) et de dioxyde de carbone (CO_2) des bovins des échanges sol-plante. Ce travail nous a permis d'estimer les émissions de CH_4 et de CO_2 par animal ainsi que de calculer correctement le bilan de GES de cette pâture. Notre travail ouvre la porte à une utilisation plus large de la CT sur les pâturages et donc au suivi de cet écosystème important.

En pratique, la CT mesure les échanges gazeux provenant d'une zone en amont du mât de mesure par rapport au vent. Chaque contribution de surface au flux mesuré peut être calculée à l'aide d'un modèle mathématique (modèle d'empreinte). Nous avons combiné ce modèle d'empreinte avec les positions du bétail sur le pâturage, obtenues à l'aide de colliers GPS, et la CT afin d'estimer leurs émissions de CH_4. La méthode proposée a été validée par une expérience avec traceur artificiel où les taux de récupération se situaient entre 90 et 113%. De plus, aucun biais n'était associé aux conditions atmosphériques ou à la distance entre la source et le mât de mesure. L'application de cette méthode validée aux vaches blanc bleues belges au pâturage a conduit à des émissions de CH_4 estimées de 220 ± 35 gCH_4 $tête^{-1}$ $jour^{-1}$. Le comportement des vaches a également été surveillé et présentait un schéma d'activité quotidien clair avec un pâturage plus intense juste après le lever du soleil et juste avant le coucher du soleil. Cependant, aucune corrélation significative avec les émissions de CH_4 n'a pu lui être associé, ce qui indique que la variation diurne des émissions pourrait être inférieure à la plage d'incertitude de mesure.

Nous avons étendu notre méthode aux émissions de CO_2 des bovins. Pour éviter le besoin de géolocalisation du bétail, nous avons utilisé les flux de CH_4 comme indicateurs de la présence du bétail dans l'empreinte. Cela nous a permis d'éviter toute manipulation du bétail, rendant ainsi notre méthode plus facile à utiliser sur un grand nombre de sites. En utilisant cette méthode, les émissions de CO_2 estimées des vaches étaient de 3,2 ± 0,5 kgC $tête^{-1}$ $jour^{-1}$. De plus, nous avons calculé un bilan de GES de notre pâture (CO_2, CH_4 et N_2O) de 629 ± 296 gCO_2eq m^{-2} an^{-1}. Ce chiffre doit être manipulé avec quelques précautions car il est spécifique au site, dépendant des frontières du système et est sujet a des variations annuelles.

Mots-clés : Méthane, Pâture, Eddy covariance, Bétail, Footprint, Géolocalisation.

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A Bernard & Marc, je lance mes premiers mots,
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Plus que vous ne le percevez, vos actes m'ont touché,
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List of acronyms

BA	Block averaging method
BE-Dor	Dorinne ecosystem station
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
DMI	Dry matter intake
DTO	Dorinne Terrestrial Observatory
EC	Eddy covariance
E_{cow}	Estimated cattle respiration rate
f_{CH4}	Methane emissions
F_{CH4}	Methane flux
FFP	Flux footprint prediction toot developed by Kljun et al. (2015)
FP	Footprint
GCF	Geolocation correction factor
GHG	Greenhouse gas
GPP	Gross primary productivity
GPS	Global Positioning System
HM	Herbage mass
IPCC	Intergovernmental Panel on Climate Change
KM	footprint model described by Kormann and Meixner (2001)
L	Monin–Obukhov length
LLS	Linear Least Square regression
LU	Livestock unit
MA120	Moving average using a time constant of 120 s
MMR	Median-median regression
N_2O	Nitrous oxide
NBP	Net biome productivity
NEE	Net CO_2 ecosystem exchange
NEE_{past}	Net ecosystem exchange without grazing animals
NEE_{tot}	Total net CO_2 ecosystem exchange
PTFE	Polytetrafluoroethylene
R_{cows}	Respiration of the animals on the field
RCP	Representative concentration pathways
RMA	Reduced Major Axis method
SDc	Stocking density during confinements
SD_f	Stocking density in the footprint
$SD_{f,hom}$	Stocking density in the footprint, assuming homogeneous cattle dispersion on the pasture
SD_p	Stocking density in the pasture

TER	Total ecosystem respiration
u_*	Friction velocity
UTC	Coordinated Universal Time
ϕ_{source}	Source contribution to the footprint (m^{-2})

CHAPTER 1

INTRODUCTION

Chapter 1. Introduction

On a sunny morning of June 2012 colleagues from the team, Alain Debacq and Bernard Heinesch, installed a fast methane analyzer at the Dorinne ecosystem station (BE-Dor). At this moment they knew many challenges would present on their path. Methane fluxes were known to mainly originate from the animals which are moving freely on the pasture but also from the soil, the vegetation and from external sources (contamination of the signal by emanations from the barn, manure heaps, neighboring cattle…). The multiplicity of sources and their moving distribution and emission level makes methane fluxes difficult to interpret. I was thus asked to develop, in the frame of my Thesis, tools in order to estimate the respective contribution of each methane source to the measured flux. Individual contributions of cows to the flux were computed and a global greenhouse gas (GHG) budget of the pasture was established. Since, as the developed tools were found not to be intrinsically linked with methane, they have been used to identify the different sources of carbon dioxide and volatile organic compounds emissions on the same site. This story of my thesis will be developed hereunder, starting with an introduction, followed by four scientific papers and ending with an integrative discussion and a conclusion.

1. ANTHROPOGENIC GREENHOUSE GAS EMISSIONS AND CLIMATE CHANGE

Human activities are associated with GHG exchanges like CO_2, CH_4 and N_2O since the dawn of civilization. However, those emissions have risen dramatically in the last decades (IPCC AR5, chapter 1, 2014) and are planned to further increase, leading to an accelerating earth global warming (**Figure 1-1**). Different scenarios of GHG emission levels called RCP (Representative Concentration Pathways) have been proposed by the IPCC (Intergovernmental Panel on Climate Change) in order to describe possible consequences of future GHG concentrations in the atmosphere. Considered RCP estimates propose temperature increases between 1 and 3°C in 2050 (anomalies relative to 1850‑1900) with consequences, among others, on sea levels and pH, sea ice extents, biochemical cycles, climate and biodiversity. Mitigation of these changes will not only require to act on the cause itself and decrease anthropogenic GHG emissions but also to sequester carbon, for instance into soils (e.g.: https://www.4p1000.org/).

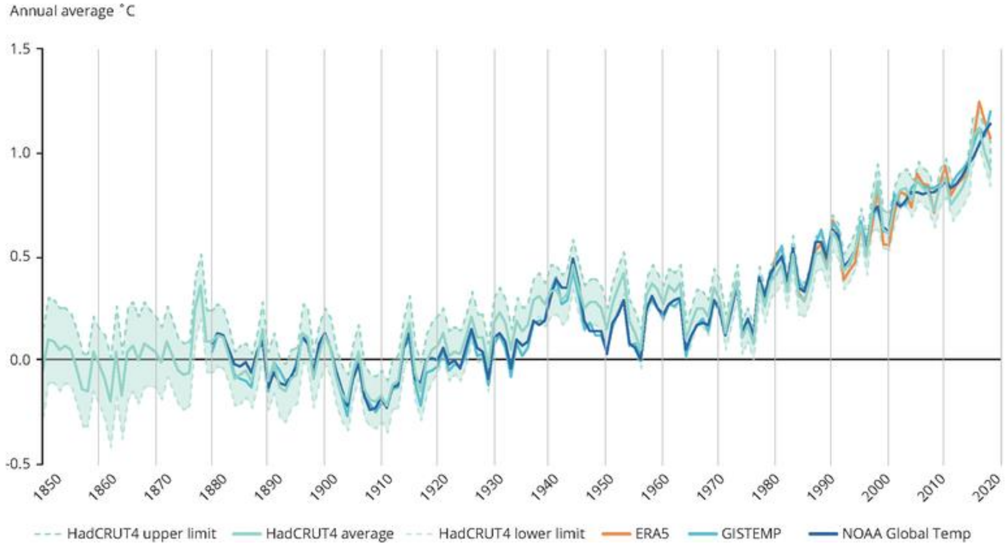

Figure 1-1: Global average near surface temperature annual anomalies since the pre-industrial period (HadCRUT4: Met Office Hadley Centre and Climatic Research Unit, GISTEMP: NASA Goddard Institute for Space Studies, NOAA Global Temp: National Centers for Environment) Credits: (European Environment Agency, 2020).

Domestic livestock produce large amounts of methane, either directly, through their digestive processes or indirectly through manure storage and handling. Those emissions are expected to represent approximately 100 Tg CH_4 $year^{-1}$ (2800 Tg $CO_{2eq.}$ $year^{-1}$) or one third of anthropogenic methane emissions (Saunois et al., 2016) which themselves represented 18% of the total anthropogenic greenhouse gas emissions in 2017 (**Figure 1-2**). In consequence livestock CH_4 emissions represent approximately 6% of all anthropogenic greenhouse gas emissions. Most of those livestock methane emissions are related to herbivores which produce methane through their digestive processes, especially cattle. Moreover, N_2O emissions are also associated with livestock and especially with manure storage and handling.

In Belgium, the current bovine population is slightly above 2.3 million heads and constantly decreasing (Statista, 2018). In 2011, those animals emitted approximately 238 Gg CH_4 yr^{-1} which represents 77% of the estimated belgian CH_4 emissions or 5.6% of all Belgian GHG emissions (National Climate Comission, 2014).

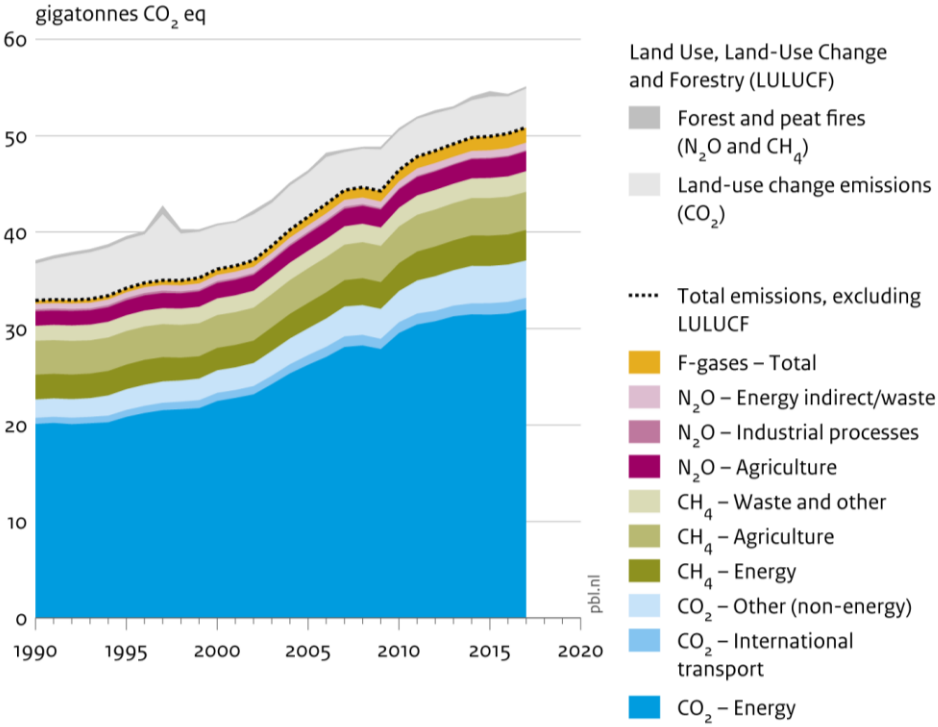

Figure 1-2: The global greenhouse gas emissions, per type of gas and source, including LULUCF. F- gases stands for fluorinated GHG. Credits: Olivier J.G.J. and Peters J.A.H.W. (2018), Trends in global CO2 and total greenhouse gas emissions: 2018 report. PBL. Netherlands Environmental Assessment Agency.

Since livestock plays an important role in terms of global GHG emissions, reducing its emissions is an important lever of action against climate change. In order to decrease those emissions different elements must be kept in mind: Which processes are involved in cattle methane emissions? How can we mitigate these emissions? How can we check that a mitigation method really works? Those questions will be discussed below.

2. Cattle methane emissions

Ruminants have the extraordinary ability to digest cellulose from grass and other forages through a fermentation process. Cattle's stomach is composed of four compartments: rumen, reticulum, omasum and abomasum. The first compartment, the rumen can be considered as a small anaerobic fermenter. Rumen microbes degrade cellulose, hemicellulose and starch into monomers through a process called hydrolysis. These products are then further degraded through a fermentation process into volatile fatty acids like acetate, propionate and butyrate which push their way through the three other stomach compartments where they are absorbed. This process is accompanied by a second fermentation process involving archaea methanogens which converts H_2 and CO_2 into methane and water (**Figure 1-3**). Most of the produced CH_4 escapes through the mouth, with 83 % of emissions associated with eructation and 15 % associated with respiration (Hammond et al., 2016). The latter are originating from the digestive tract and transported by the blood. Methane emissions vary throughout the day with peak emissions reached approximately 2 hours after feeding and then decreasing over time, till the next feeding event (Blaise et al., 2018). Cattle eruct (burp) every 130 to 230 seconds based mainly on their methane production but also on other physiological individual variations (Blaise et al., 2018).

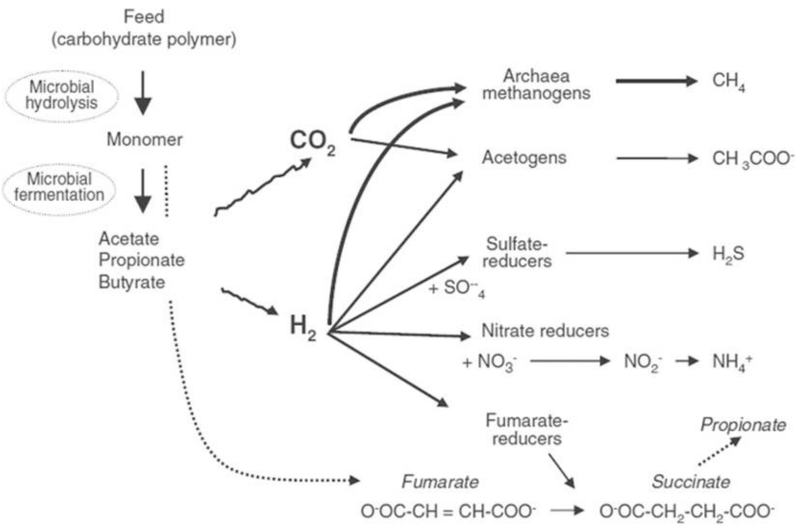

Figure 1-3: Rumen metabolic pathways. Credits : (Haque, 2018).

An adult cow emits from 150 g to 500 g CH_4 day^{-1} according to breed, weight, forage quality, forage availability, activity and other parameters (Broucek, 2014). Many of those parameters do evolve throughout the day and throughout the year, leading to varying cattle emissions. Not only do these emissions contribute to climate change. They also represent a huge energy loss, generally ranging between 2 to 12% of the ingested energy (Johnson et al., 1993). The mitigation of livestock methane emissions is a large subject, abundantly discussed in literature (see the synthetic reports of (Gerber et al., 2013; Hristov et al., 2013; Livestock Research Group et al., 2014). This includes solutions like feed adaptation or supplementation, manure management or improved animal productivity. Mitigation options will not be discussed further, our focus being more on the available methods to estimate associated methane emission reductions.

3. Cattle methane emission measurement

Throughout this thesis, CH_4 *fluxes* (F_{CH4}) will refer to an emanation per surface unit and will be commonly given in nmol^{-1} m^{-2} s^{-1} while CH_4 *emissions* (f_{CH4}) will refer to an emanation per LU and will commonly be given in g LU^{-1} day^{-1}.

Mitigation of cattle methane emissions requires the availability of methods to quantify those emissions, in the barn as well as on the field. Moreover, those measures should not impact cattle behavior and need to be precise enough to assess the impact of mitigation options. Hammond et al. (2016) or Hegarty (2013) published good summaries of available cattle emission measurement methods. **These methods are briefly presented and commented here below**.

Respiration chambers are considered as the golden standard. The principle is simple; an animal is placed in an airtight chamber where all inlet and outlet flows and compositions are measured. This measurement technique is very accurate (providing the chamber is properly calibrated) and allows measurement of diel variations in methane emission. On the other hand, confining each cow in an airtight room is costly, in terms of money as well as in manpower and cannot be applied on the field.

The **sulfur hexafluoride (SF_6) tracer technique** is more recent than respiration chambers and can be applied on the field. A permeated tube is placed in the rumen and allows a known release of SF_6 inside the rumen. Air is continuously collected around the mouth and around the animal body. The ratio $\Delta[CH_4]/\Delta[SF_6]$ in the collected gases can then be used to deduce methane emissions. The accuracy and precision of the SF_6 technique has been evaluated in numerous studies and generally differed by less than 10% from respiration chambers. The main drawbacks of this technique are that it is not adapted for indoor measurements (background concentrations are too high) and requires lots of animal handling. It's also worth noting that it provides time averaged measurement over typically one or two days. The same technique can be based on the $\Delta[CH_4]/\Delta[CO_2]$ ratio but would be much more prone to errors as CO_2 production depends on cattle activity and metabolism.

Recently, new methods based on the use of **proxies** are emerging. Those methods rely on relations between CH_4 emissions and related, easier to measure, parameters such as composition of feces or milk (Dehareng et al., 2012). While the measurement process is easier, allowing cheap, large scale measurements, those methods are by essence less direct, relying on more hypotheses.

Different techniques can also be used to measure instantaneous methane emissions from cattle several times a day. However, in these situations the representativeness of the measures depends on the number and timing of measurements relative to diurnal patterns of CH_4 emission. **Automated head chambers** (e.g. GreenFeed (C-Lock Inc., Rapid City, South Dakota, USA)) is a static device within which cattle placed their heads for a few minutes from time to time, generally during milking or at an automatic feeding device. A fan is driving a known air flow around cattle's head so that the difference in methane concentration between incoming and outgoing air is directly proportional with methane emissions. The drawback of this method is that it can be biased as cattle tend to visit the device more frequently during the day than during the night and as their emissions are only measured when they are active. Other experimental measurement methods are being developed. Among them we can cite the **laser gun**, a hand held portable device which allows real time measurements of methane concentration in the mouth vicinity and the **sniffer** which is based on the same principle but is fixed on milking or feeding devices. Both methods consider that the CH_4 concetration around cattle is related to cattle CH_4 emissions. The drawback of these methods is that this relation is weak and is heavily dependent on wind speed and background methane concentrations.

Finally, **micro-meteorological methods** initially developed to measure ecosystem gas exchanges can be used to measure cattle CH_4 emissions on the field, continuously, in an automated way with minimal animal handling. Despite adding complexity in the experimental set-up and data treatment, those methods are promising because they allow measurement of the emission rate of the whole herd without disturbing the cow's natural behavior. According to the scientific literature, different micro-meteorological methods can be used to estimate cattle CH_4 emissions. Those methods are synthetized by McGinn et al. (McGinn, 2013) or Harper et al. (2011) and will be briefly described hereunder:

- Integrated horizontal flux: This method requires one vertical wind profile and several concentration profiles (typically 5 sampling heights or more) enclosing the entire source perimeter, typically using open path lasers. The flux calculation is then based on the difference in mean concentrations between upwind and downwind sensors and its vertical variation. This technique is well adapted for small surfaces and does not require a homogeneous source distribution within the measurement area. However, this technique cannot be adapted for wide areas.
- Dispersion modeling: Particle dispersion can be modelled, generally using a backward Lagrangian stochastic model (e.g. WindTrax (Thunder Beach Scientific, Canada)). It allows relating the measured concentration within the plume to an estimated source emission. Dispersion models require mean concentrations at one point in the plume and turbulence characteristics (generally collected by a sonic anemometer). The model also requires to know sources location and to measure background concentrations.
- Methods combining a measurement of the gaseous flux at one point, supposed representative of the whole field, and a footprint model (see section 5):
    - Eddy covariance (EC): This method is based on the covariance of the wind vertical velocity and of the gas concentration, both measured at high frequency. This covariance corresponds to the vertical turbulent flux at one specific point. Alternatively, this covariance could be computed through wavelet analysis (Göckede et al., 2019). This new development, although promising, is still in its infancy, has never

been applied to cattle and is therefore not developed in the papers of McGinn et al. (2013) or Harper et al. (2011).

- Relaxed eddy accumulation: This method is very similar to EC except that it removes the need for a fast-response gas sensor. A high speed valve is used instead so that up and down gases are collected separately when the air is going up or down. Average concentrations are then measured for each case and the flux is related to the difference in concentration between up and down going air. The main drawbacks of this method is that it adds an approximation step in comparison with EC, requires precise wind velocity measurement and does not allow recalculations (e.g. following an anemometer calibration).
- Flux gradient: This method requires a vertical wind and concentration profile (typically 5 sampling heights or more) at one location. The main drawbacks of this method is that it adds an approximation step (theoretical relation between fluxes and concentration profile), requires precise concentration measurements and present the same theoretical limitations than EC.

Among micrometeorological methods, dispersion modeling, flux gradient and EC are well suited for measurements in a pasture (low cattle density over big areas). Dispersion modelling is well adapted for point sources enteric CH_4 emissions but the low source strength would put the method close to its detection limit. EC is challenging due to a combination of source complexity (i.e. spatial and temporal variation) and limitations in methodology (Wohlfahrt et al., 2012). An emission per cow can nevertheless be estimated provided we have information about the footprint (upwind area that influences the sensor's measurements) and cattle positions in the footprint (McGinn, 2013). Since then, the combination of the EC technique with a footprint model has been developed in different studies (Coates et al., 2018; Dumortier et al., 2019; Felber et al., 2015; Gourlez de la Motte et al., 2019; Prajapati and Santos, 2017). Each measurement method strength and weaknesses are further discussed and compared with the hereby developed method in Chapter 6, §1.3.

4. Challenges associated with the use of eddy covariance on a pasture

The EC method is used to measure the vertical flux of a scalar at one specific point, the measurement mast. The flux measured at this point is representative of a surface upwind from the mast called the footprint (FP). The FP corresponds to the "effective upwind source area sensed by the observation" (Schuepp et al., 1990) and is described by a FP function weighing the respective contribution of each element of the surface to the measured vertical flux (Rannik et al., 2012). The measured flux therefore depends on the mix of emission sources present in the FP at the time of the measurement. For CH_4, for instance, those sources could be divided in three categories:

- Cattle emissions which are localized, intermittent and vary over time according to cattle physiology.
- Soil / plant exchanges which are supposed to be homogeneous on the whole pasture and mainly dependent on soil characteristics and meteorological parameters.
- Other sources located outside our target pasture like neighboring manure heaps, barns or cattle from other pastures. Those sources generate noise in our measurements and their contribution to the measured flux should be kept as low as possible.

The varying contribution of all three sources contribution to the measured flux is a major drawback for EC. EC is indeed based on the principle of ergodicity which assumes that the selected measurement point is representative of all points at the same height above the selected ecosystem. It implies that the time average of one spatial point, taken over a sufficiently long observation time, is used as a substitute for the ensemble average for temporally steady and spatially homogeneous surfaces (Aubinet et al., 2012). When working with intermittent, point sources this hypothesis is breached and EC measurements at the selected point are not representative of the whole ecosystem anymore. However, different working hypotheses can be used to overcome the challenge and to deal with spatial and temporal heterogeneity. Firstly, different detrending methods may be used to deal with temporal heterogeneity issues associated with the intermittent nature of methane exchanges inside the FP (section 4.1). Secondly, two tactics allows dealling with the spatial heterogeneity challenge: the FP is considered as representative either of the whole target pasture (homogeneous source distribution, section 4.2) or only of the sources present inside the FP (heterogeneous source distribution, section 4.3).

Finally, other challenges are associated with the use of eddy covariance on pastures like modification of roughness/friction velocity due to grass height variations throughout the year and cattle movements in and out from the FP or the detailed description of turbulence at different heights which would be useful for the parametrization of some types of footprint models. However, those last challenges are not dealed with in the present thesis.

4.1. *REMOVING TEMPORAL TRENDS*

EC allows measuring fluxes from a whole ecosystem at one specific point, the top of the measurement mast, by combining vertical wind velocity (w) and gas concentration (c) deviations from the mean ($'$) over time using Equation 1.1.

$$F = \overline{w'c'}$$ **Equation 1.1**

However, this equation is based on the ergodicity hypothesis. When working with intermittent, point sources, mean gaseous concentrations are not stable over time, leading to invalid concentration deviations from the mean (c'). Different options to deal with this difficulty have been considered:

- ⇨ Removing invalid periods from the dataset by using stayionartity tests is the most classic method (Foken and Wichura, 1996). However, this solution is not adapted to intermittent point sources as it would result in the removal of too many periods and was thus discarded.
- ⇨ Reducing the averaging period length would reduce variations in concentration throughout an averaging period. However, the potential is limited as a reduction in period length is associated with low frequency loss (Kaimal et al., 1972). Moreover, this solution would not remove the need for a filtering method and significant variations in gaseous concentrations could still be observed inside an averaging period.
- ⇨ Apply a detrending method on the time series would allow to subtract the average concentration variations from the signal (Gash and Culf, 1996). This method was selected for our dataset and is further discussed in Chapter 3.

4.2. *HOMOGENEOUS CATTLE DISTRIBUTION HYPOTHESIS*

While instantly cattle are never homogeneously distributed on the pasture, average position over long periods of time (several months) might be associated with homogeneous ditributions. If cattle are, on average, homogeneously distributed in the pasture and no contamination sources are present in the neighborhood of the mast, the source can be considered as homogeneous, removing the need to use a FP model. In this case, the flux measured by the EC mast may be considered as representative of the whole pasture. Moreover, if soil exchanges are neglected (one order of magnitude lower than fluxes associated with cattle) and the stocking density in the pasture (SD_p) is known, cattle CH_4 emissions (f_{CH4}) can be estimated using **Equation 1.2**. This hypothesis and the associated results are presented in Chapter 2.

$$f_{CH4} = \frac{F_{CH4}}{SD_p}$$ **Equation 1.2**

4.3. *HETEROGENEOUS CATTLE DISTRIBUTION HYPOTHESIS*

Considering that cattle distribution on the pasture is heterogeneous is probably more realistic but leads to a much more complicated approach as the measured F_{CH4} cannot be considered as representative of the whole pasture but only of the FP area. The question is then to identify the FP area (using a FP model) and to locate the methane sources (cattle, barn, manure heaps) present in this area. The combination of the measured methane flux, a FP model and point sources location can be used to estimate methane emissions per source (f_{CH4}).

The calculation method used to estimate CH_4 or CO_2 emissions (f_{CO2}) on the pasture is fully described in Chapters 3 (General method), 4 (specificities associated with f_{CH4}) and 5 (specificities associated with f_{CO2}). However, the main elements to keep in mind when analyzing the results are summarized hereunder:

- Different FP models can be used to weigh the respective contribution of each element of the surface to the measured vertical flux. It explains why we talk about emission estimates instead of measurements.
- This method only estimates the average emission of sources present in the FP. There is thus no way to estimate each animal emission except if the emission ratio of each source is known beforehand. This could be the case for instance for cattle if emissions are considered proportional to a known animal characteristic like the body mass, the grass ingestion or the milk production.
- Theoretically, emissions could be estimated for each half-hour. However, as results are noisy, estimated emissions only makes sense when compiling tenths to hundreds of half-hours.

5. SITE DESCRIPTION

All experiments presented in the present thesis took place on the Dorinne Terrestrial Observatory (DTO), located at Dorinne, in the Belgian Condroz (location: 50˚ 18’ 44.00” N; 4˚ 58’ 7.00” E; 248 m asl.). This site has been extensively described by Dumortier et al. (2017a, 2019) and only its main characteristics are presented hereunder. The DTO is a 4.2 ha pasture surrounded by pastures in all directions except at the south-west where a crop field is found (**Figure 1-4**). A tiny village road is bordering the east side of the pasture and a slightly larger country road with limited traffic is found 200 m south of the site.

Figure 1-4: Satellite view from the Dorinne Ecosystem Station. The pasture is highlighted in white, the red cross indicates the mast and the ellipse indicate the barn location. Credits: Google earth.

The pasture is grazed by Belgian blue beef cattle, a Belgian breed of cattle known for its blue-grey mottled hair color and its double-muscling phenotype. The site is included in a cow-calf operation system run by Adrien Paquet, a farmer who raises approximately 235 adult cows and 95 calves per year and manage 100 ha of crops and 45 ha of pastures. Adrien Paquet manages his farm as any commercial farm from this region and we always considered ourselves as observers, ensuring realistic pasture management. Each year cows are placed on the pasture with their calves around the first of April and are removed around mid-November. Within this period the stocking density varies according to weather conditions, grass growth, animal health, weaning periods and practical constraints. If we consider that a breeding bull (1,300 kg) or a suckler cow (± 800 kg) represents 1 Livestock unit (LU), whereas a heifer and a calf represent 0.6 and 0.4 LU, respectively the mean annual stocking density is of 2.3 LU ha $^{-1}$. Cattle were not supplemented except in case of drought when the stocking rate was increased (the farmer tries to concentrate cattle in pastures close to the farm) and feed was provided in a trough at the north-east of the pasture, close to the pasture main entry. The site has a gentle SW-NE slope of 0 to 5%. According to the FAO classification system, the pasture is dominated by colluvic regosols (DGARNE, 2015).

The measurement mast is placed at the center of the site and measures the vertical flux at a height of 2.6 m (**Figure 1-5**). Since 2012 the mast is equipped with a sonic anemometer and a fast-response gas analyzer monitoring air CH_4, CO_2 and H_2O concentrations along with classic weather station instruments (soil moisture and temperature at different depths, global and net radiation, atmospheric pressure, air temperature, pluviometry and relative humidity). Relevant technical information about the site instrumentation is given in the material & methods section of each chapter. Winds are tipically coming from the south-west or from the north-east which means that most measured fluxes are originating from these directions. A hedge and a tree, near which cattle tend to aggregate during the night, are found at the north of the pasture. There are two drinking troughs at the pasture edges, shared with adjacent pastures. When calves where present on the pasture, a calf creep-feeder was placed near the tree. There was a fenced pond 100 m east of the mast.

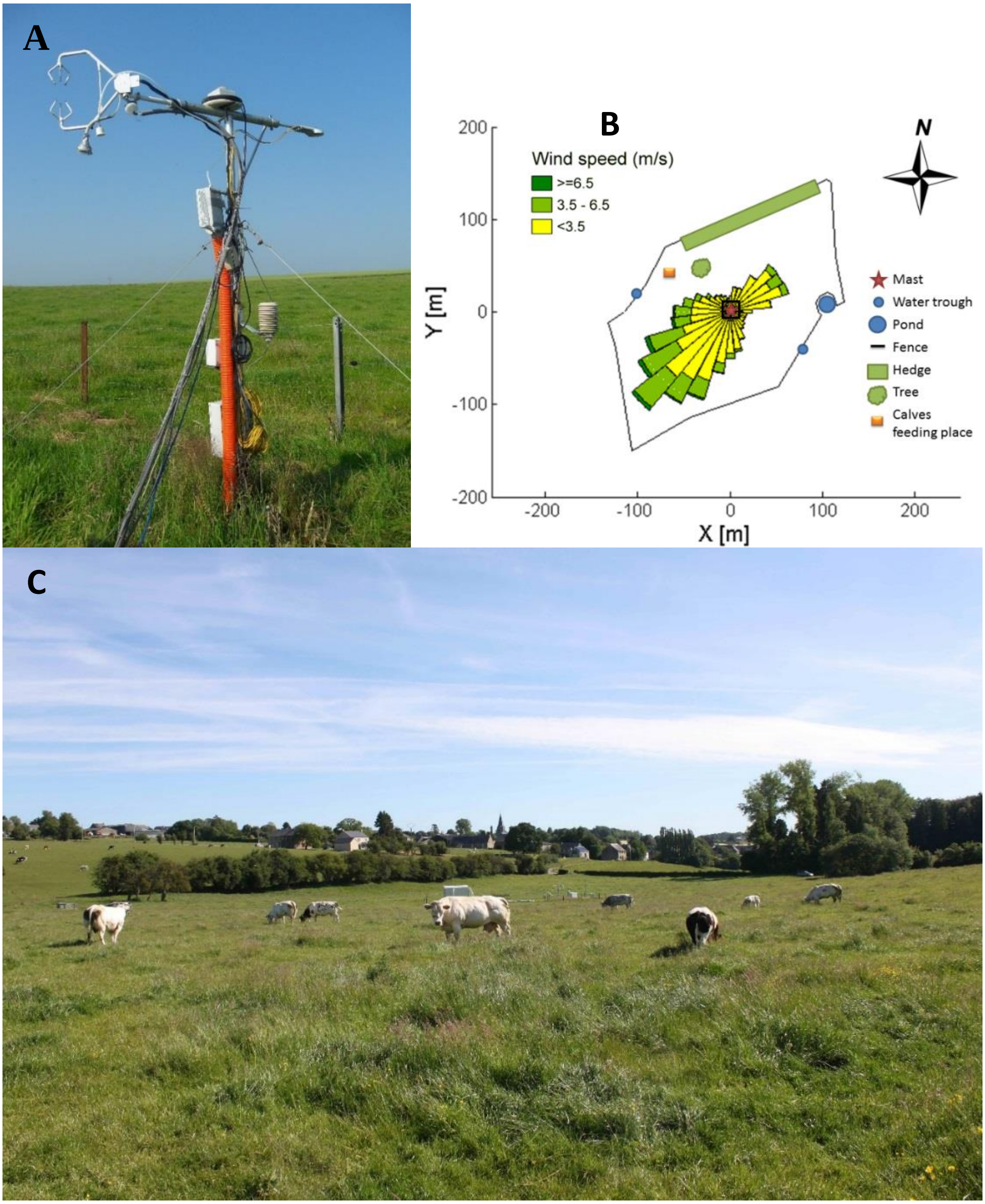

Figure 1-5: Measurement mast with sonic anemometer and sampling tube (A), schematic view of the pasture with main wind directions and velocities overlaid on the mast location (B) and general view of the site, the instrumentation being partly hidden by the white cow.

6. OBJECTIVES

The following working question guided us through the whole thesis: Can EC be used as a standard measurement method to measure cattle methane emissions on a pasture?

In this context, our objectives were the following:

1. To adapt EC to deal with situations where mobile and intermittent emission sources are found inside the target area. Short title: Ergodic hypothesis.

2. To identify the respective contribution of cattle and soil / plant to the CH_4 and CO_2 exchanges measured above a grazed pasture. Short title: Flux allocation.

3. To develop a method allowing estimation of cattle CH_4 emissions per LU (f_{CH4}) on a pasture using EC. This method is applied to quantify Belgian Blue CH_4 emissions at typical Walloon cow-calf operation and the associated error. Short title: f_{CH4} estimation.

4. To characterize diel and seasonal variations in cattle CH_4 emissions and its underlying drivers. Short title: Drivers.

5. To contribute to the Be-Dor GHG budget by estimating the pasture CO_2 and CH_4 exchanges. Short title: GHG Budget.

Moreover, the thesis is structured as follows:

- Chapter 2 discusses methane fluxes measured at the BE-Dor station from June 2012 to December 2013 and mainly aims at measuring soil/plant methane fluxes and dynamics and provides a first estimate of cattle methane emissions based on homogeneous distribution hypothesis. Il also allowed us to fully understand the importance of contaminations to measurements. Those results were necessary when estimating point source emissions on the pasture (Chapter 3 to 5).
- Chapter 3 establishes and validates through an artificial tracer experiment the point source emission estimation method used in the following chapters.
- Chapter 4 uses this method in order to estimate cattle CH_4 emissions.
- Chapter 5 uses the same method to estimate cattle CO_2 emissions and further expand on it in order to estimate the respective contribution of cattle and of the soil-plant continuum to measured CO_2 fluxes.
- Chapter 6 provides a general discussion covering all chapters simultaneously.

7. Personnal contribution to the research presented in this manuscript

All papers presented in this thesis are the result of a team work. The site was made available by Adrien Paquet who welcomed us on his farm and helped us whenever he could. The technical maintenance of the site was successively done by Henry Chopin, Frederic Wilmus, Gino Mancini, Alain Debacq and Alwin Naiken. My specific contribution to each chapter is detailed below.

- Chapter 2 (articles 1): I analyzed the data and wrote the paper.
- Chapter3 (article 2): I was responsible for the conception and realization of the artificial source experiment, analyzed the data and wrote the paper.
- Chapter 4 (article 3): I was responsible for the cow geolocation campaigns (GPS being built by Alain Debacq), analyzed the data and wrote the paper. Nicolas De Cock studied the impact of the source height on the estimated methane emissions and therefore further defined the measurement conditions.
- Chapter 5 (article 4): I was responsible for the GPS data acquisition and associated data analyses and was deeply involved in the writing process. Louis Gourlez de la Motte led the paper writing and performed the major part of data analysis.

In addition, I was responsible for the day to day follow-up of the CH_4 measurement at the site.

CHAPTER 2

METHANE BALANCE OF AN INTENSIVELY GRAZED PASTURE AND ESTIMATION OF THE ENTERIC METHANE EMISSIONS FROM CATTLE

Chapter 2. Methane balance of an intensively grazed pasture and estimation of the enteric methane emissions from cattle

This chapter has been published as:

DUMORTIER, P., AUBINET, M., BECKERS, Y., CHOPIN, H., DEBACQ, A., GOURLEZ DE LA MOTTE, L., JÉRÔME, E., WILMUS, F., HEINESCH, B., 2017. Methane balance of an intensively grazed pasture and estimation ofthe enteric methane emissions from cattle. *Agricultural and Forest Meteorology* **232**, 527–535. doi: 10.1016/j.agrformet.2016.09.010.

Abstract

The methane turbulent fluxes of an intensively grazed pasture were measured continuously from June 2012 to December 2013 at the Dorinne Terrestrial Observatory (DTO) in Belgium. During grazing periods, the fluxes were dominated by enteric fermentation and were found to be strongly related to cow stocking density. In 2013, total emission from the pasture was found between 9 and 11 g CH_4 m^{-2}, 97% of which being emitted during grazing periods. Emission per LU (livestock unit) was estimated in a non-invasive way by integrating eddy covariance fluxes over large periods and by assuming a homogeneous average cattle distribution on the pasture.

This estimate was compared to the one obtained during confinement periods, where cows were confined in a small part of the pasture. The emission per LU varied between 104 and 134 g CH_4 $LU^{-1}day^{-1}$ (13 and 17 g CH_4 kg DMI^{-1}), depending on the dataset and the computation method used. Diel course was characterized by two emission peaks, one in the morning and a larger one in the afternoon. For rest periods (no cattle on the pasture), small emissions were observed (median and mean values of 0.5 and 1.5 mg CH_4 m^{-2} day^{-1}, respectively).

Keywords

Eddy covariance; Methane; Pasture; Cattle; Footprint; Livestock emissions.

1. INTRODUCTION

Between 1750 and 2014, the atmospheric methane dry molar fraction rose from 0.722 to 1.8 µmol mol^{-1} (MacFarling Meure et al., 2006; NOAA, 2014). This radical increase in methane concentration accounted for almost 30% of the total greenhouse gas (GHG) radiative forcing of all well-mixed GHG over the period from 1750 to 2011 (Myhre et al., 2013). The accurate monitoring of ecosystem CH_4 fluxes and balances is therefore of crucial importance.

About 50% of all sources of terrestrial methane are thought to be linked to human activities, with the husbandry of domestic ruminants representing 25% of this amount (Ghosh et al., 2015). Grazed grassland is therefore one of the most important ecosystems in terms of methane exchange. Its methane budget comprises two main components: first, ruminants present on pasture produce methane when digesting grass; and second, soil bacterial communities that can either produce or consume methane, depending on the soil's physical and biological conditions (Smith et al., 2003).

Monitoring these fluxes is usually conducted separately for grasslands and for animals, soil emissions being measured using chambers or micro-meteorological techniques on ungrazed grasslands (Oertel et al., 2016) and cattle emission using metabolic chambers or a tracer method (typically involving SF_6) (Storm et al., 2012a). Such separated monitoring can lead to biases as it doesn't take into account the interaction between grasslands and animals during grazing. Moreover, metabolic chambers or tracers are typically applied to a limited number of cows while important emission differences may appear among individuals. Finally, the tracer technique, which has often the advantage to be applied with 'in-situ" conditions, has a limited duration, typically a couple of days, and does not allow studies of emission diel cycle. The presence of equipment (saddle, bottles, hoses…) can also affect the behavior of the animals during these short measuring periods. The use of the eddy covariance (EC) method over pastured ecosystems can overcome some of these limitations (McGinn, 2013).

EC is a micrometeorological technique adapted to the continuous measurement of tracer fluxes over ecosystems.

It measures fluxes originating from a zone (footprint area) situated mostly upwind of the measurement point and has the advantage of integrating all the exchange processes at work in the footprint, thus providing the net methane exchange of the ecosystem. Its drawbacks include its inability to detect the origin of fluxes or to disentangle simultaneous incoming and outgoing fluxes. Soil and cattle respective contributions to the net methane exchange can however be identified by separating rest periods (without cattle on the pasture), when only soil fluxes are operating, from grazing periods, when cow emissions are dominating the exchanges. In this latter situation, the EC technique has the advantage to provide flux estimates from the whole herd, over long periods and with high time resolution. However, in the absence of information on cow location and activity, the interpretation of the measured flux is challenging because cows constitute punctual, moving and intermittent sources. Many teams working on grazed ecosystems methane exchanges are presently facing this challenge (Baldocchi et al., 2012; Dengel et al., 2011; Tallec et al., 2012).

In this study, our objectives were therefore: (i) to evaluate the feasibility of estimating animal methane emissions in the field on the basis of eddy covariance measurements and of simple hypotheses on cattle dispersion and (ii) to provide an estimate of the methane net emission by an intensively grazed pasture in Belgium.

2. MATERIAL AND METHODS

2.1. *SITE DESCRIPTION AND CATTLE MANAGEMENT*

The study was performed at the Dorinne Terrestrial Observatory (DTO), a pasture situated at Dorinne, in Condroz region, in Belgium (location: 50˚ 18’ 44.00” N; 4˚ 58’ 7.00” E; 248 m asl.). The site has a gentle SW-NE slope varying between 0 and 5% along this transect and averaging to 1-2%. According to the FAO classification system, the pasture is dominated by colluvic regosols (DGARNE, 2015). More details about the site are given by Jérôme et al. (2014) and Gourlez de la Motte et al. (2016).

The pasture covers 4.2 ha and is intensively grazed by Belgian Blue cattle, following regional common practices for a cow-calf operation system. The cattle graze from mid-April to mid-November (growing season) at varying stocking densities (**Figure 2-1**), with a mean density of 2.3 10^{-4} livestock units (LU) m^{-2} in 2013. At the beginning of the season (May, June) the herd consists of up to 30 cows, accompanied by their calves and a bull. During this period calves’ diet is supplemented with concentrates. After weaning (July), only the adults remain on the pasture. Cattle density is estimated by considering that a breeding bull (1,300 kg) or a suckler cow (600-900 kg) represents 1 LU, whereas a heifer (400 - 600 kg) and a calf (100 - 200 kg) represent 0.6 and 0.4 LU, respectively.

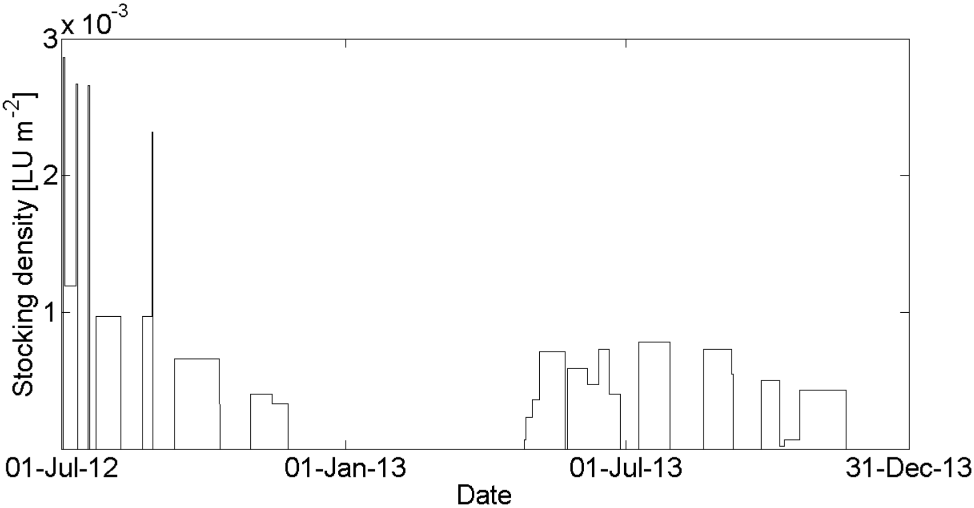

Figure 2-1: Stocking density evolution throughout the measuring period; the periods with stocking densities above 15 10^{-4} LU m^{-2} correspond to confinement periods.

The measuring mast was placed at the center of the pasture (**Figure 2-2**), which is totally surrounded by other pastures except in the south-west (main wind direction) where it is bordered by a crop. There are two drinking troughs shared with adjacent pastures at the edge of the pasture. During the monitoring study, the studied herd and the neighboring herd often gathered at the north-western drinking trough, but little social activity was observed at the south-eastern trough. There was a fenced pond 100 m east of the mast. In the northern part of the pasture lie a hedgerow and a tree under which the cattle often repose. A calf creep-feeder was placed near the tree and was filled when calves were on the pasture.

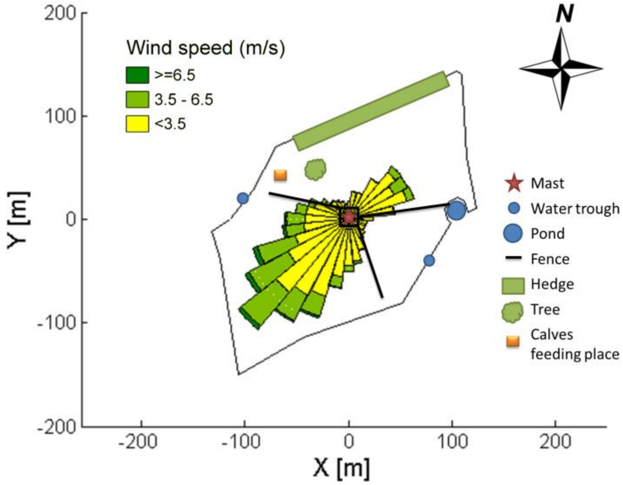

Figure 2-2: Schematic view of the pasture. During confinement periods, gates in internal fences were closed and the cattle were confined to the south-western part of the pasture.

The measurements were performed from June 2012 to December 2013. During this period, the farmer adjusted stocking density to grass availability, which led to an alternation of rest and free-ranging periods during which the herd was spread in the pasture. In addition, four one day confinement periods were established during which the cattle were confined to about a third of the pasture (1.7 ha), roughly covering the flux source area (footprint) in the main wind direction (Jérôme et al., 2014). This allowed stocking density in the footprint to be more homogeneous. Free-ranging and confinement periods were regrouped under the term ‘grazing periods’.

2.2. *INSTRUMENTATION*

2.2.1. Eddy covariance and meteorology

Methane fluxes exchanged in the pasture were measured continuously using a fast CH_4 analyzer (PICARRO G2311-f, PICARRO Inc., USA) and a sonic anemometer (CSAT3, Campbell Scientific Ltd., UK) placed 2.6 m above ground. Air sampled near the anemometer (0.216 m N, 0.125 m E and 0.23 cm below) was carried to the analyzer through a 1 µm filter (ACRO50 PTFE 1 µm, Pall, NY, USA) and a heated tube (inner diameter 6 mm, length 6.85 m, flow rate 9 10^{-5} m^3 s^{-1}). Wind speed components collected at 10 Hz by the anemometer were synchronized with gas CO_2 and CH_4 dry molar fractions and stored by the gas analyzer. The analyzer calibration was checked every 3 months using a N_2 bottle (Alphagaz 1, Air Liquide, Liege, Belgium), a 2.02±0.04 nmol CH_4 mol^{-1} bottle (Crystal mixture, Air Liquide, Liege, Belgium) and a dew point generator (LI-610, Licor Inc, Lincoln, USA). However, no deviation of the analyzer was ever noticed.

Various micro-meteorological and soil variables were measured continuously, including global and net radiation (CNR4, Campbell Scientific Ltd, UK), air temperature and moisture (RHT2, Delta-T Devices Ltd, Cambridge, UK), soil temperature at 2, 5, 10, 25 and 50 cm (Pt 1000, Jumo, Eupen, Belgium), soil moisture at 5, 25 and 50 cm (ThetaProbe, Delta-T Devices Ltd, Cambridge, UK), atmospheric pressure (144S BARO, SensorTechnics, Puchheim, Germany) and precipitation (52203 Young Tipping Bucket Rain Gauge, Campbell Scientific Ltd, UK).

2.2.2. Herbage mass, cattle dry matter intake and stocking density

Cattle dry matter intake during each free ranging period was estimated from difference in herbage masses at the beginning and the end of the period. Herbage masses were estimated from herbage height measured with a rising plate meter and from locally established allometric relationships. Application of this procedure in the field and in restriction areas allowed grass growth rate to be estimated in the presence and in the absence of cattle. Cattle dry mass intake was finally estimated by the difference between these two estimates. The detailed procedure was described by Gourlez de la Motte et al. (2016).

Stocking density evolution and all management activities (e.g., fertilizer application, calf feeding periods) were recorded by the farmer.

2.3. DATA TREATMENT

2.3.1. General corrections

Turbulent fluxes were calculated on a 30-min basis using EddyPro® (LI-COR Inc, Lincoln, NE, USE) open source software (Version 6). We use the micrometeorological convention that upward fluxes are positive, corresponding thus to emissions, while downward fluxes are negative. All calculations were adapted from standard EC computation procedures (Aubinet et al., 2012, 2000). Data were rotated (2D) in order to align the streamwise velocity component with the direction of the mean velocity vector (Rebmann et al., 2012).

A fundamental assumption of the EC method is that fluctuations are statistically stationary during the chosen averaging time. However, a large proportion of the methane fluxes are very small (between -0.5 and 0.5 nmol m^{-2} s^{-1}) so that the classical stationarity test, based on the relative variation of the measured flux within averaging times (Foken and Wichura, 1996), could not be correctly used. On the one hand, applying the stationarity test would lead to the removal of too many small fluxes (Béziat et al., 2010) (**Figure 2-3**), which would have induced a bias in summed fluxes, especially during rest periods. On the other hand, applying block average without stationarity test screening would have produced many inconsistent flux values caused by a deviation of the mean methane concentration during the half hour, due for instance to the intermittent presence of cattle in the footprint. Some of these inconsistencies were easy to spot because they corresponded to sudden strongly negative methane fluxes of otherwise unexplained origin. Therefore, in order to avoid both problems, we decided to compute fluctuations with a running mean and to not apply stationarity screening. The running mean time constant was adjusted in order to obtain the largest one that minimized the number of inconsistent values. In practice, a time constant of 240 s appeared to be the best compromise.

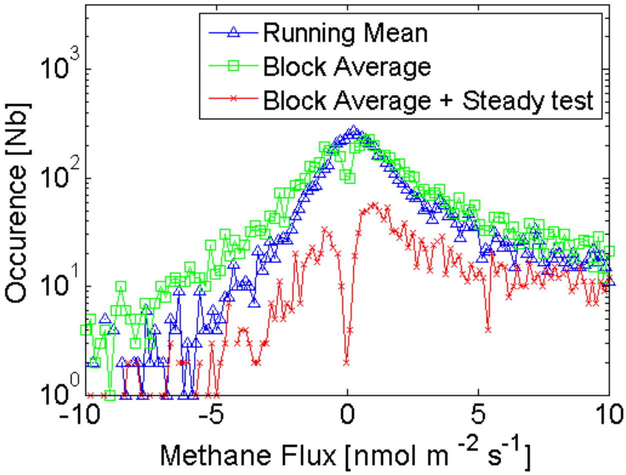

Figure 2-3: Methane flux occurrence distribution for three data treatment methods. Data were filtered for low friction velocity (u_*) and signal contamination (see text). For better readability, only fluxes between -10 and 10 nmol m^{-2} s^{-1} are shown.

Time lag was estimated by covariance maximization inside a time window of 3 ± 1 s with the center of the window corresponding to the time lag mode (72% of the records were found within this window for methane and 85% for CO_2). If no time lag was detected inside the window, a default time lag of 3 s was used. Spikes in the 10 Hz time series were removed from the dataset and replaced by linear interpolation using a procedure described by Mauder et al. (2013). Spectral corrections were applied to the fluxes by using the method described by Fratini et al. (2012). The half-power cut-off frequency was about 0.50 Hz for methane and 0.54 Hz for CO_2. Half-hours hard-flagged for spikes, drop-outs, discontinuities or inputs outside the absolute limits were discarded from the dataset. Fluxes were also corrected for storage according to the method proposed by Aubinet et al. (2012).

Nighttime half-hours with low friction velocity (u_*) were removed from the dataset using a site-specific u_* threshold of 0.13 m s^{-1}, obtained from a night-time CO_2 flux analysis performed by Jérôme et al. (2014) on the same site. This value coincided with the methane flux vs u_* relationship (**Figure 2-4**). However, below the u_* threshold, methane fluxes headed toward negative values instead of approaching zero and were associated with larger confidence intervals due to the presence of outliers.

System detection limit was computed using the method proposed by Finkelstein and Sims (2001) and set at 2 nmol m^{-2} s^{-1}.

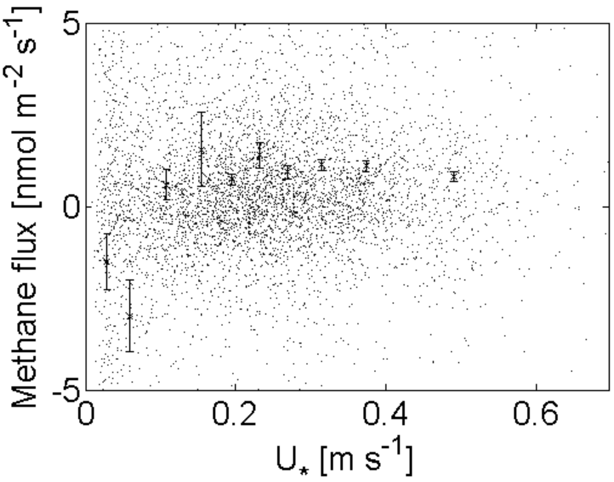

Figure 2-4: Scatterplot of methane fluxes vs u_* during rest periods. Fluxes are filtered for contamination by distant sources (see text). For better readability, only fluxes between -5 and 5 nmol m^{-2} s^{-1} and u_* values below 0.7 are shown. Crosses correspond to bin averages on one tenth of the half-hours each. Error bars correspond to the 95% confidence interval.

2.3.2. Footprint correction

The footprint corresponds to "the effective upwind source area sensed by the observation" (Horst and Weil, 1992) and can be described by a two dimensional weighing function computed as the fraction of the measured flux provided by each point of the space around the measurement tower.

As the footprint area often extended beyond the paddock in zones free of cattle, a footprint correction was introduced to estimate emissions per LU. Two different models were used to calculate the footprint function: an analytic model based on the steady state advection diffusion equation (Kormann and Meixner, 2001) (KM) and a prediction tool based on backward Lagrangian stochastic particle dispersion (Kljun et al., 2015)(KJ).

During grazing periods fluxes from the paddock were computed by dividing measured fluxes by the contribution of the pasture to the footprint. This correction assumes that soil fluxes were negligible in comparison with enteric emissions (refers to section 4.2 and **Figure 2-7**). Moreover, independently from cattle presence on the pasture, measurements were removed when the pasture contribution to the footprint was below 60% in order to remove irrelevant data while keeping a sufficiently large dataset.

2.3.3. Flux contamination by distant sources

Being very small, methane fluxes exchanged during rest periods could be contaminated by sources beyond the pasture limits. Contamination by these distant sources can be easily identified by looking at the relationship between methane fluxes and wind direction (**Figure 2-5**). This relationship is season dependent. During winter

(December to March), high fluxes (> 5 nmol m^{-2} s^{-1}) were detected only in a narrow north-eastern sector, corresponding to the barn direction, while fluxes remained very low (less than 5 nmol m^{-2} s^{-1}) in the other wind directions. Considering an emission factor of 164 g CH_4 LU^{-1} day^{-1} (IPCC, 2006), a barn with 200 cows confined on 1000 m² would indeed represent a local source of 22 000 nmol m^{-2} s^{-1}. Even with a footprint weighing as low as 0.1 %, this would correspond to a contribution of 22 nmol m^{-2} s^{-1} to the measured flux.

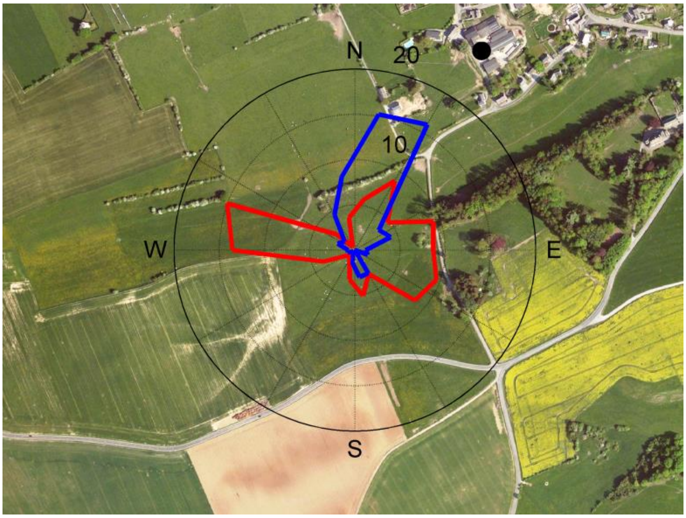

Figure 2-5: Directional intensity of methane fluxes (nmol m^{-2} s^{-1}) during rest periods in winter (dark blue) and during growing season (light red). The circle is centered on the measurement mast. The barn is indicated by the black dot, 350 m north-east (30° N, clockwise) of the mast.

During the growing season, important fluxes (5-15 nmol m^{-2} s^{-1}) were detected during rest periods for all wind directions but South-West (below 1 nmol m^{-2} s^{-1}). Signal contamination was also suspected here, due to the barn (which was partly occupied), the presence of cattle grazing in adjacent pastures and the occasional gathering of cattle near water troughs. In contrast, the south-western sector was associated with the lowest methane fluxes during the growing season. The studied pasture here is bordered by a crop field, cancelling out the risk of neighboring cattle contaminating the signal.

In order to avoid a flux bias due to this contamination during rest periods, contaminated half-hours were eliminated. Only measurements with mean wind direction between 75 and 315° N, clockwise, during winter and 210-240° N, clockwise, during the growing season were kept. Although the excluded sectors are large, especially during the growing season, they correspond to less frequent wind directions so that a large proportion of the fluxes remained (73 and 30% of rest period fluxes during winter and growing season, respectively). The same exclusion criterion was applied to data during free-ranging periods in order to make sure that the measured fluxes were not related to emissions from neighboring paddocks. During confinement periods, no filtering was applied as fluxes were one order of magnitude larger than during rest periods (mean flux between 249 and 255 nmol m^{-2} s^{-1}) and therefore unlikely to have been significantly affected by contamination.

A synthesis of the available data after each treatment step using the KM and KJ footprint models is presented in **Table 2-1**.

Table 2-1: Number (and percentage) of remaining half-hours after the application of each data treatment step for the whole dataset and for the three types of cattle management.

	Whole dataset	Rest periods	Free-ranging periods	Confinement periods
Measurement period	26834	15018	11621	195
Available half-hours	23785 (89%)	13818 (92%)	9786 (84%)	181 (92%)
Test for spikes, drop-outs, absolute limits and discontinuities	21676 (80%)	12462 (82%)	9048 (78%)	166 (85%)
u_* correction	13865 (52%)	8111 (54%)	5658 (48%)	96 (49%)
Footprint correction	KM: 13151 (49%) KJ: 13702 (51%)	8111 (54%)	KM: 4967 (40%) KJ: 5509 (47%)	KM: 73 (37%) KJ: 82 (42%)
Environmental contamination	KM: 5431 (20%) KJ: 5468 (20%)	4153 (28%)	KM: 1205 (10%) KJ: 1233 (11%)	KM: 73 (37%) KJ: 82 (42%)

3. RESULTS

3.1. *FOOTPRINT FUNCTION*

At the DTO the area contributing to 80 % of the measured flux typically extends from 22 to 614 m away from the mast, according to KM predictions, and from 19 to 452 m away, according to KJ predictions. The peak contribution is at about 25 m (KM) and 33 m (KJ). On average, the paddock represented 68 and 86 % of the footprint contribution for KM and KJ respectively. A typical footprint function is represented in **Figure 2-6**.

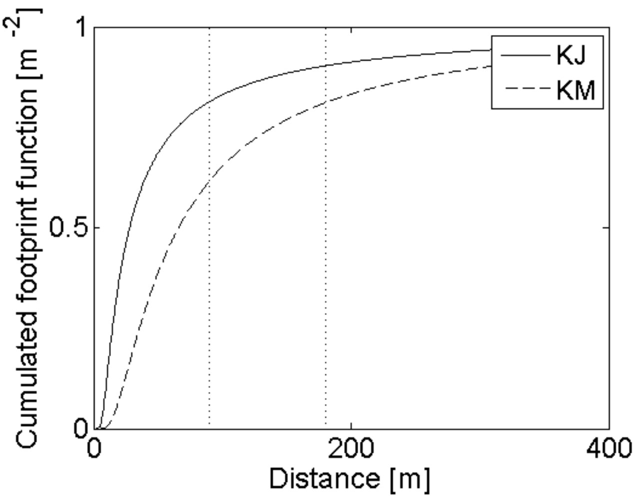

Figure 2-6: Cumulated footprint function along the main wind direction for June 09 2013 at 6:00 u_*= 0.25 m s^{-1}, z/L=-0.036). Dotted lines indicate the shortest (north-west) and longest (south-west) distances between the mast and the border of the paddock.

3.2. *METHANE DRY MOLAR FRACTION AND FLUX EVOLUTION OVER TIME*

The methane dry molar fraction ranged from 1860 nmol mol^{-1} to 2100 nmol mol^{-1}, with intermittent peaks of up to 2450 nmol mol^{-1} (**Figure 2-7**). The relationship between dry molar fraction and cattle density appeared weak, most of its variability being likely due to unidentified sources sporadically present upwind and far away from the pasture.

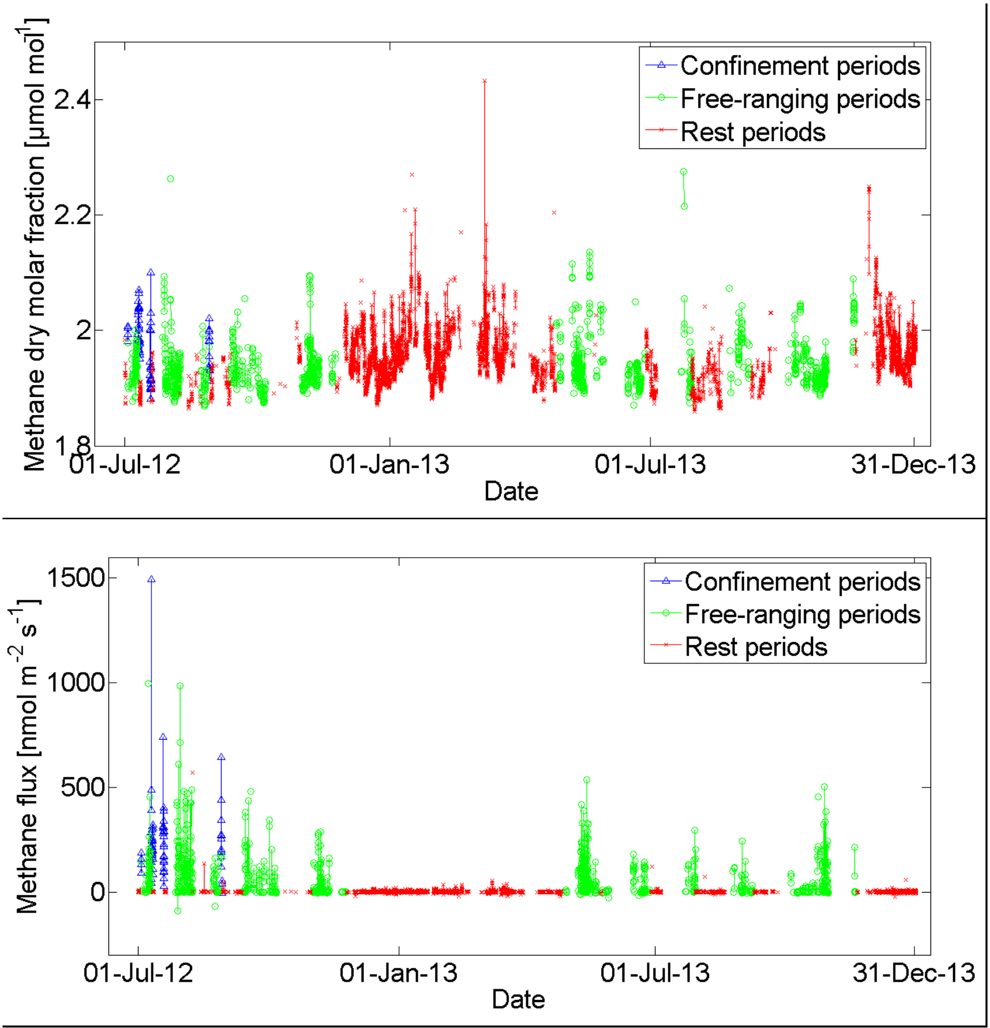

Figure 2-7: Evolution over time of methane dry molar fraction (A) and fluxes (B) using KM. Each point corresponds to a half-hour and the colors indicate level of cattle presence on the pasture.

In contrast, the methane flux variations were closely linked to cattle presence or absence. They varied by one to several orders of magnitude between rest and free-ranging periods (**Table 2-2**). In addition, during free-ranging periods, fluxes were highly variable, even over short time periods. This variability could be explained by cow movements from, to or within the footprint area, leading to stocking density changes in the footprint area or, to a lesser extent, by variations in cow digestion rhythm, leading to source intensity changes. In order to disentangle these two potential causes, cattle confinement periods, during which cattle were confined to the footprint area, were organized. During these confinement periods, the fluxes were indeed higher and less variable. Most of the variability could be attributed to the heterogeneity of cattle dispersion within the footprint, their digestion rhythm and random errors linked to the stochastic nature of turbulence.

Table 2-2: Mean fluxes, median and quartiles for each measurement period and for the two footprint calculation models (nmol m^{-2} s^{-1}).

	Rest periods	Free-ranging periods	Confinement periods
Mean value	1.09	KM: 58.3 KJ: 47.9	KM: 249 KJ: 255
Lower quartile	-0.49	KM: 0.5 KJ: 0.4	KM: 153 KJ: 146
Median	0.39	KM: 11.5 KJ: 8.8	KM: 216 KJ: 205
Upper quartile	1.58	KM: 87.4 KJ: 71.7	KM: 305 KJ: 297

Methane dry molar fraction diel evolution (**Figure 2-8 A)** shows a typical oscillation with lower values during the day and larger values at night, suggesting methane accumulation in the absence of turbulence. Although molar fractions didn't differ between periods during day, at night, their increase depended on cattle density, reaching 40-50 % during confinement periods, 20 % during free-ranging periods and 3-5 % during rest periods. The presence of a night increase during rest periods suggests the presence of local methane sources at the site, even in the absence of cattle

Methane fluxes were an order of magnitude higher during confinement than during free-ranging periods and two orders of magnitude higher than during rest periods (**Figure 2-8 B**). No clear diurnal evolution of the fluxes was observed during rest periods. During confinement periods, fluxes presented a daily pattern, with higher methane fluxes in the early morning and the afternoon. Here again, during free-ranging periods, daily evolutions were impacted by intermittent presence of cattle in the footprint, making interpretations more difficult. No notable impact of the footprint model on fluxes diurnal evolution pattern was noticed, whereas mean values were affected by the choice of the model. Fluxes were therefore only represented for the KM footprint model.

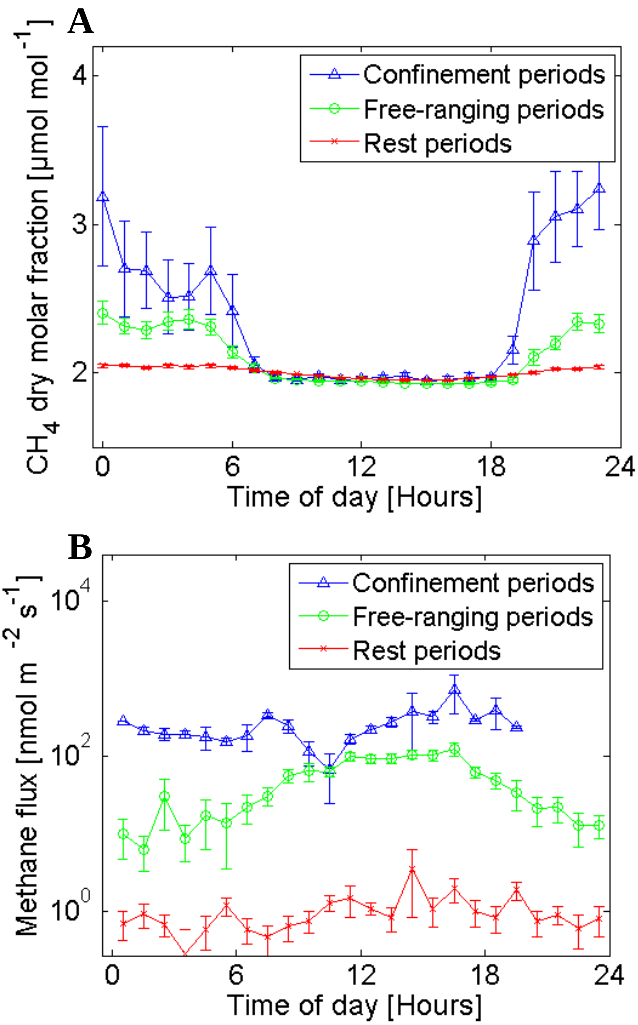

Figure 2-8: Diurnal pattern of methane dry molar fraction (A) and fluxes (B) using the KM footprint model. Error bars correspond to standard errors of the mean. Fluxes are filtered for contamination by distant sources and for low u_*, whereas methane dry molar fractions are filtered for contamination by distant sources only. Note the use of a logarithmic scale for the vertical axis.

3.3. *ENTERIC EMISSIONS*

Given that cattle were the main methane source, the net methane flux should have been proportional to grazing density. On a half-hourly scale, however, the correlation was poor (not shown), obviously due to cattle movements within the footprint area and variations in digestion rhythm. When working with averages, however, the spread was greatly reduced and defensible regressions could be inferred (**Figure 2-9**).

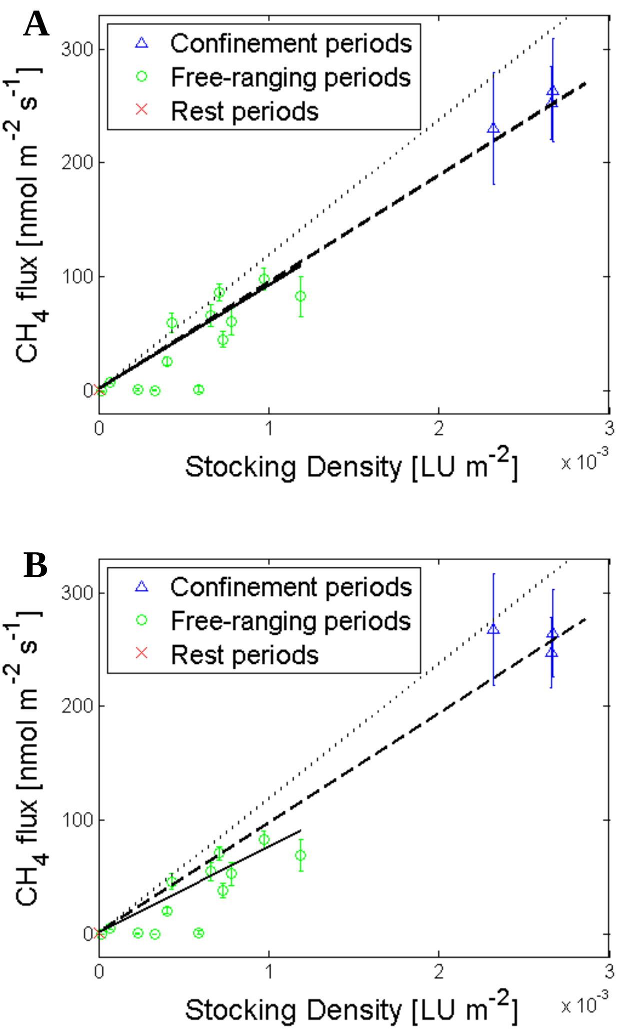

Figure 2-9: Relation between methane flux and stocking density. Methane fluxes are measured by eddy covariance and corrected for footprint using (A) the KM and (B) the KJ footprint model. Each point is the mean over one grazing period with constant stocking density. Only periods gathering more than 20 valid measurements are represented here. Error bars are 95% confidence intervals. The dotted line correspond to the predicted response (IPCC, 2006); solid and striped lines correspond to linear least square regressions on individual half-hours grouping rest periods and either free-ranging (R^2=0.26) or confinement (R^2=0.61) periods.

At first glance, the regression slopes may be considered as an estimate of the emission per LU. During free-ranging periods, fluxes were estimated between 126 (KM) and 104 (KJ) g CH_4 LU^{-1} day^{-1} while during confinement periods, emissions were estimated between 131 (KM) and 134 (KJ) g CH_4 LU^{-1} day^{-1}.

Emission per LU (**Figure 2-10**) also showed a pronounced and significant mean diurnal pattern with emissions ranging from 1 to 17 g CH_4 LU^{-1} $hour^{-1}$ depending on the time of day. Despite the small amount of data obtained during confinement periods, fluxes measured during free ranging and confinement periods showed similarities, with a small peak in the night/early morning and a larger peak in the afternoon. The choice of the footprint model had a limited impact on fluxes dynamics. In addition, during free-ranging periods, the diurnal pattern differed from month to month (data not shown), probably due to differences in cattle positioning according to the period of the year.

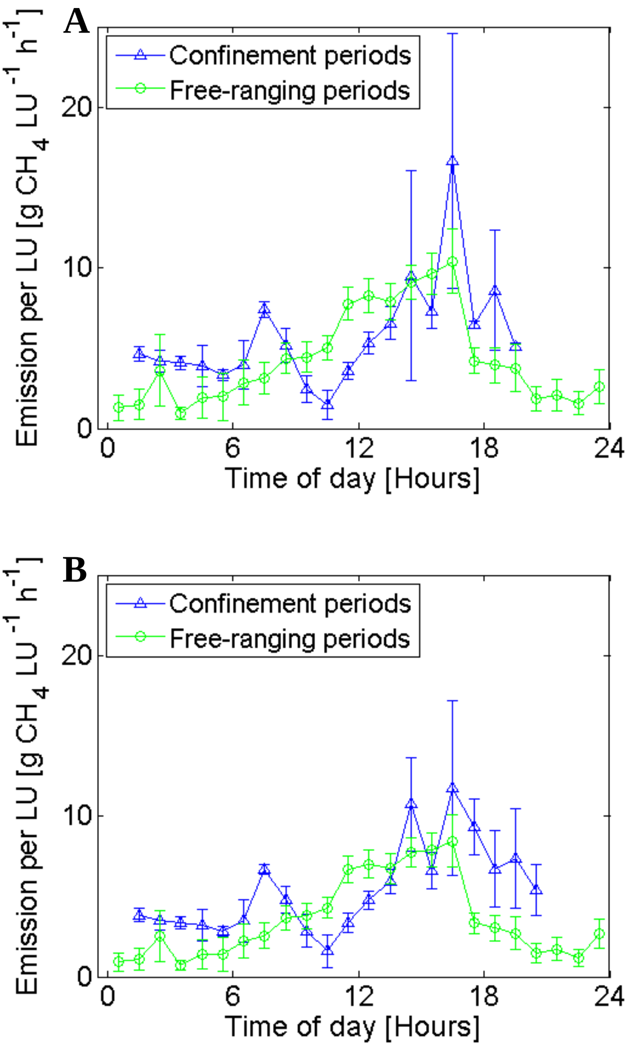

Figure 2-10: Average diurnal course of methane emissions per livestock unit during free-ranging periods (squares) and confinement events (triangle) calculated using (A) the KM and (B) the KJ footprint model. Error bars correspond to standard errors of the mean. Time is given in local time without daylight saving time (UTC+1).

3.4. *GRASSLAND EMISSIONS AND METHANE BUDGET OF THE PARCEL*

During rest periods, the mean flux was of 1.09 nmol m^{-2} s^{-1}. However the median was of only 0.39 nmol m^{-2} s^{-1}, indicating a dissymmetrical flux distribution, due to sporadic high fluxes. Linear correlations between methane fluxes and main environmental variables (soil temperature at 5, 25 and 50 cm, air temperature, soil moisture at 5, 25 and 50 cm, air relative humidity, methane dry molar fraction, footprint length and global radiation) were tested for various periods (growing season, winter and whole year)[1]. However, despite being sometimes significant, only very poor relationships were observed ($R^2<0.02$, data not shown). As soil moisture and temperature are often considered to be the most important methane fluxes drivers for temperate grasslands (e.g., van den Pol-van Dasselaar et al. (1998) and Grosso et al. (2000)) a combined effect of both variables was also sought by working with classes, without success.

Finally, on the basis of cattle and grassland emission estimates, annual cumulated fluxes may be assessed at the parcel scale. With this aim, missing data (80% of the data) were gap filled using the relationships between methane fluxes and stocking density established above. For 2013, the cumulated fluxes amounted to 10.6 (KM) and 8.8 (KJ) g CH_4 m^{-2} $year^{-1}$ during grazing periods and to 0.3 g CH_4 m^{-2} $year^{-1}$ during rest periods (similar for the two footprint models).

4. DISCUSSION

4.1. *ENTERIC EMISSIONS*

The proportionality between methane fluxes and stocking density as well as the reduced dispersion of this relationship suggest that the hypothesis of homogeneous cattle distribution in the pasture is reasonably met at the grazing season scale and that defensible estimates of methane emission per LU can be obtained. These findings are particularly promising because they were obtained *in situ* with minimal influence on cattle activity. The sole intrusion was the presence of a mast placed in the center of the pasture and a reduction of the available area to 1.7 ha during the short-duration confinement periods. This method provided estimates of methane emissions per LU in the range of 104 to 134 g CH_4 LU^{-1} $year^{-1}$. Considering the measured dry-matter intake of 7.6 kg day^{-1}, these results correspond to emission levels between 13 to 17 g CH_4 kg DMI^{-1}.

So far as we know, only one other study has measured methane emissions from the Belgian Blue cattle breed (Mathot et al., 2012). They found emissions ranging between 8 and 25 g CH_4 kg DMI^{-1} (63 and 175 g CH_4 LU^{-1} day^{-1}) with 20-month-old

[1] While more complex relations might be expected, only linear relations were looked for. However, at first sight, a scatterplot did not reveal any relation at all.

heifers weighing about 440 kg, put in a tie-stall barn and fed with 37-85% concentrates.

Besides, predictions based on tier 1 and tier 2 IPCC (2006) emission factors, with a default raw energy content of 18.45 MJ kg^{-1} and a default methane conversion factor of 6.5%, were of 156±78 and 164±33 g CH_4 LU^{-1} day^{-1}, respectively. With 104 - 134 g CH_4 LU^{-1} $year^{-1}$ our estimates are all within Tier 1 estimations and below or just at the limit of the range for Tier 2 estimations.

Our approach is however subjected to some uncertainties.

A first one is related to the footprint correction and can either be due to the model choice or to the input parameters. An estimate of the former was obtained by comparing two models, conceptually different, one based on the steady state advection diffusion equation, the other on backward Lagrangian stochastic particle dispersion. Differences between emission estimates per LU amounted to only 3 g CH_4 LU^{-1} day^{-1} for confinement periods but to 22 g CH_4 LU^{-1} day^{-1} (18 % of the flux calculated with KM) for free ranging periods. It was indeed shown (**Figure 2-6**) that the KM model provided larger footprint areas than the KJ model, leading to larger correction factors. The difference between methane emissions per LU estimated by the two tested footprint models was however low considering the differences between footprint functions. The even smaller difference between the two estimates during confinement periods was probably linked with meteorological conditions favoring lower footprint lengths.

Slope sensitivity to footprint model input parameters was also tested and a variation of 10 % in one of the inputs (u_*, measurement height, Monin Obukhov length, wind direction, wind velocity or standard deviation of cross wind speed) led to a difference of less than 5 % in the emissions per LU. Moreover, the combined effect of the application of a 10 % variation in each input led to a maximum difference of 15 % (KM) and 6 % (KJ) in these emissions (data not shown).

Another possible cause of bias is the data selection which leads to an over representation of day periods compared to night periods. However, considering an equal contribution of each available period of the day would lead to lower emissions per LU (KM: 104 g CH_4 LU^{-1} day^{-1}, KJ: 85 g CH_4 LU^{-1} day^{-1}) during free-ranging periods and to slightly higher emissions per LU (KM: 140 g CH_4 LU^{-1} day^{-1}, KJ: 131 g CH_4 LU^{-1} day^{-1}) during confinement periods.

Equipment of cows with embarked activity sensors would help improving these estimates. An experimentation very similar to this paper has already been conducted with Holsteins by Felber et al. (2015) who compared estimated methane emissions per LU considering 3 different options: free-ranging cattle and no footprint correction, confinement with footprint correction, and the combined use of geolocalization devices with a footprint model. All 3 methods delivered comparable results but the uncertainty was reduced when working with more elaborate options (95% confidence interval of 39 %, 8 % and 6 % respectively).

4.2. *GRASSLAND EXCHANGES AND COMPLETE BUDGET*

Grasslands in Europe can behave as methane sources (Dengel et al., 2011; Herbst et al., 2011; Merbold et al., 2014), sinks (Kammann et al., 2001) or both (Merino et al., 2004). At DTO, even during rest periods, the site was a small net methane source with an average flux and standard error of 1.09 ± 0.15 nmol m^{-2} s^{-1} (equivalent to 1.5 ± 0.2 mg CH_4 m^{-2} day^{-1}). This was corroborated by the diurnal methane dry molar fraction pattern during rest periods (**Figure 2-8 A**), which showed that methane was stored in low atmosphere layers during low turbulence periods and suggesting methane production by local sources.

One possible explanation lies in the soil characteristics, as the pasture is mainly grown on colluvic regosols (loam of colluvic origin, (DGARNE, 2015)). Heavy soils (clay or loam) are indeed known to have lower methane oxidation rates and grasslands have lower oxidation rates than arable lands and forests (Boeckx et al., 1997; Schaufler et al., 2010). Cattle presence probably also affects methane fluxes during rest periods through the feces and urine patches that remain on the pasture and soil trampling at some spots creating very specific conditions for local methane emissions (Boon et al., 2014; Saggar et al., 2007).

Overall, we estimated the net annual methane balance of 2013 to 10.9 g CH_4 m^{-2} using KM and to 9.1 g CH_4 m^{-2} $year^{-1}$ using KJ with a mean stocking density of 2.3 10^{-4} LU m^{-2}.

In comparison, a study by (Soussana et al., 2007) involving nine grassland areas in Europe and different measurement techniques reported annual emissions of 6.57 ± 2.05 g CH_4 m^{-2}, with stocking densities varying between 0.12 10^{-4} and 1.32 10^{-4} LU m^{-2}. Moreover, many other publications presented fluxes from grazed peatlands or wetlands. Those ecosystems differ greatly from the one studied in this paper as methane is produced as much by cattle as by soils, making comparisons less straightforward. However, Baldocchi et al. (2012) using the same measurement method and a similar stocking density (2.6 10^{-4} LU m^{-2}), reported 17.47 ± 8.89 g CH_4 m^{-2} $year^{-1}$ for a peatland pasture , of which 11.6 g CH_4 m^{-2} $year^{-1}$ were due to cattle. Those values are in agreement with our results and also confirm that methane fluxes are linked to stocking density. However, none of these authors provided estimates of methane emissions per LU and, in the absence of information about the footprint, possible filtering issues and eddy covariance computation hypotheses, it is not possible to infer them simply from their results.

Random uncertainty was quite small at annual scale (< 1%, assuming an uncertainty of 50 % on every single measurement) due to the random character of turbulence and the long duration of data series. Systematic errors linked with methodological choices in the eddy covariance data treatment (running mean vs block average, cut-off frequency, filter validity, etc) or with non-homogeneous cattle dispersion on the pasture were thought to be greater.

5. CONCLUSIONS

- In this study, the methane budget of a grazed pasture was established on the basis of *in situ* measurements with the attempt to minimize cattle perturbation and to approach real conditions as close as possible. The budget included estimates of cattle emission and grassland exchange.
- For cattle emission, two approaches, both based on the eddy covariance technique, were followed: on the one hand, long term measurements were performed at the pasture during free-ranging periods with varying stocking densities (from 0 to 12 LU ha^{-1}); on the other hand short measurement campaigns were organized during confinement events when the herd was concentrated on a small area in the system footprint (> 25 LU ha^{-1}).
- The first method has the advantage to be non-invasive and to provide emission follow-up during the whole season. However, as animals are moving and emitting methane intermittently (about one eructation every 45 seconds; (Garnsworthy et al., 2012), measurements are highly variable and subjected to biases, especially if animals move out the footprint area. The approach requires thus careful footprint analysis in order to avoid biases, strong hypotheses on herd average repartition in the pasture and can provide realistic estimates only on long term averages.
- The second method circumvents these problems by concentrating cattle in a small zone, supposedly situated in the footprint area, and limiting thus their movements in, from and to the zone. On the other hand it is more invasive, as the confinement is not the usual herd configuration and it could have modified animal behavior. In addition, as the grazing pressure is high during the confinement, grass availability limits necessarily campaigns to a few days. Finally, experiment feasibility depends on the conjunction of grass availability and wind directions compatible with footprint during the whole campaign, conditions which are fulfilled only three or four times a year.
- In our case the two methods gave results that differ by 5 to 30 % according to the footprint model used. Considering that the impact of confinement is less important than footprint variability, our best emission per LU estimate would be 131 - 134 g CH_4 LU^{-1} day^{-1}.
- For grassland exchanges, the eddy covariance technique was also used during rest periods, in the absence of cows. In view of the small flux values, however, a careful footprint analysis was necessary in order to eliminate periods when flux is contaminated by sources external to the footprint area (barn, neighboring grazed pasture). After this filtering, results show that the pasture behaves as a small source. Total balance is however mainly impacted by cattle, 97 % of the emission coming from the cows.
- The present approach and, especially, methane emission by cows during free-ranging periods could certainly be improved. Combination of eddy covariance measurements with cattle geo-localization would reduce uncertainties due to

animal movements. In addition, the placement of motion sensors on cows could allow relating emission intensity with animal activities.

6. ACKNOWLEDGMENTS

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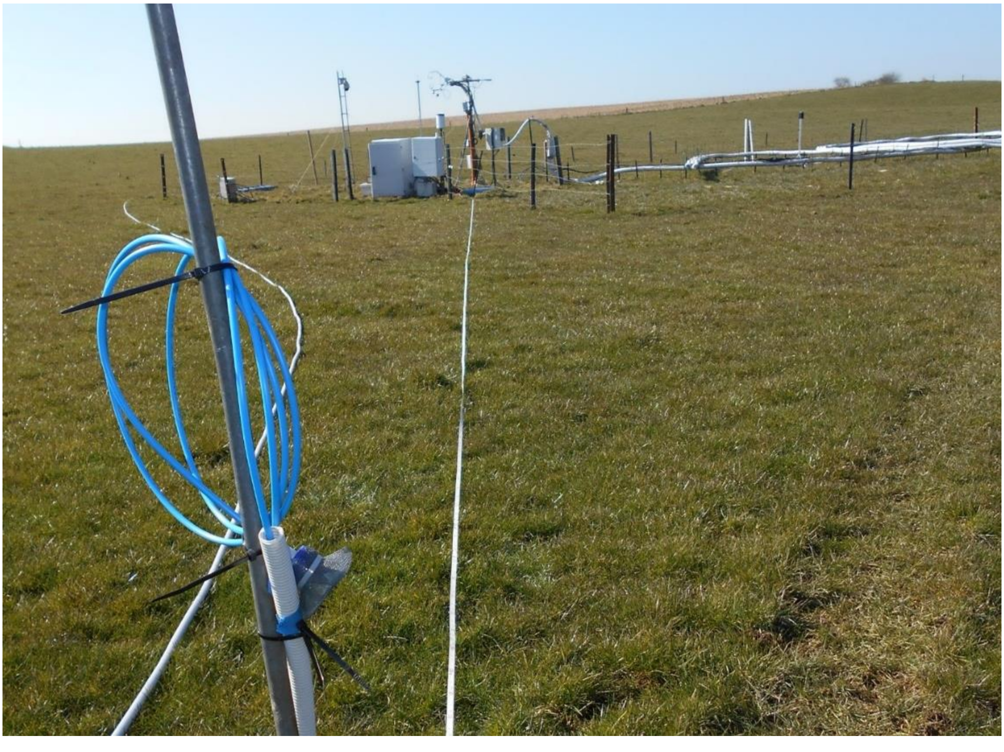
CHAPTER 3

POINT SOURCE EMISSION ESTIMATION USING EDDY COVARIANCE: VALIDATION USING AN ARTIFICIAL SOURCE EXPERIMENT



Chapter 3. Point source emission estimation using eddy covariance: validation using an artificial source experiment

This chapter has been published as:

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Abstract

Eddy covariance is increasingly used to monitor cattle emissions. However, the turbulent flux calculation method and the footprint models upon which calculations are based are insufficiently validated. In addition, available footprint models presume the source to be placed at soil height, which is obviously not the case for cattle. The present study uses a single known artificial point source placed at cow's muzzle height in order to assess the impact of the flux calculation method (averaging method, averaging period, quality filters) and of the footprint model on the emission estimates. The optimal calculation method and footprint model combination (running mean, 15 minutes averaging periods, no application of the Foken & Wichura (1996) stationarity filter, and the use of the Kormann & Meixner (2001) footprint function) led to estimated emissions between 90 and 113% of the true emission, leading to the conclusion that the use of eddy-covariance for point-source emission estimation is feasible provided an adequate calculation method is selected.

Keywords

Eddy covariance; Point source; Footprint; Tracer dispersion; Cattle.

1. INTRODUCTION

The eddy covariance method is one of many methods used to monitor ecosystem gas exchanges. It allows measurement of scalar exchanges between horizontally homogeneous surfaces and the atmosphere (Foken et al., 2012a). Gathered data are typically representative of an area of a few hectares and are typically averaged over a 30 minutes interval. The technique is, for instance, at the basis of monitoring networks (FLUXNET; https://fluxnet.fluxdata.org/, ICOS; https://www.icos-ri.eu/) for CO_2, N_2O, and CH_4 exchanges over various landscapes.

A challenge commonly associated with eddy covariance is that real measurement sites are rarely homogeneous. Therefore, scientists had to identify a footprint area or "effective upwind source area sensed by the observation" (Schuepp et al., 1990) in order to make sense of the measurements. This led to the development of footprint functions weighting the respective contribution of each element of the surface to the measured vertical flux (Rannik et al., 2012). A promising use of footprint models would be to extend the use of eddy covariance to quantify point source emissions, such as methane emissions from livestock or emissions from vents in geothermal areas (Etiope et al., 2007).

Three main issues are raised when estimating point source emissions. Firstly, footprint models are designed for perfectly flat and homogeneous landscapes without any obstacles (hedges, trees, etc.), an ideal situation almost never met for real measurement sites. However, these models are only useful when dealing with heterogeneous surfaces (e.g. two different adjacent crop lands) and remain valid if flux heterogeneity occurs only for "passive" scalars (in the sense of not affecting local stability). Therefore, the question arises whether these models are accurate enough to be used for extreme cases of heterogeneity like point sources (Leclerc and Foken, 2014). Secondly, Footprint models are designed for sources emitted at soil height (or at least below the displacement height) while cattle emit methane at muzzle height, typically around 80 cm[2]. To our best knowledge, no information about the impact of the release height on the eddy covariance footprint is yet available in the literature. Thirdly, the eddy covariance method is based on the assumption of stationarity of the time series, while point source emissions are only intermittently present in the footprint, due to wind characteristics (direction, speed, stability) variations within one averaging period. The assumption of flux stationarity is thus breached and it is unclear how well the covariance of the scalar concentration and the vertical wind component is representative of the true flux (Foken et al., 2012a). The present study is thus designed in a pragmatic way in order to tell how much the available tools can be "abused" in order to correctly estimate methane emissions despite methodological issues.

Cattle methane emissions in a pasture represent an interesting application for point source emission measurements. These emissions are of great importance for the greenhouse gas balance of grasslands yet their field measurement is challenging (Harper et al., 2011). Felber et al. (2015) have used eddy covariance to estimate methane emissions from a grazing herd. Over 7 months, all 20 cows grazing on a pasture divided into 6 sub-plots were located using GPS trackers, while methane fluxes were measured using eddy covariance. Cattle contribution to the footprint was then estimated using the Kormann & Meixner (2001) footprint model and combined with the measured flux to obtain cows' emissions. While estimated emissions should be independent from the distance between the source and the mast, Felber observed lower and less plausible estimated emissions when cows were located in a sub-plot

[2] Muzlle height does vary according to cattle behavior and is often found below 80 cm. When cattle are grazing their muzlle is typically less than 10 cm above ground. When cattle are idling, they are often lying down, bringing their muzzle to a height of about 40 cm. Finally, when cattle are standing their muzzle is found at a height of about 80 cm.

further away from the mast (> 50 m), revealing a weakness in the approach. Coates et al. (2017) renewed the experience but with artificial known and constant methane sources scattered across a paddock, at an height of 0.8 m, in order to mimic animal distribution. Emissions were estimated using a Lagrangian stochastic footprint model for two distances between the mast and the paddock: 5 and 55 m. The results showed again an impact of distance between the source and the mast on estimated emissions. Emissions were overestimated when sources were close from the mast while correct when further away.

Moreover, while the study from Felber et al. (2015) was lacking a true reference emission, the study from Coates et al. (2017) was based on known and constant methane sources, authorizing investigation of methodological sources of uncertainties. However, the sources were distributed almost homogeneously on the field leading to a situation very close to an area emission, which reduced the importance of the accuracy of the footprint model. Heidbach et al. (2017) built on this research by estimating methane emission from a single point source placed at grass level at 20 or 35 m from the mast. In this case, four different footprint models were compared: Kormann & Meixner (2001), Kljun et al. (2015), Hsieh et al. (2000), and Schmid (1994). The conclusion once again was that most models overestimate emissions from points close to the mast (distance = 20 m). The notable exception was the Kljun et al. (2015) footprint model which performed very well at all distances.

Additional studies are required to validate the results from Heidbach et al. (2017) for different sites, source heights and distances between the mast and the source. Moreover, while efforts have been made for testing footprint models, little interest has yet been given to the impact of point source characteristics on the flux calculation method (potential un-stationarity). The purpose of this paper is therefore to validate the ability of the eddy covariance method to estimate methane emissions from cattle. For this purpose, a single artificial point source, placed at different distances from the mast at cattle muzzle height (0.8 m) was used. The use of a single source constitutes a worst case because it increases the risks of methodological difficulties when computing fluxes and requires high accuracy of the footprint function. Two major challenges are addressed: (i) identification of the flux calculation method (averaging method, averaging period, quality filters) which is best suited for point source emission estimation, and (ii) selection of a footprint model which could deliver results consistent with the real emission rate for all tested distances between the source and the mast.

2. MATERIALS & METHOD

2.1. *SITE DESCRIPTION*

The experiment took place at the Dorinne Station (50˚ 18’ 44.00” N; 4˚ 58’ 7.00” E.), a 4.2 ha grazed grassland located in Belgium. The eddy-covariance mast was placed in the center of the grassland. The pasture is entirely surrounded by other grasslands except in the south-west (main wind direction) where a crop field is present. Data were only gathered during the rest season, when no cattle were present on the grassland and when grass height was of approximately 5 cm. During the 2016 measurement period (winter and early spring), this latter parcel was covered with remains of mustard (grown as a catch crop). During measurements in 2017 (winter and early spring), it bore winter wheat. The grassland has a gentle slope (0 to 5°)[3] from the south-west (higher part) to the north-east (lower part) and a barn was located approximately 350 m to the north-east of the mast. Additional information about the site can be found in Gourlez de la Motte et al. (2016).

2.2. *EXPERIMENTAL SETUP*

Methane fluxes exchanged in the pasture were measured continuously using a fast CH_4 analyzer (PICARRO G2311-f, PICARRO Inc., USA) and a sonic anemometer (CSAT3, Campbell Scientific Ltd., UK) placed 2.6 m above ground. Additional information about the instrumentation, filters, tube dimensions, and calibration frequency can be found in Dumortier et al. (2017a).

An artificial methane point source was deployed in the field during three measurement campaigns: at 23 m north-east of the mast from March 17 to 23, 2016 (23 NE), at 60 m south-west from March 29 to April 5, 2016 (60 SW), and at 80 m south-west from February 23 to April 5, 2017 (80 SW). The 23 m distance corresponds to the mean peak footprint contribution using the Kormann & Meixner (2001) footprint model. The two other distances were chosen to represent a panel of distances found within the pasture, the closest and furthest borders of the pasture being 80 and 180 m away from the mast, respectively. The selected distances were thus representative of usual cow positions. During each campaign the artificial source was placed in the forecasted main wind direction in order to maximize data collection.

Bottles containing pure methane (N25 bottles, 99.5 % CH_4, Air Liquide, Liège, Belgium) were placed at the center of the grassland and were connected to an outlet situated approximately 80 cm above the ground (average cattle muzzle height) at the chosen distance and direction from the eddy covariance mast. The methane flow was regulated at 1544 ± 15 g day^{-1} (1.5 standard liters per minute) by a pressure regulator (HBS200 3−2.5, Air Liquide, Liège) and a mass flow controller (Brooks 5850E, Brooks Instrument LLC, PA, USA), an emission that corresponds to approximately nine adult meat cows. In order to reduce methane consumption, the system was programmed to emit methane only when winds were coming from the artificial source direction (± 45°), and when u_* was above 0.13 m s^{-1} in the previous 15 minutes.

2.3. *SOURCE EMISSION QUANTIFICATION*

Turbulent fluxes were calculated using EddyPro® version 6 open source software (Li-Cor Inc., Nebraska, USA). However, as point sources can cause sudden fluctuations in measured methane concentration (**Figure 3-1**), which is not in

[3] Errata : 0 to 5 %

accordance with the stationarity hypothesis behind eddy-covariance, different flux computation methods were tested. The following computation parameters were modulated to calculate fluxes:

- Averaging method: In addition to the traditional block averaging method (BA) an auto-regressive method (moving average using a time constant of 120 s, MA120) was tested. The auto-regressive method consists of replacing the block average by a moving average (or running mean) in the covariance computation.
- Averaging period: Fluxes and footprints were computed using an averaging period of 5, 15, or 30 minutes.
- Quality filters: While the Foken & Wichura (1996) stationarity test (using a 30% threshold) is widely applied to surface fluxes, the relevance of flux filtering using this "stationarity test" should be verified for point source emissions. The quality of the fluxes before and after this filtering step was therefore also investigated.

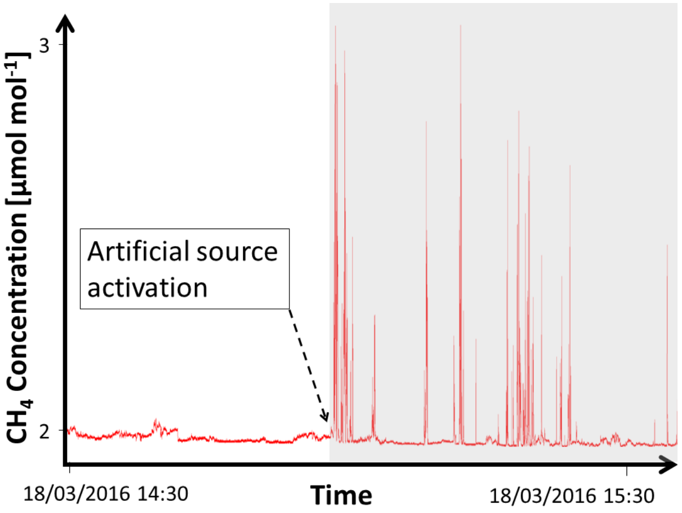

Figure 3-1: Methane concentration evolution before (no shading) and after (shading) activation of the artificial source.

For all flux calculations, time lags were calculated using a covariance maximization method with a default value of 2.3 s and a window size of 1 s (71% of the records were found within this time window for methane). Time lag values outside this window were not accepted as they were considered unrealistic. Frequency correction was applied using an *in situ* spectral correction method (Fratini et al., 2012), following the procedure of Mamadou et al. (2016). Data were also filtered on the basis of friction velocity, using a u_* threshold of 0.13 m s^{-1} (Dumortier et al., 2017a; Gourlez de la Motte et al., 2016), and integral turbulence characteristics according to the method proposed by Foken & Wichura (1996) and using a threshold value of 30% in order to only keep well developed turbulent conditions. Among the statistical tests for raw data screening proposed by Vickers & Mahrt (1997a) some choices were made. The spike filtering, drop-out, absolute limit, and discontinuities tests were applied using the default settings proposed by EddyPro®. Those tests removed less than 3% of the dataset. On the other hand, amplitude resolution, skewness and kurtosis tests were disabled as they deleted almost all periods involving an artificial source in the footprint (the test failure was probably due to real emission peaks).

Emission per source was computed by combining turbulent flux measurements with source positions through the use of a footprint function. According to the definition of the footprint function, we have:

$$F_X = \sum_i \sum_j F_{ij} \phi_{ij} \Delta x_{ij} \Delta y_{ij} \qquad \textbf{Equation 3.1}$$

where F_X is the measured flux density of the scalar X (nmole m^{-2} s^{-1}), F_{ij} is the flux density from the cell ij (nmole m^{-2} s^{-1}), ϕ_{ij} is the value of the footprint function in the cell ij (m^{-2}), and Δx_{ij} and Δy_{ij} are the x and y-size of the cell ij (m).

As only one cell contains a source, we can consider that **Equation 3.1** can be shortened as follows:

$$F_X = F_{ij,source}\ \phi_{ij,source}\ \Delta x_{ij}\ \Delta y_{ij} \qquad \textbf{Equation 3.2}$$

where $F_{ij,source}$ is the flux density from the cell containing the source (nmole m^{-2} s^{-1}) and $\phi_{ij,source}$ is the value of the footprint function in the cell containing the source (m^{-2}).

If we introduce f_X, the emission per source (nmole s^{-1} $source^{-1}$), we can write:

$$F_{ij,source} = f_X / (\Delta x_i \Delta y_j) \qquad \textbf{Equation 3.3}$$

Combining (2) and (3) gives:

$$F_X = f_X\ \phi_{ij,source} \qquad \textbf{Equation 3.4}$$

And therefore allows the emission per source (f_X) to be computed using:

$$f_X = F_X / \phi_{ij,source} \qquad \textbf{Equation 3.5}$$

where the denominator, ϕ_{source}, corresponds to the source contribution to the footprint.

The footprint function (ϕ) was calculated according to two different footprint models: an analytical footprint model described by Kormann and Meixner (2001) (KM) and a flux footprint prediction tool (FFP) based on backward Lagrangian stochastic particle dispersion developed by Kljun et al. (2015). Two input parameters required for FFP had to be estimated. The boundary layer height (h) was considered to be equal to 1500 m during daytime and to 300 m during night time. This rough estimation was sufficient as the resulting ϕ_{source} was only very weakly impacted by the boundary layer height, probably because most stable situations were eliminated by the u_* and integral turbulence characteristic filters. The aerodynamic roughness length (z0) estimation was more challenging as it had a major impact on FFP outputs (estimated emission variation of up to 17% for z0 values ranging from 6 to 20 mm). According to the literature, typical z0 values should be found between 6 mm and 2 cm for a pasture (Stull, 1988). However, Graf et al. (2014) describe a combination of z0 estimation methods which, when applied to our site (grass height of approximately 5 cm), resulted in estimates between 8 mm and 4 cm according to the method. After some testing a z0 value of 8 mm was selected as it appeared that lower z0 inputs were associated with more coherent emission estimates (higher precision and reproducibility, see **Table 3-1**) while z0 values lower than 8 mm were considered as unlikely. Moreover, both footprint models were designed to estimate the contribution of emission sources placed at soil height, with no flexibility being given to investigate the impact of source height in relation to the ground. To our best knowledge the impact of this factor has not yet been quantified and will not be considered in this publication.

Finally, the source emission and the associated uncertainty was estimated by the slope of the linear regression between measured F_{CH4} and computed ϕ_{source}, according to **Equation 3.4**. The linear regression was calculated by the linear least square method, a method which is valid if the x-axis (ϕ_{source}) is considered as known exactly and if the uncertainty is attributed to the y-axis (F_{CH4}) only (Webster, 1997). In the present work ϕ_{source} is indeed calculated according to a chosen calculation method whose input (mast position, source position and wind characteristics) are known with sufficient precision. This method provides only one emission estimate for each campaign but has the advantage of reducing the bias caused by potential background fluxes. Two situations can be considered. When background fluxes are uncorrelated with ϕ_{source} (e.g. soil emissions), these background fluxes will only affect the intercept and will have no impact on the slope of the regression curve. In this case, estimating the source emission with this method is more robust than computing it on individual points and calculating the average. When background fluxes are correlated with ϕ_{source} (e.g. localized contamination such as manure piles) the intercept and the slope of the regression curve are both affected. In this latter case, the target source estimation will unavoidably be biased to a degree, depending on the magnitude and source position of the background fluxes.

Different options to estimate f_{CH4} were considered: 2 footprint models, 3 averaging periods, 2 averaging methods, and 2 modalities of stationarity test (application or not). In order to select the most appropriate emission estimation method, each of the 24 tested combinations was associated with a performance score indicating its accuracy (closeness to the real emission), reproducibility (homogeneity of emissions between campaigns), and the quality of the relation between F_{CH4} and ϕ_{source} (R^2 of the linear least square regression). Those scores were computed using:

$$Accuracy\ score = 0.25 \sum 1 - \frac{x - x_{min}}{x_{max} - x_{min}} \qquad \textbf{Equation 3.6}$$

$$Reproducibility\ score = 1 - \frac{x - x_{min}}{x_{max} - x_{min}} \qquad \textbf{Equation 3.7}$$

$$Precision\ score = 0.25 \sum \frac{x - x_{min}}{x_{max} - x_{min}} \qquad \textbf{Equation 3.8}$$

where x is the tested parameter described in **Table 3-1**. **Equation 3.6** to **3.8** allowed to attribute to each combination a score between 0 (worst score) and 1 (best score). The accuracy and precision scores are calculated as the sum of 4 scores (each three campaign + all 3 campaigns together) and are thus divided by 4. Finally, the total performance score corresponds to the sum of the accuracy, reproducibility and precision scores, therefore capping to three.

Table 3-1: Performance score calculation method.

	Accuracy score	Reproducibility score	Precision score
Tested parameter	$\lvert f_{estimated} - f_{emitted} \rvert$	$\sigma^2_{f,estimated}$	R^2 of the linear regression
Application	For each campaign + all 3 campaigns together	For all campaigns	For each campaign + all 3 campaigns together
Maximum total score	1	1	1

3. RESULTS & DISCUSSION

3.1. *CONTAMINATION BY UNCONTROLLED SOURCES*

A precedent study run on the site by Dumortier et al. (2017a) revealed that measured methane fluxes were impacted by the barn; a strong methane emitter which was situated approximately 350 m to the north-east of the mast. The same phenomenon was observed during this study. However, as only wind directions from the artificial source direction ± 45° were kept, methane emissions from the barn direction were as a matter of fact discarded from the dataset during the 60 SW and 80 SW campaigns. Moreover, during the 23 NE campaign mean methane fluxes reached 538 nmol m^{-2} s^{-1} when the wind was coming from the north-east and were thus much higher than the mean measured methane fluxes in the absence of cattle or active artificial sources, which was below 30 nmol m^{-2} s^{-1} for all wind directions (**Figure 3-2**). Therefore, even during the 23 NE campaign (source placed in the barn direction) the impact of the barn on the estimated artificial source emissions was considered to be limited. The barn had thus almost no impact on estimated f_{CH4} during these campaigns.

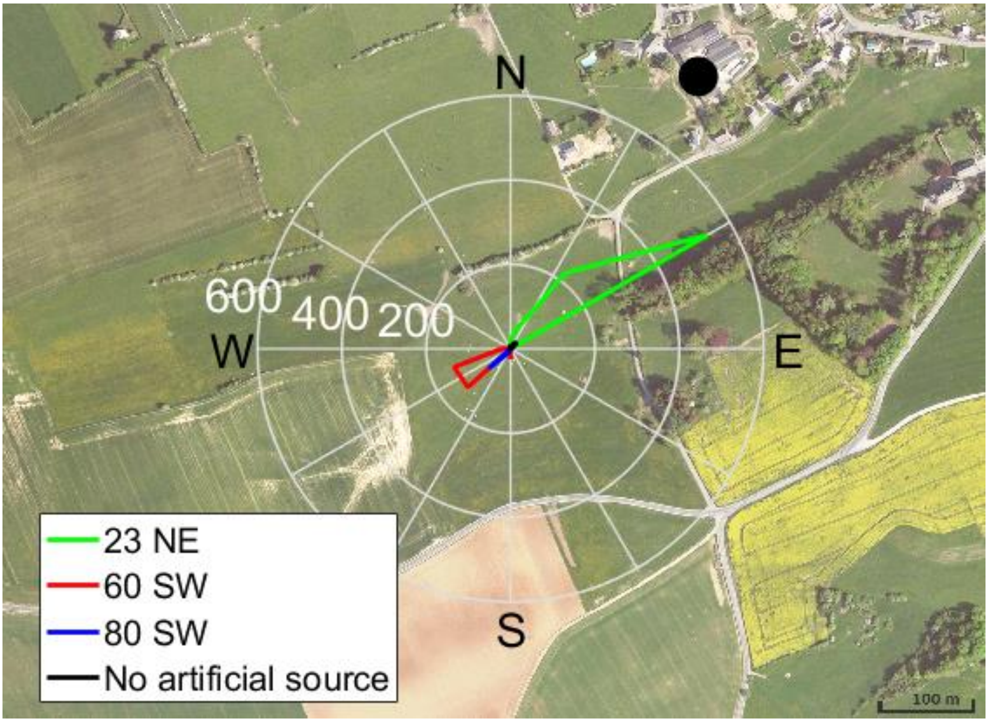

Figure 3-2: Mean measured methane flux (nmol m^{-2} s^{-1}) during each campaign according to wind direction, overlaid on the map of the site. The 23 NE, 60 SW, and 80 SW campaigns only include periods with an active artificial source. The no artificial source line refers to data collected a few days before, during (with inactive artificial source), and a few days after each campaign. The dark spot indicates the barn location.

3.2. *METHANE EMISSION ESTIMATION*

For each emission estimation method a performance score (see Section 2.3) was calculated. The performance score of each combination (**Table 3-2**) indicates that the best suited combination for emission estimation was obtained by using the running mean method on a 15 minutes averaging period, without application of a stationarity test, and using the KM footprint model. In these conditions, when considering all campaigns together, estimated emissions (± 95% confidence intervals) were of 1502 ± 78 g CH_4 day^{-1}. The real emission was of 1544 ± 15 g CH_4 day^{-1} which is within the uncertainty range of the estimates.

For comparison, the estimated emissions using FFP would range from 748 ± 142 (BA, 30 minutes, with stationarity test) to 1386 ± 88 g CH_4 day^{-1} (BA, 5 minutes, with stationarity test) according to the selected calculation method. The dependency of the estimated emissions according to the calculation method (footprint choice, averaging interval and averaging method) will be further examined in the next sections.

Table 3-2: Performance indicators for each of the 24 tested computation methods. The 24 combinations correspond to two footprint models: the one from Kormann and Meixner (2001) and a flux footprint prediction tool (FFP) developed by Kljun et al. (2015) raging (BA) and moving average using a time constant of 120 s (MA120) The combination associated with the higher performance score is highlighted in light grey.

Footprint Model	Averaging Interval	Averaging Method	Stationarity Test	Accuracy	Reproducibility	Precision	Total
KM	5	BA	N	0.8	1.0	0.3	2.1
KM	5	BA	Y	0.8	1.0	0.5	2.2
KM	5	MA120	N	0.9	1.0	0.3	2.2
KM	5	MA120	Y	0.7	1.0	0.4	2.2
KM	15	BA	N	0.8	0.9	0.8	2.5
KM	15	BA	Y	0.8	0.9	0.7	2.4
KM	15	MA120	N	0.9	1.0	0.8	2.7
KM	15	MA120	Y	0.9	1.0	0.6	2.5
KM	30	BA	N	0.6	0.9	0.8	2.3
KM	30	BA	Y	0.5	0.8	0.7	2.0
KM	30	MA120	N	0.7	1.0	0.9	2.6
KM	30	MA120	Y	0.7	1.0	0.7	2.4
FFP	5	BA	N	0.4	0.6	0.2	1.2
FFP	5	BA	Y	0.4	0.5	0.3	1.3
FFP	5	MA120	N	0.5	0.7	0.1	1.3
FFP	5	MA120	Y	0.5	0.6	0.2	1.3
FFP	15	BA	N	0.4	0.6	0.5	1.6
FFP	15	BA	Y	0.4	0.6	0.4	1.4
FFP	15	MA120	N	0.5	0.7	0.5	1.7
FFP	15	MA120	Y	0.4	0.7	0.3	1.4
FFP	30	BA	N	0.2	0.2	0.6	1.0
FFP	30	BA	Y	0.0	0.0	0.4	0.5
FFP	30	MA120	N	0.5	0.8	0.5	1.8
FFP	30	MA120	Y	0.4	0.7	0.4	1.6
			Maximum	1	1	1	3

3.2.1. Footprint calculation method

The footprint calculation method had a major impact on estimated emissions. Systematically, the use of the FFP tool led to less accurate, less reproducible, and less precise emissions than the use of the KM footprint model (**Table 3-2**). The difference is obvious when comparing the relation between measured methane fluxes and ϕ_{source} for both footprint models (**Figure 3-3**). While all regressions fit for the KM footprint model, each campaign leads to a different regression line when using FFP. A closer look at the footprint functions (**Figure 3-4**) explains the difference between the footprint models. The FFP tool presents its contribution peak at shorter distances than the KM footprint model, resulting in higher contributions for sources close to the mast and lower contributions for sources further away, relative to the KM footprint function (**Figure 3-3**).

The difference of behavior between the two tested footprint models is well known and has recently been discussed in the literature (Arriga et al., 2017; Heidbach et al., 2017; Kljun et al., 2015; Prajapati and Santos, 2017). While Arriga et al. (2017) and Prajapati & Santos (2017) could not identify the best suited model, Heidbach et al. (2017), in a similar artificial source experiment but with the artificial emission released at soil level, found better correlations between ϕ_{source} and fluxes when using FFP rather than KM, contrary to our results.

Several hypotheses concerning the different efficiencies of footprint models between studies can be proposed. The first is that the difference is linked to the topography of the site. However, this hypothesis is unlikely as different source directions (north east and south west) were tested. A second hypothesis is that Heidbach et al. (2017) only works with relatively short distances between the mast and the source (less than 35 m) and that the results would not be the same for larger distances. However, as the shapes of the footprint function at short and large distances are correlated, this hypothesis seems unlikely too. A third hypothesis is that in the present study the artificial source is at a height of 80 cm, a significant fraction of the measurement height (2.6 m), while the models expect a source at ground level, thereby impacting the footprint function. To our knowledge, no quantitative information about the impact of the release height on the footprint function is available in the literature. However, if the source is placed at a higher level, two options can be considered:

-The smaller vertical distance to bridge between the source and measurement height will result in a footprint peak being higher and closer to the mast. This information is in agreement with a publication from McGinn et al.(2011) based on the concentration footprint

-Particles would travel much faster from the start, as wind speed and velocity fluctuations are higher when higher up. This would increase the extent of the footprint and move the peak further away from the mast and reduce the peak intensity.

Considering the present measurements, pushing the footprint peak further away from the mast would have a negative impact on the KM performance (as the model is performing well without considering the source height), and a positive impact on the FFP performance (**Figure 3-4**) as ϕ_{source} would decrease for the 23 NE campaign and increase for the other campaigns. The more coherent ϕ_{source} estimates delivered by the KM footprint model might thus be the result of two opposing errors, an imprecision of the footprint model and a source release height which is not properly considered. However, in the absence of available tools incorporating the effect of the source height we selected, in a very pragmatic way, the KM model due to its better performance in our specific situation, regardless of the origin of the good relation obtained in **Figure 3-3 A**.

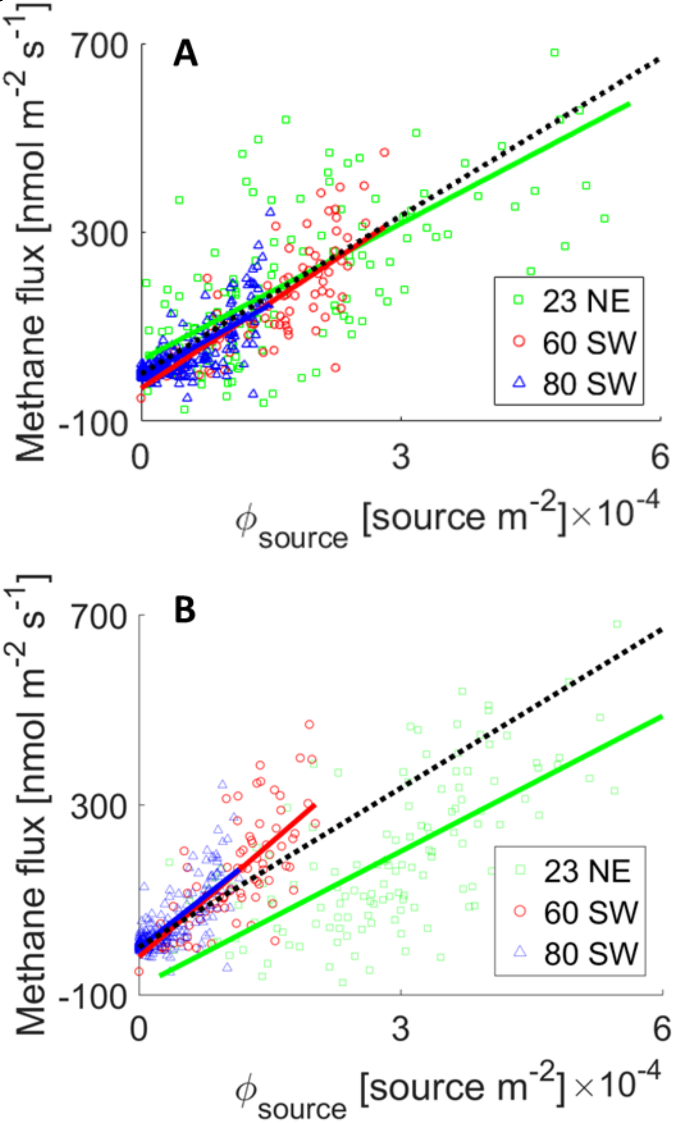

Figure 3-3: Measured methane fluxes (F_{CH4}) according to the source contribution to the footprint (ϕ_{source}). Each point corresponds to a 15 minutes integration period and is represented only when the artificial source is emitting. ϕ_{source} values were calculated using the KM (Kormann and Meixner, 2001) footprint model (A) or the FFP (Kljun et al., 2015) tool (B). Solid lines correspond to the linear least square regression line and the dotted line

corresponds to the expected relation (intercept of 0 and slope equal to the real emission). Fluxes were calculated using a running mean and without application of the Foken & Wichura (1996) stationarity test.

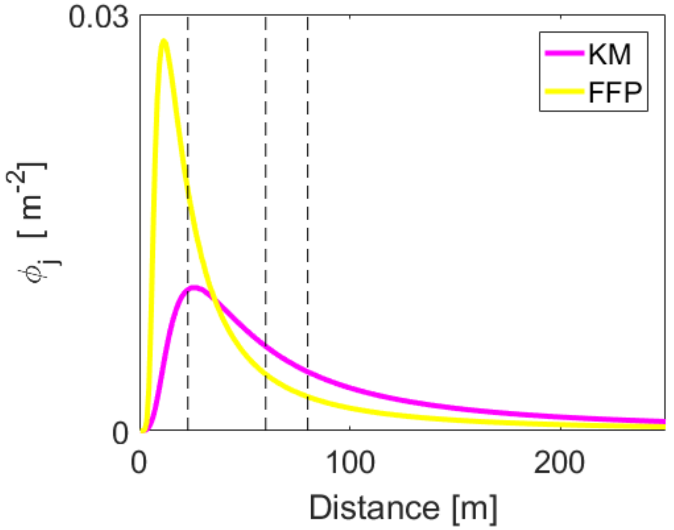

Figure 3-4: Crosswind integrated footprint function (ϕ_j) averaged over all three campaigns using the KM footprint model or the FFP tool. Dashed lines indicate tested distances (23, 60, and 80 m).

3.2.2. Averaging period

Measuring point sources questions the relevance of working with 30 minutes averaging periods. Considering that the artificial source, although static, is moving in the footprint (or that wind velocity and direction are changing over time) a lower averaging period might seem more appropriate (Coates et al., 2017; Felber et al., 2015). At the same time, footprint estimation methods are based, among other factors, on the covariance of the wind velocity vertical and horizontal components which implies the use of a sufficient averaging period. The results given in **Table 3-1** indicate the best compromise and show that better performance scores were associated with the 15 minutes averaging periods.

However, the better performance of 15 minutes averaging periods was not linked to the averaging period length itself but rather to the fact that, according to the length of the averaging period, other quality tests (stationarity test, u_*, wind direction, or integral turbulence characteristics) removed different data, leading ultimately to different data sets (e.g. if u_* decreases during a half hour the whole half-hour might be kept while at a 15 minutes scale only the first part of the half-hour is kept). When the same data sets were considered (i.e. limited to the data which were accepted for all averaging period durations), the impact of averaging period length no longer appeared (flux variation smaller than 4%). On this basis, and in agreement with literature (Coates et al., 2017; Felber et al., 2015) the 15 minutes averaging period was considered to be the most adequate compromise.

3.2.3. Averaging method

The choice of the averaging method had an impact on the measured methane fluxes and thus on the estimated emissions (**Table 3-2**). Performance indicators were systematically higher using an autoregressive filter, such as the moving average, rather than the classic method (BA with stationarity filtering). Although auto-regressive filters are not recommended for classical eddy covariance measures (Rebmann et al., 2012), in this particular case they perform better than block average because they can avoid biases linked with background trends in concentration (Gash and Culf, 1996), which are more frequent here due to the sporadic presence of the artificial methane source in the footprint (**Figure 3-1**). The use of a moving average is thus advised when working with point sources, while BA is advised when working with relatively homogeneous sources. As a result, the choice of the averaging method had little impact on CO_2 and H_2O fluxes (data not shown) while it had an impact on methane fluxes.

3.2.4. Quality filters

The standard eddy covariance protocol involves a filtering step in order to remove measures associated with un-stationarity. However, as discussed by Dumortier et al. (2017a), as the Foken & Wichura (1996) stationarity test is based on the relative variation of the flux, it more frequently discards small fluxes (close to zero) than large fluxes associated with large methane concentration variations, which leads to a bias in f_{CH4} estimates (Dumortier et al., 2017a; Sparks and Toumi, 2010). This removal of small methane fluxes independently of ϕ_{source} generally resulted in an increase of f_{CH4} (for 5 out of 6 combinations) but sometimes increased the intercept of the regression curve, resulting in a decrease of f_{CH4} (for 1 out of 6 combinations). The proposed alternative to overcome this bias was to work with a running mean which allowed the reduction of stationarity biases and therefore removed the need for a stationarity test. Moreover, this option was always associated with the highest performance scores (**Table 3-2**).

The selected option to estimate methane emissions was thus the combination of the KM footprint function with methane fluxes measured using a running mean over a 15 minutes averaging period without stationarity filtering.

3.3. *SENSITIVITY ANALYSIS*

Quality checks were run to make sure that the selected option would work in a wide range of situations. This means that the estimated emissions should be insensitive to specific situations such as the distance between the source and the mast, the nature of the turbulence (stable, unstable and neutral conditions), or the angular deviation between the source and the wind direction. To analyze these parameters, we divided our data into subsets containing the same amount of samples and presenting increasing values of the parameter of interest.

The homogeneity of methane emission across campaigns, and thus across distances between the mast and the source, was already used as a selection criteria to choose the optimal methane emission estimation method. As a result the distance between the mast and the source had only little impact on f_{CH4} with emissions (± 95 % confidence interval) of 1398 ± 214, 1738 ± 271, and 1421 ± 113 g CH_4 day^{-1} for 23 NE, 60 SW, and 80 SW campaigns respectively (**Figure 3-5A** and **B**). Nevertheless the real emission was slightly outside the 95% confidence interval for the 80 SW campaign. This is mainly due to a reduced confidence interval for this distance.

Footprint models are based, among other factors, on friction wind velocity (u_*) and on the stability of the atmospheric surface layer (Kljun et al., 2015) which can be estimated by the stability parameter ((z-d)/L), where z corresponds to the measurement height, d to the displacement height, and L to the Monin Obukhov length. No significant impact of the atmospheric surface layer stability parameter (**Figure 3-5C**) on the mean estimated emission was observed. As a consequence, no difference between day-time (1479 ± 103 g CH_4 day^{-1}) and night-time (1505 ± 131 g CH_4 day^{-1}) emission estimates was observed. On the other hand, emissions were overestimated when u_* was above 0.4 (**Figure 3-5D**). However, filtering emissions to remove data associated with u_* values above 0.4 m s^{-1} did not result in improved performance scores (4.5/6 instead of 5.5/6).

Emissions can only be estimated when the source is in the footprint. However, the footprint might be better defined on some portion of this range. For instance, Heidbach et al. (2017) only calculated an emission when the source was in the wind direction ± 40°. The impact of the angular deviation between the wind and the source direction was observed in **Figure 3-5E**. Estimated emissions were close to the real emission even when the wind was not aligned with the source. This result indicates that the selected option performs well when the source was in the wind direction ± 40°.

Finally, wind direction variations within an averaging period were suspected to have an impact on emissions as they could be linked with a mean (over the averaging period) footprint not representative of the real source contribution. An extreme example of this situation would be a 180° wind direction change during an averaging period. To analyze this parameter, we divided our data into subsets presenting increasing degrees of wind direction variance (**Figure 3-5F**). Wind direction variance had no impact on estimated emissions, indicating that the extreme example described above is not commonly encountered in the field.

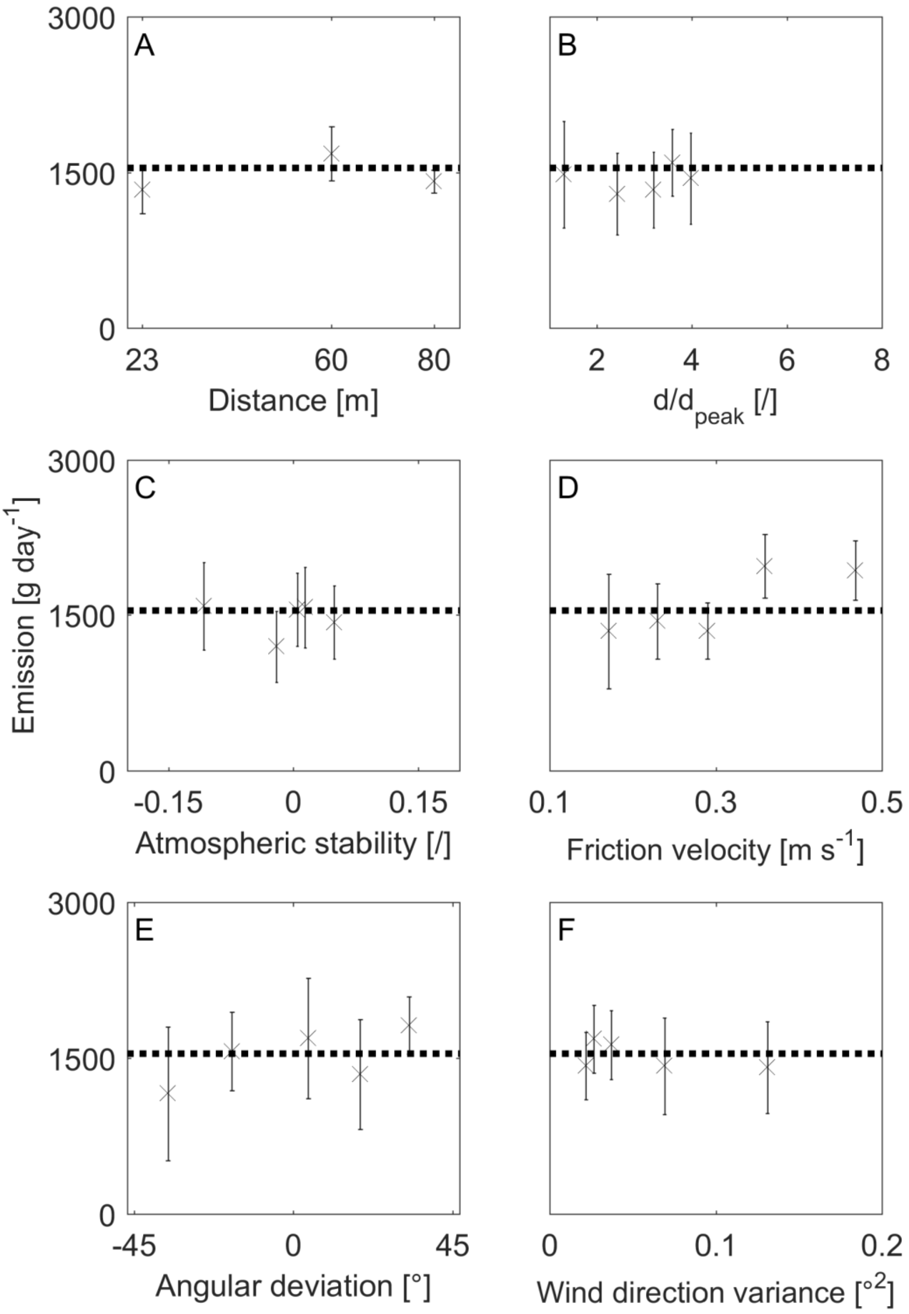

Figure 3-5: Impact of the distance from the mast (A), relative distance to the KM footprint peak (B), atmospheric stability parameter (z-d)/L) (C), friction velocity (u_*) (D), angular deviation between the source position and the wind direction (E), and wind direction variance (F) on the estimated methane emission (f_{CH4}). For each subfigures f_{CH4} was calculated using the best performing calculation method. Atmospheric stability, friction

velocity, angular deviation, wind speed and direction variances are organized in 5 categories containing the same number of samples and plotted at the category mean. The error bars correspond to the 95% confidence interval of the slope. The dotted line indicates the artificial source emission.

4. CONCLUSION

The main goal of this work was to validate the combined use of eddy covariance and a footprint tool in order to estimate cattle methane emissions. Measured fluxes originating from an artificial point source were subject to large variations, even in the presence of unchanging meteorological conditions. Nevertheless, the slope of the relation between the measured methane flux and the source contribution to the footprint allows estimation to be made of point source emissions (**Equation 3.4**).

Among the tested options to estimate methane emissions the best choice proved to be the use of the running mean over 15 minutes averaging periods without application of the Foken & Wichura (1996) stationarity filter associated with the Kormann & Meixner (2001) footprint model. This method led to estimated emissions between 90 and 113% of the true emission, despite the fact that we tested a worst case, with a single point source. The true emission rate was found inside the 95% confidence interval associated with the estimate for two out of three campaigns (23 NE and 60 SW), the 80 SW campaign resulted in an estimated emission slightly outside the confidence interval (less than 1%). Nevertheless, we consider that the eddy covariance technique can be successfully used to estimate methane emission from point sources when working with averages over periods longer than few weeks.

The FFP tool developed by Kljun et al. (2015) did not work as well as the KM footprint model in this case and led to an overestimation of methane emissions, especially for long distances between the measuring point and the methane source. Both KM and FFP consider a source placed at ground level and not at the actual release height of 80 cm. This element is not trivial as a higher source height might displace the footprint peak distance to the mast. Additional studies would be required in order to quantify the impact of the source height on the footprint function. The present study, in a very pragmatic way, led to the selection of a footprint model (KM) that performs well in the situation of an elevated release corresponding to the average height of a cow’s mouth. This does not indicate that the result would be the same if the source was placed at surface height; prior comparisons (Heidbach et al., 2017; Kljun et al., 2015; van de Boer et al., 2013) might in fact be right and the impact of the released height might cancel some systematic error associated with the KM footprint model.

Unlike the studies from Felber et al. (2016) or Heidbach et al. (2017) no systematic bias was associated with the distance between the artificial source and the measuring point, or with the meteorological conditions. Discrepancies between studies can originate from the impact of source height, as discussed above. The range of tested distances between the mast and the source might also play a role, our focus being on distances larger than the position of the footprint peak. Additional studies would thus be required in order to better understand the impact of the release distance and height on emissions estimates. Ideally, such a study should include distances both shorter and longer than the position of the footprint peak and both elevated and ground-level emissions. More fundamentally, improving footprint models to include the source height as an input would be very useful for the whole community.

The next step would be to estimate emissions from natural, moving, point sources (e.g. cattle). In this study, the source was motionless in the soil referential but, as wind direction and speed varied throughout the averaging interval, the source was mobile in the air referential from which the measurement took place. This indicates that the present technique could be as reliable for moving as for motionless sources. Its use is thus suitable for the estimation of methane emissions from cattle.

5. Acknowledgment

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CHAPTER 4

BEEF CATTLE METHANE EMISSION ESTIMATION USING THE EDDY-COVARIANCE TECHNIQUE IN COMBINATION WITH GEOLOCATION

Chapter 4. Beef cattle methane emission estimation using the eddy-covariance technique in combination with geolocation

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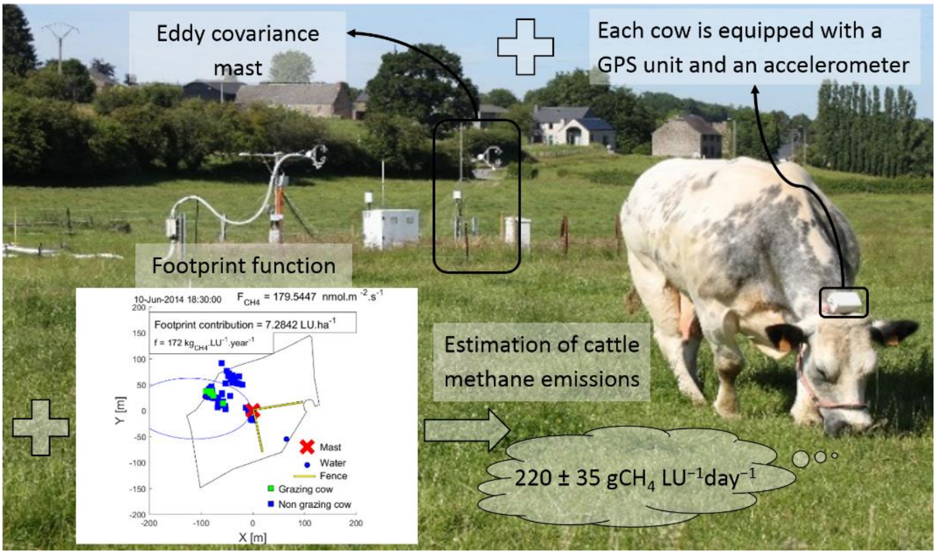
Graphical abstract



Abstract

Methane emissions of a grazing herd of Belgian Blue cattle were estimated per individual on the field by combining eddy covariance measurements with geolocation of the cattle and a footprint model. This method allows the measurement of outdoor non-invasive methane emissions but is complex and subject to methodological issues. Estimated emissions were 220 ±35 g CH_4 LU^{-1} day^{-1} (grams of methane per livestock unit per day), where the uncertainty corresponds to the random error and does not include any possible systematic error. Cattle behavior was also monitored and presented a clear daily pattern of activity with more intense grazing after sunrise and before sunset. However, no significant methane emission pattern could be associated with it, the diurnal emission variation being lower than the measurement precision.

Keywords
Eddy covariance; Cattle; Methane; Footprint; Geolocation.

1. INTRODUCTION

Ruminants are able to digest cellulose which makes them incredibly apt to transform raw forage, like grass, into high quality products. This digestive characteristic is due to an association with a very specific microbial flora present in the rumen or hindgut which allows the transformation of complex plant material into digestible fatty acids (acetate, lactate, propionate or butyrate). However, this transformation is accompanied by the co-production of methane, a potent greenhouse gas, which is mostly released through eructation (Broucek, 2014).

The current standard measurement method for cattle methane emissions is the metabolic chamber. This method calculates a mass balance between methane entering and leaving a sealed ventilated chamber containing an animal. Tracer methods are the major alternative for grazing ruminants; they involve the use of an external (e.g., SF_6 released by an ingested canister) or internal (e.g., metabolic CO_2 emissions) tracer released at a known rate from the animal's rumen. Measuring tracer and methane concentration ratios in excreted gases allows the computation of methane fluxes. Both techniques are accurate with a precision commonly higher than 90%, but require lots of animal handling (Storm et al., 2012b), are rather invasive and could impact the natural grazing behavior of cattle. Emerging methods rely on the use of proxies; they are based on the relationship between methane emissions and the composition of matrices that are easy to sample such as feces or milk (Dehareng et al., 2012; Vanlierde et al., 2018). This method is valid as long as the composition of the proxies and the characteristics of the sampled animals (i.e., breed, intake level, physiological status, etc.) remain within the range of variability of the database that was used to develop the relationship. In addition to these animal-centered approaches, measurement methods have been developed that work at the scale of the environment in which the animals evolve. Some of these techniques simply reproduce lower scale methods (i.e., by considering the barn or the feeding trough as a chamber or by adding a tracer gas in a ventilated barn at a known rate and measuring the methane/tracer ratio) while others involve micro-meteorological methods (Johnson and Johnson, 1995; Storm et al., 2012b). The latter are promising because they allow measurements to be recorded of the emission rate of the whole herd, on the field, with a half-hour time resolution, little animal handling and without disturbing the cow's natural behavior. Among micrometeorological methods, eddy-covariance (EC) is well suited for measurements in a pasture with low cattle density over large areas, and has become more affordable with the release of fast and precise optical methane analyzers. Nevertheless, applying this measurement method to grazed pastures is challenging due to a combination of source complexity (i.e., spatial and temporal variation in animal locations and emission intensities) and limitations in methodology specific to EC (Dumortier et al., 2017b; Wohlfahrt et al., 2012).

Cattle emissions are not constant over time. Most of the CH_4 produced escapes through the mouth, with 83% of emissions associated with eructation and 15% associated with respiration (Hammond et al., 2016). Cattle eruct 15 to 28 times each hour (every 130 to 230 s) according to the composition of their diet, feed intake levels and physiology (Blaise et al., 2018). Moreover, methane emissions vary throughout the day, peaking approximately 2 hours after feeding followed by a decrease until the next feeding event (Blaise et al., 2018). Cattle methane emissions thus present a 24-hour emission pattern which can be related to their feeding behavior (Hammond et al., 2016; Hegarty, 2013).

When using EC, the measured covariance corresponds to the vertical flux at one specific point that is representative of exchanges within the footprint, the area "sensed" by the flux measurement device. This footprint can be modeled through a set of functions that weight the respective contribution of each element of the surface to the measured vertical flux (Rannik et al., 2012), known as a footprint model. However, animals act as moving CH_4 sources which may wander in or out of the footprint. Therefore, fluxes measured through eddy covariance must be combined with a footprint model as well as information about the cattle's location on the pasture in order to estimate the animals' contribution to the measured flux. The ability of this approach to provide reliable emission estimates was previously tested using artificial sources (Dumortier et al., 2019). Previous investigations by Heidbach et al. (2017) showed that the FFP (Flux Footprint Prediction) model presented by Kljun et al. (2015) was the most efficient of the four tested models as long as the artificial source was located further from the mast carrying the sensors than the footprint peak (maximum of the footprint function). One of the main drawbacks of this model is that sources are assumed to be at ground level, while cattle emissions are emitted at muzzle height (i.e., up to 1 m height). To tackle this issue, Coates et al. (2017) simulated free-range cattle with artificial methane sources scattered on a field at a height of 0.8 m. They were able to estimate artificial source emissions with an error of 10% regardless of the distance between the source and the mast by using a Lagrangian stochastic model which could consider source heights. Because stochastic approaches require high computational power, Dumortier et al. (2019) tried to assess to what extent ready-to-use footprint models, that do not consider source height, could be stretched beyond the conditions for which they were designed in order to estimate methane emissions from elevated artificial sources. They concluded that emissions could be correctly estimated (error of less than 15%) using the analytical Kormann & Meixner (2001) footprint model when the artificial source was located further from the mast than the footprint peak.

These results strengthen the idea that EC can be used to estimate point source emissions of methane from cattle in field conditions. Felber et al. (2015) were the first to put this idea into practice. They calculated an emission per dairy cow by combining EC with cow geolocation data and the Kormann & Meixner (2001) footprint model. The experiment was run on a 3.6 ha pasture divided into 6 paddocks which were either very close to or distant from the mast. Every few days animals were transferred from one paddock to another (rotational grazing). This resulted in high stocking densities at the pasture level (5.5 LU ha^{-1}; LU, livestock unit) but very high stocking densities in the occupied paddock (up to 33 LU ha^{-1}). For paddocks close to the mast (less than 60 m), measured methane emission levels compared reasonably well (difference of less than 5%) with those obtained from metabolic chambers hosting dairy cows with similar milk production levels and body weights. However, for paddocks more distant from the mast, measured emissions per animal were lower and compared poorly to metabolic chambers, suggesting an imprecision of the footprint model. Other authors have successfully used a similar approach in different contexts (Prajapati and Santos, 2017), researching different gases (Gourlez de la Motte et al., 2019) or using different footprint tools (Coates et al., 2018).

In this work, free ranging cattle methane emissions on the pasture are estimated by combining eddy covariance with geolocation. This approach provides a variety of situations with the herd at rest, gathered at various distances from the mast, and cows more dispersed on the pasture during grazing. Moreover, we are able to rely on a methane emission estimation method previously validated on the same site with an artificial tracer (Dumortier et al., (2019). Our main objectives are:

- To adapt an existing method combining the EC technique and a footprint model (Dumortier et al., 2019) with cattle geolocation data in order to estimate mean enteric emissions per livestock unit (LU). The validity of this approach is estimated by the internal consistency of the results (stability of emissions, uncertainties and impact of meteorological conditions).
- To estimate methane emissions of Belgian Blue cattle on a typical Belgian commercial farm and to compare these with existing estimates (including IPCC default values).
- To investigate the relation between methane emissions and cattle behavior.

2. MATERIAL AND METHODS

2.1. *EXPERIMENTAL SITE*

The ICOS-candidate Dorinne Ecosystem Station (BE-Dor) is a 4.2 ha pasture located in Dorinne, Belgium (location: 50˚18’42.84”N; 4˚58’4.8”E; 248 m above sea level). The site is the location of previous investigations and is fully described in Dumortier et al. (2017b) and in Gourlez de la Motte et al. (2019). The pasture is situated on a loamy plateau with a calcareous and/or clay substrate. Its species composition is: 66% grasses, 16% legumes and 18% other species. The dominant species are perennial ryegrass (Lolium perenne L.) and white clover (Trifolium repens L.). The pasture is used for cow-calf grazing operations with Belgian Blue cattle with a mean annual stocking density in the pasture (SD_p) of 2.0 LU ha^{-1} (livestock unit per ha). An eddy-covariance measuring mast is located in the center of the pasture (**Figure 4-1**). Wind speed and direction are measured on this mast using a sonic anemometer (CSAT3, Campbell Scientific Ltd, UT, USA) at a height of 2.6 m. Air sampled near the anemometer (0.216 m N, 0.125 m E and 0.23 cm below) is carried through a 2 µm filter (SS-4FW4-2, Swagelok Company, OH, USA) and a heated PTFE tube (inner diameter 3.18 mm, length 6.85 m, flow rate 9 10^{-5} m^3 s^{-1}) to the fast methane analyzer (G2311-f, Picarro, Inc, CA, USA).

Figure 4-1: Satellite view from the Dorinne Ecosystem Station. The pasture is highlighted in white, the red cross indicates the mast and the black ellipse indicates the location of the barn.

Four measurement campaigns were organized involving 8 to 19 cows weighing between 700 and 850 kg, up to one breeding bull (±1300 kg) and up to 19 calves (**Table 4-1**). During each of these campaigns, cattle positions and behavior were monitored as described in §2.2, fluxes were measured as described in §2.3, and cattle emissions were computed as described in §2.4.

Table 4-1: Description of the four measurement campaigns.

Campaign	Start and end date	Number cows /calves	Stocking density [LU ha^{-1}]	Main wind direction
Spring 2014	**27 May 2014 – 25 Jun 2014**	**17-19 /17-19**	**6**	**N-E**
Spring 2015	**14 Apr 2015 – 7 May 2015**	**12 /0**	**2.8**	**S-W**
Summer 2015	**14 Aug 2015 – 2 Sept 2015**	**12 /10**	**3.8**	**S-W**
Autumn 2015	**19 Oct 2015 – 2 Nov 2015**	**8 /0**	**1.9**	**S-E**

2.2. POSITION AND BEHAVIOR MONITORING

During the four measurement campaigns, the position and behavior of each adult cow were monitored using a homemade tracking device consisting of a GPS unit and an accelerometer which was located on the top of the cow's neck (**Figure 4-2**). Data were collected by a GPS antenna module (Fastrax UP 501, Fastrax Ltd., Finland) and a low power 3 axis accelerometer (ADXL335, Analog Devices Inc., MA, USA) and were stored on a micro SD card. Power was supplied by four batteries (3.8 V, 4 × 2000 mAH). The tracker could work for approximately 30 days on a single charge, avoiding too frequent handling of cows for battery replacement. In order to reach this autonomy, the data collection had to be discontinuous. Every 5 minutes, the tracker would wake up, wait for the acquisition of at least 3 satellite signals (which typically took about 30 s), record the position and acceleration components (used to detect behavior) in 3 dimensions at 20 Hz for 20 s, and then return to sleep mode. Neither the calves nor the bull were equipped with tracking devices. The GPS module precision was assessed by leaving the device motionless at a known position in the pasture for 41 days. During this period, 50% of the points were found within 3 m of the true location, 76% within 5 m and 95% within 11 m.

For animals which were not correctly geolocated (GPS malfunctions, representing 3.7 to 18.8% of the dataset from one campaign to another, or calves), their contribution to the footprint had to be estimated, resulting in an additional correction. Cattle footprint contributions were corrected by a geolocation correction factor (GCF) using **Equation 4.1**, with a cow corresponding to 1 LU and a calf (4 to 10 months) to 0.4 LU. Data were excluded from the dataset when the GCF was larger than 1.5 (up to 56% of the dataset for the Spring 2014 campaign). The calves' conversion factor of 0.4 is based on the Walloon region criteria for the Common Agriculture Policy ("Arrêté ministériel exécutant l'arrêté du Gouvernement wallon du 3 septembre 2015 relatif aux aides agro-environnementales et climatiques") and is in agreement with the estimated emission levels of calves which should be between 30 and 40% of an adult cow (Basarab et al., 2012; Dämmgen et al., 2013; Lockyer, 1997).

$$GCF = \frac{\sum LU\ on\ the\ pasture}{\sum Detected\ LU}$$ **Equation 4.1**

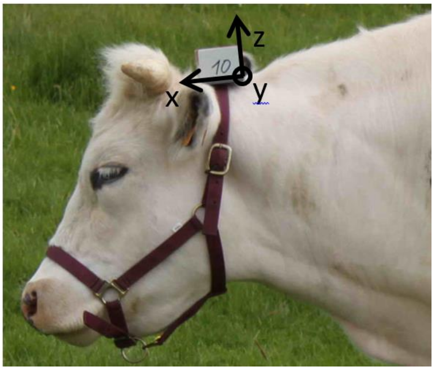


Figure 4-2: Position and activity tracking device represented with the three axis system of the accelerometer.

Cattle behavior was sorted into three categories (grazing, ruminating and other) on the basis of the acceleration mean value and standard deviation along the x-axis as represented in **Figure 4-2**. The use of the x-axis was selected because it was discriminating and had a physical interpretation. The measured acceleration can be divided into two terms: a low frequency component which corresponds to gravity projection along each axis and allows identification of the cattle's neck position, and a high frequency component due to the cattle's movements (Andriamandroso et al., 2016). During grazing, the cow's neck is oriented downward (positive values of a_x, the mean x acceleration component) and is moving abruptly for each bite (high σ_{ax}, the standard deviation of this value), while during rumination the cow's neck is horizontal or raised slightly upwards (a_x, values close to 0 ms^{-2} or slightly negative) with small movements related to mastication (low σ_{ax}). Other behaviors are characterized by a large array of a_x and σ_{ax} values, which sometimes overlap with rumination or grazing characteristic values (Andriamandroso et al., 2017). Attributing a behavior using universal absolute thresholds of a_x and σ_{ax} was not possible due to the specific positioning of the device on each cow. However, as cattle spend approximately 60% of their time grazing and 15% ruminating (Braghieri et al., 2011), these behaviors were detected by an algorithm which was looking for combinations of a_x and σ_{ax} occurring more frequently. For each cow-collar combination, a 2D histogram was created with 20 categories of a_x and 20 categories of σ_{ax}. For each of these 400 categories (20 × 20), the ones with the highest occurrence (threshold set at 3 times the average occurrence) were considered as rumination or grazing according to a_x and σ_{ax} (**Figure 4-3**).

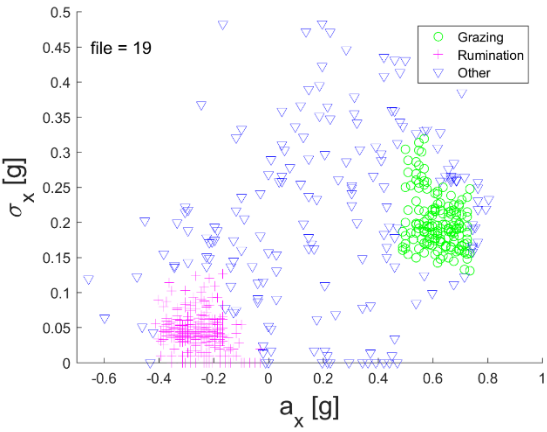


Figure 4-3: Scatterplot of acceleration characteristics along the x-axis for a single cow and during a single measurement campaign. The horizontal axis corresponds to the mean acceleration and the vertical axis corresponds to the standard deviation. Each point represents a 20 s sample and is automatically associated with a behavior by an algorithm.

The precision of the behavior detection method was assessed by comparison to the behavior of cows which were visually observed for two hours, resulting in the acquisition of 115 5-minute measures. Those results are presented in **Table 4-2**. Detected behaviors agreed with observations in 85, 80 and 23% of the time for grazing, rumination and other behaviors respectively, while observations agreed with detections 96, 45 and 38% of the time for grazing, rumination and other behaviors respectively. This means that the grazing behavior was well characterized, while rumination and other behaviors where poorly distinguished.

Table 4-2: Confusion matrix of the behavior detection algorithm. Each row of the matrix represents the instances in a predicted class while each column represents the instances in an observed class.

Observation / Prediction	Grazing	Rumination	Other	Total	Observation corresponding to prediction
Grazing	48	0	2	50	96 %
Rumination	0	20	24	44	45 %
Other	8	5	8	21	38 %
Total	56	25	34	115	
Prediction corresponding to observation	86 %	80 %	24 %		

2.3. *FLUX MEASUREMENT AND PROCESSING*

Turbulent methane fluxes were calculated using EddyPro® version 6.2.2 open source software (Li-Cor Inc., NE, USA). The computation was the same as the method used by Dumortier et al. (2019) with the exception of the averaging period (30 minutes instead of 15 minutes) due to the presence of outliers that could not be filtered for the 15-minute averaging interval. The main differences from the default calculation method were the use of a running mean with a 120 s time constant, and the absence of stationarity filtering because animals could cause sudden fluctuations in the methane dry mixing ratio.

Time lags between measured vertical velocity and methane dry mixing ratio were calculated using a covariance maximization method with a default value of 2.3 s and a window size of 1 s (79% of the records were found within this time window for methane). A correction for high-frequency losses was applied using an in situ spectral correction method (Fratini et al., 2012). Data were also filtered on the basis of friction velocity, using a u_* threshold of 0.13 m s^{-1} (Dumortier et al., 2017b; Gourlez de la Motte et al., 2016). Among the statistical tests for raw data screening proposed by Vickers and Mahrt (1997b), some choices were made. The spike filtering, drop-out, absolute limit and discontinuities tests were applied using the default settings proposed in EddyPro®. These tests removed less than 3% of the dataset. Amplitude resolution, skewness and kurtosis tests were disabled as in a previous artificial source campaign (Dumortier et al., 2019); they induced a removal of almost all periods involving the artificial source in the footprint, although these signal characteristics were obviously generated by a real phenomenon.

An additional filter was added to remove data associated with poorly defined footprint functions (z/L>0.05). Moreover, as cattle muzzles are not found solely at ground level but at a height ranging from ground level to approximately 0.8 m high, a minimum distance between the source and the mast was defined. The impact of the source height had been tested using FIDES (Loubet et al., 2010), a pseudo Gaussian footprint model which includes the height of the source as an input variable. The conclusion was that for a source located further than 12 m from the mast for unstable conditions and 16 m from the mast for neutral conditions, the source height impact on the footprint function was below 15% if the source is found below 0.8 m. These distances were therefore selected for data filtering.

The footprint function extended well beyond the pasture borders (**Figure 4-4**) which means that events occurring outside of the pasture could be unintentionally detected. This was the case during the Spring 2015 campaign which started early in the season (14 April), resulting in contaminated fluxes originating from the barn (**Figure 4-1**) which was a strong methane source when cattle were still housed indoors, and from a manure heap located 500 m south-west from the mast. For this campaign, contaminated wind directions (5 to 50 and 200 to 230° N, clockwise) were thus removed from the dataset. Other campaigns were not affected by these issues as, for later dates, no (or only a few) cows were present in the barn and the manure had been used for crop fertilization.

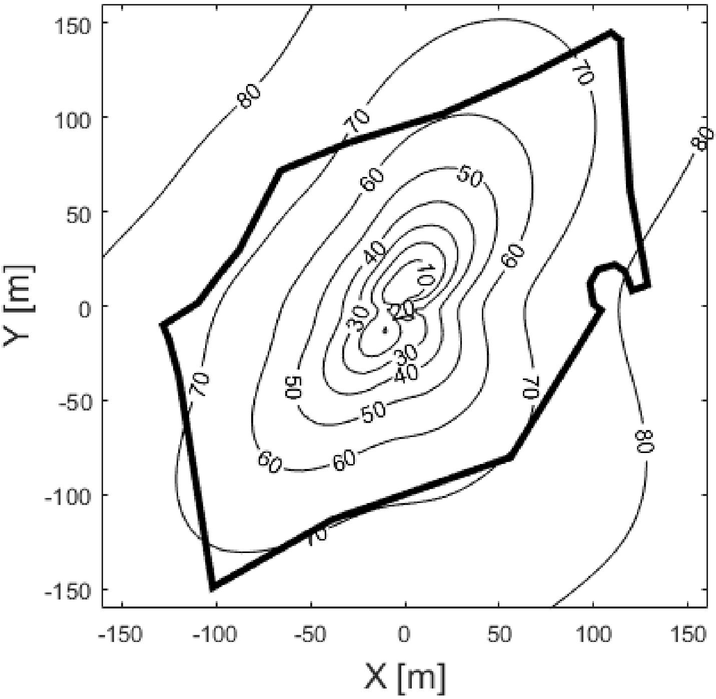


Figure 4-4: Mean cumulative footprint during the whole measurement period using the Kormann & Meixner footprint model. The isopleths represent the area responsible for x% of the measured flux (proportion of the footprint found inside a specific area). The bold line corresponds to the pasture limits.

Applied filters and associated data loss are described in **Table 4-3**. According to this table, the proportion of high quality flux data (meaning data without instrument malfunctions and with u_* above 0.13) was between 40 and 67% from one period to another. Moreover, 60 to 80% of the remaining dataset was eliminated due to poorly defined cattle contribution to the footprint (which corresponds to a z/L ratio above 0.05), unavailable cattle positions (GCF above the threshold), presence of cattle too close to the mast (12 to 16 m according to meteorological conditions) or wind coming from a strong and undesired methane source (barn or manure heap) for the Spring 2015 campaign. The remaining high quality dataset was used for this study. No filter was associated to a minimum cattle contribution to the footprint.

Table 4-3: Number (and percentage) of half-hours remaining after the application of each filtering step for each measurement campaign.

	Spring 2014	Spring 2015	Summer 2015	Autumn 2015
Measurement period	1385	1097	913	669
High Quality flux data	859 (62%)	730 (67%)	415 (45%)	267 (40%)
+ well defined cattle contribution to the footprint	299 (22%)	136 (12%)	156 (17%)	171 (26%)

2.3.1. Enteric emission estimation

Methane emissions per LU (f_{CH4}) were estimated according to the method described by Dumortier et al. (2019), which is equivalent to the method proposed by Felber et al. (2015). f_{CH4} were computed by combining turbulent flux measurements with cattle positions through the use of a footprint function using **Equation 4.2**, where F_{CH4} is the measured methane flux (nmole m^{-2} s^{-1}), i corresponds to the cow identification number and ϕ_i the value of the footprint function at the *i* cow location (m^{-2}). As cattle locations were recorded every 5 minutes, the one sixth ratio allows the calculation of an average ϕ_i for each 30-minute interval as each animal occupied 6 locations during an averaging interval.

$$f_{CH_4} = \frac{F_{CH4}}{GCF \times \frac{1}{6}\sum_i \phi_i} \qquad \textbf{Equation 4.2}$$

where $GCF \times \frac{1}{6}\sum_i \phi_i$ corresponds to the stocking density in the footprint (SD_f). The footprint function (ϕ) was calculated according to the footprint model described by Kormann & Meixner (2001)(KM) on a 30-minute averaging period. However, f_{CH4} values estimated through this method were subject to high variations, especially for low SD_f. A method more robust than a division was therefore considered.

Equation 4.2 implies a direct relationship between measured methane fluxes and cattle density in the footprint. In other words, f_{CH4} can be calculated as the slope of the linear regression associated with the relation between SD_f and the measured methane flux. Different regression methods can be used to infer the slope of the linear regression. The most common one, the Linear Least Square regression (LLS) minimizes residues associated with the vertical axis and supposes no uncertainty associated with the horizontal axis. However, when uncertainties are associated with both axes, as was the case here, functional relations must be used (Webster, 1997). The Reduced Major Axis method (RMA, Matlab code provided by Trujillo-Ortiz & Hernandez-Walls (2020)) minimizes residues along the normalized horizontal and vertical axis, this method is therefore able to deal with uncertainties on both axes. Another way to estimate the slope of the regression is the Median-Median Regression (MMR) which is obtained by dividing the dataset into two groups (based on the median value of the x axis). For each group the central point is calculated as the median value along horizontal and vertical axes. The regression line then corresponds to the line passing through the center of each group. The main advantage of the MMR method is that it doesn't involve a hypothesis about the distribution shape or the uncertainty associated with each axis. We applied these last two methods (RMA and MMR) to our dataset, resulting in two f_{CH4} estimates. Both methods were far more robust than a simple division. For both options, the confidence interval of the slope was estimated through a bootstrapping method. This resampling method is adapted to almost any distribution and allows numerical estimation of the uncertainty of the parent population and not only of the sample. The 95% confidence interval was computed as the 2.5 and 97.5 percentile of the slope distribution after 5000 draws, and the 95% uncertainty range corresponded to the half of this confidence interval.

3. RESULTS

3.1. *CATTLE BEHAVIOR AND DISTRIBUTION*

For each campaign, cattle were found to be well spread over the whole pasture when grazing, while they gathered near the water troughs and the trees bordering the pasture when ruminating or idling (**Figure 4-5**). We also observed that grazing behaviors followed a diurnal pattern; animals grazed mainly during the day with peak activities just after sunrise and before sunset (**Figure 4-6**). This behavior was confirmed by GPS trackers which revealed a strong correlation between cattle movement and grazing behavior. Cows were covering larger distances during the 5-minute interval between two consecutive measurements when they were grazing (**Figure 4-6**). These results confirm the validity of the animal behavior detection method presented in §2.2.

One might wonder if cattle geolocation was really necessary in order to estimate f_{CH4}. Without information about cattle's location, f_{CH4} could be estimated for each campaign considering a homogeneous cattle disposition in the pasture as done by Dumortier et al. (2017). However, as showed in **Erreur ! Source du renvoi introuvable.**, cattle disposition on the pasture is generally heterogeneous. The only notable exception is during grazing events which are observed at sunrise and sunset. These periods could thus be used to estimate cattle emissions without requiring any knowledge about cattle location.

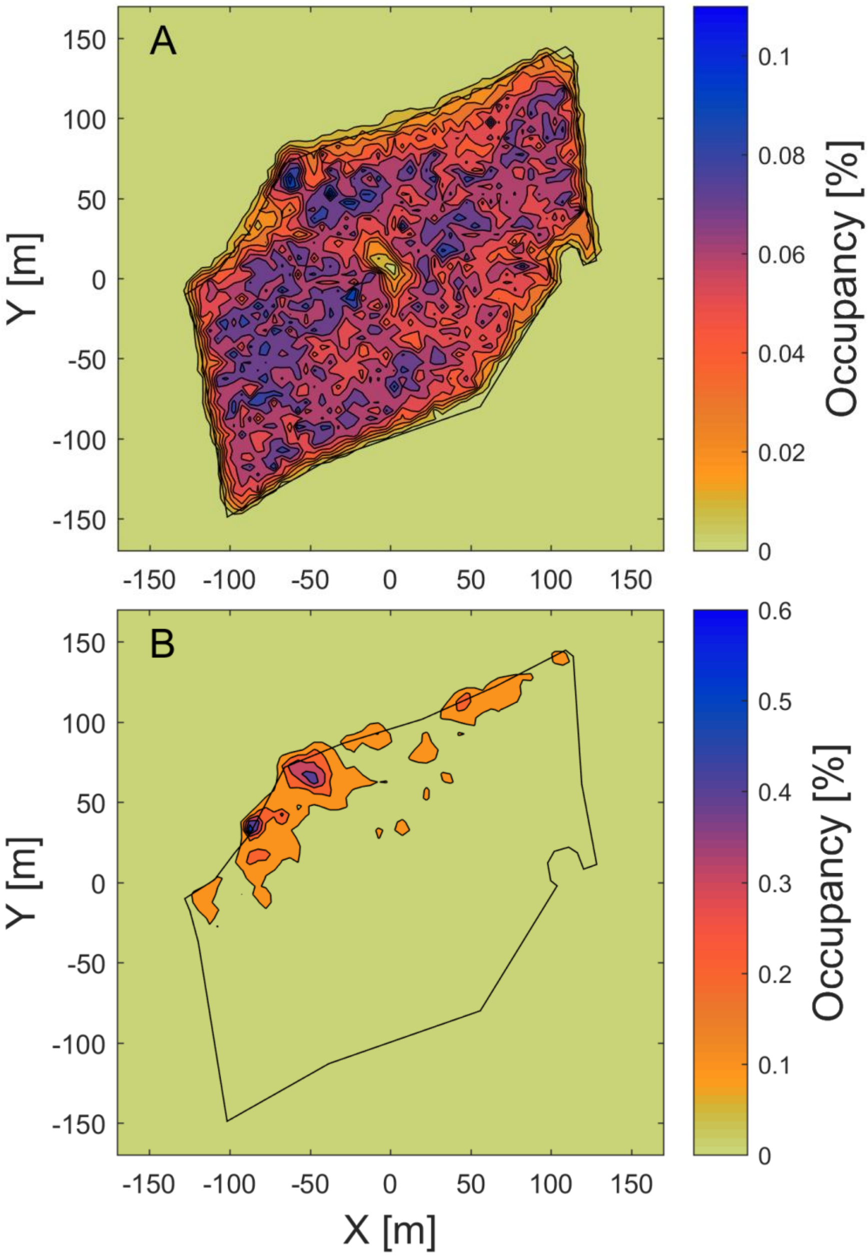


Figure 4-5: Density maps of cows' positions when grazing (A) or expressing other behaviors (B) for all four campaigns combined. The black line represents the limits of the pasture. The occupancy is calculated as the percentage of the time spent by cattle in each square meter. A homogeneous cattle distribution would result in a 0.06% occupancy over the whole pasture.

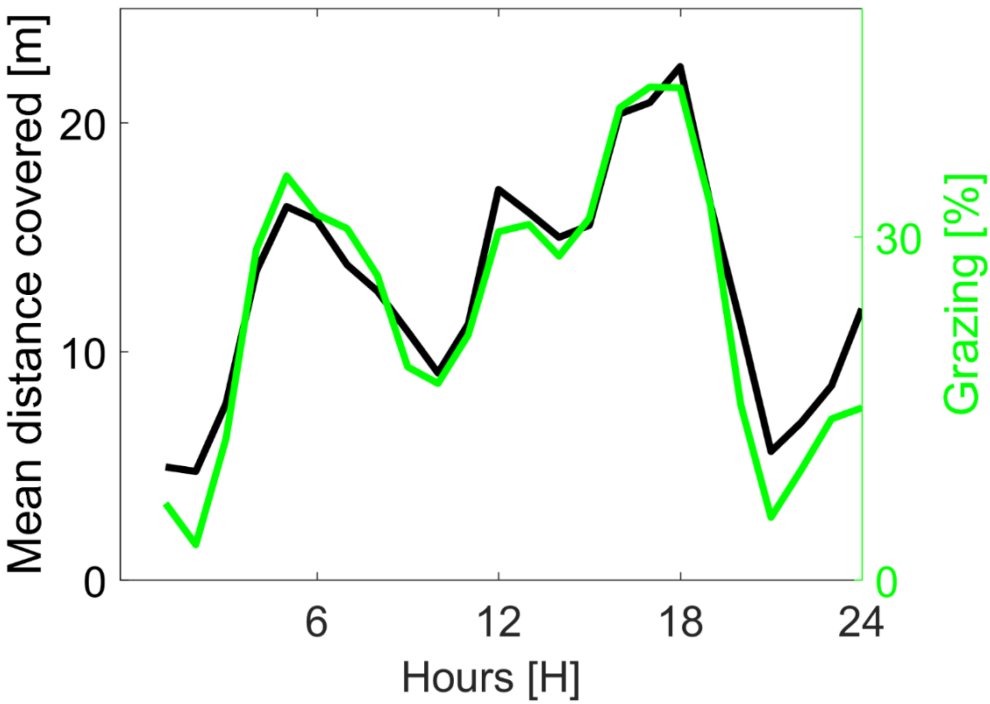


Figure 4-6: Average percentage of the herd grazing (green) and distance covered between each measurement (black; each 5 minutes) according to the time of day for all four campaigns combined.

3.2. *ENTERIC METHANE EMISSIONS*

Enteric methane emissions were estimated by the slope of the linear regression associated with the relation between SD_f and measured methane fluxes. In **Figure 4-7**, the two selected regression lines are drawn for the Spring 2014 campaign, along with the LLS regression line for comparison purposes. The slope of these regression lines were used to estimate f_{CH4}. For each campaign, f_{CH4} values are represented in **Table 4-4**. As slopes estimated using the RMA method were more stable and associated with smaller confidence intervals, this method was selected for the rest of the paper. Over the course of all four campaigns, f_{CH4} obtained using RMA was found to be between 184 and 255 (95% confidence intervals) which corresponds to 220 ±35 g CH_4 LU^{-1} day^{-1}. This indicates an estimated random error of 16%. No significant differences in methane emission levels were observed between campaigns (overlapping confidence intervals).

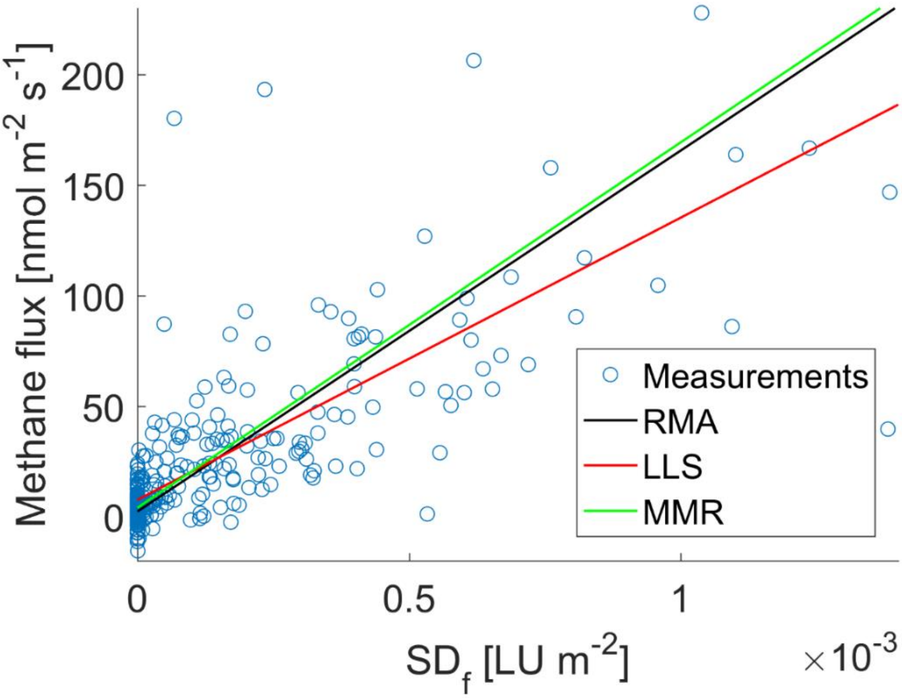


Figure 4-7: Relation between measured methane flux and stocking density in the footprint (SD_f) calculated according to the Kormann & Meixner footprint model for the Spring 2014 campaign with each point corresponding to a 30-minute measurement interval. The different regression lines correspond to the reduced major axis method (RMA), the linear least square (LLS) and the median-median regression method (MMR) (see §0 for more details about each method).

Table 4-4: Estimated cattle emissions per livestock unit (f_{CH4}) for each campaign using two different methods: reduced major axis regression (RMA) and median-median regression (MMR). All estimations are presented through a 95% confidence interval and a 95% uncertainty range.

Campaign	RMA [gCH_4 LU^{-1} day^{-1}]	MMR [gCH_4 LU^{-1} day^{-1}]	Homogeneous [gCH_4 LU^{-1} day^{-1}]
Spring 2014	188 – 268 228 ± 40	168 – 266 217 ± 49	50 – 72 61 ± 11
Spring 2015	158 – 237 197.5 ± 39.5	93 – 415 254 ± 161	117 – 149 133 ± 16
Summer 2015	137 – 321 229 ± 92	125 – 426 275.5 ± 150.5	76 – 218 147 ± 71
Autumn 2015	172 – 270 221 ± 49	166 – 409 287.5 ± 121.5	76 – 216 146 ± 70
All Seasons	185 – 255 220 ± 35	183 – 254 218.5 ± 35.5	82 – 118 95 ± 13

The uncertainty associated to a measurement method is critical when assessing its ability to quantify emissions and, more importantly, to identify the impact of any mitigation of this emission. The error associated with f_{CH4} estimates can be divided into two categories: the precision, which can be dealt with by increasing the size of the dataset, and the accuracy, which is associated with the method and was previously analyzed at the same site by Dumortier et al. (2019). In order to investigate the impact of the size of the dataset on the random error associated with cattle CH_4 emissions estimates, a bootstrapping method was used (a random part of the dataset was sub-sampled) (**Figure 4-8**). Using this method, we observed that at least 480 valid half-hours are needed in order to obtain a 95% uncertainty range below 20%, while only 190 measures are needed in order to obtain an uncertainty range below 30%.

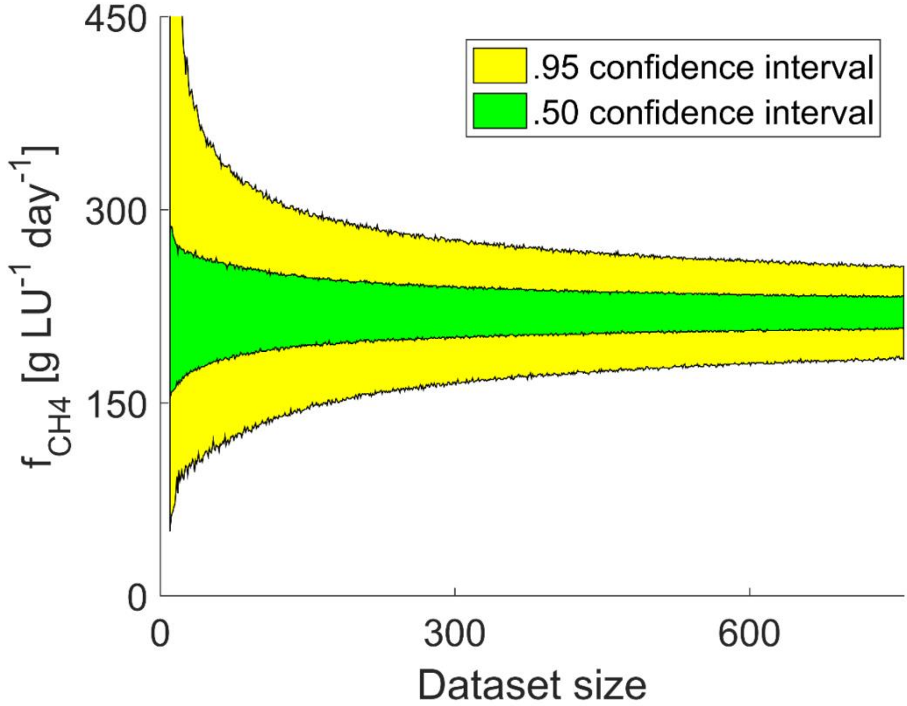


Figure 4-8 Impact of the size of the dataset on methane emissions per livestock unit (f_{CH4}) confidence intervals estimated using a bootstrapping method. For each possible size of the dataset, 5000 sub-samples were analyzed in order to compute associated f_{CH4} estimates. For x% of those runs, estimated f_{CH4} values were found within the .x confidence interval, x corresponding to 95 (yellow) or 50 (green).

Quantifying the relation between the uncertainty range and the size of the dataset allows an estimation to be made of the amount of data required when designing an experiment. If one wishes to be able to distinguish a significant impact of a specific mitigation action, the amount of data required to observe differences above a certain threshold can be estimated. However, this uncertainty estimation method is numeric and only based on our dataset. Other sites may provide different relations between methane fluxes and stocking densities in the footprint, leading to different curves. This result is thus difficult to extrapolate to other datasets.

3.3. *RELATIONS BETWEEN CATTLE BEHAVIOR AND EMISSIONS*

During each campaign cattle mainly grazed after sunrise and before sunset, with intermediate grazing events during the day when the photoperiod was long or during the night on shorter days (**Figure 4-9**). However, significant f_{CH4} variations throughout the day were only observed for the Spring 2014 and Spring 2015 campaigns where emissions were significantly lower for one 4-hour period (2 to 6 pm and 6 to 10 am respectively). Due to this very weak f_{CH4} diurnal variation, no detection of any significant impact of cattle behaviors on methane emissions was possible.

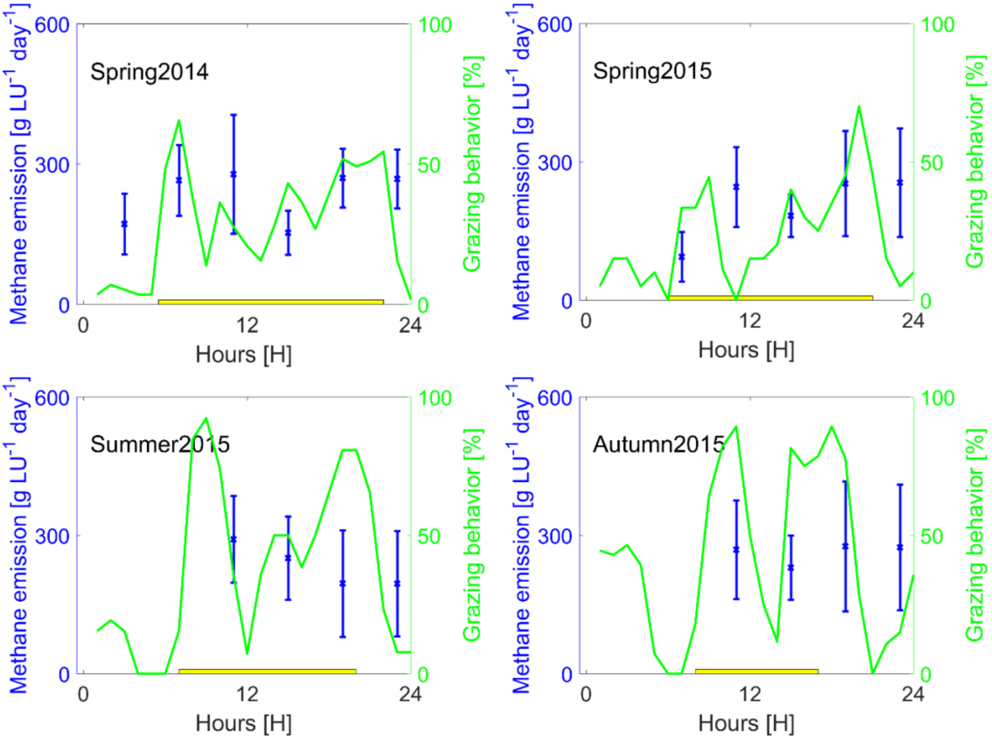


Figure 4-9: Methane emission per livestock unit (f_{CH4}) evolution throughout the day for each measurement campaign computed with the reduced major axis (RMA) regression method and the Kormann & Meixner footprint model. The whiskers indicate the 95% uncertainty range of f_{CH4} for each 4-hour period (bootstrapping). The green line indicates the percentage of animal grazing and the yellow strip indicates the photoperiod for this specific time of year. Whiskers are only represented when more than 10 points were available for a given interval.

An impact of the time since grazing peak was assessed when all campaigns were grouped together (**Figure 4-10**). However, no significant impact of this time on cattle methane emissions was observed.

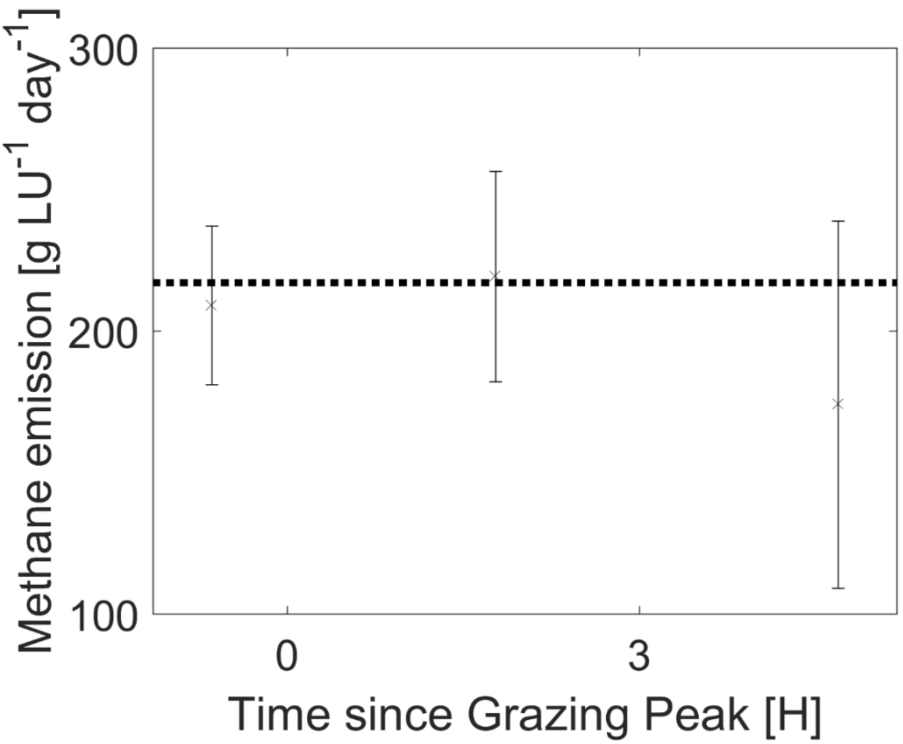


Figure 4-10: Methane emissions per livestock unit (f_{CH4}) according to time since grazing peak for all campaigns together. Times since grazing peak were organized into 3 categories containing the same number of samples and plotted as the category mean. The error bars correspond to the 95% confidence intervals of f_{CH4} (bootstrapping method). The dotted line indicates the f_{CH4} estimated using all data. All values have been computed with the RMA regression method and the KM footprint model.

3.4. *CATTLE METHANE EMISSIONS BIAS ANALYSIS*

Atmospheric conditions or cattle movements on the pasture should not have any impact on estimated f_{CH4}. Nevertheless, in order to detect possible biases, such relations were examined. We observed no significant impact (largely overlapping confidence intervals) of the distance between the closest cow and the mast, atmospheric stability, u_*, average distance covered by animals and wind direction on estimated f_{CH4}. For each variable and when using the complete dataset (all four campaigns grouped together), significant relations were assessed after dividing the dataset into 3 equal size categories of the selected variable. The absence of an impact of u_* (even for values below 0.13 m s^{-1}), of the distance between cattle and the mast (even when below 12 m) or atmospheric conditions (even for z/L values above 0.05) does not indicate the absence of bias from any of the previously listed variables on f_{CH4} but rather that the bias is lower than the uncertainty range associated with the measurements (relative 95% uncertainty ranges around 27% when the dataset was subdivided into 3 categories).

4. DISCUSSION

4.1. *VALIDITY OF THE METHOD*

The first objective was to provide estimates of the mean enteric CH_4 emissions per livestock unit by combining the EC technique with a footprint model and cattle geolocation data. The combination of EC with geolocation allows stable and realistic estimations of cattle methane emissions to be made with measurement campaigns as short as one month (197 to 229 g CH_4 LU^{-1} day^{-1}). Obtained methane emissions were realistic and the regression slope 95% uncertainty range was estimated between 18 and 40% for each campaign, despite the heterogeneous distribution of cattle on the pasture. As already highlighted by Gourlez de la Motte et al. (2019), cattle were not homogeneously dispersed on the pasture at all times (**Figure 4-5**). Therefore, the use of GPS trackers was a great improvement compared with the homogeneous cattle distribution hypothesis. As a result, the assumption used in Dumortier et al. (2017b) that cattle are spread homogeneously over the pasture is only valid when cattle are grazing. This might explain why the homogeneous cattle distribution hypothesis can lead to good results if cattle are confined in a delimited area, upwind from the mast, whose average footprint contribution is known (Dengel et al., 2011; Dumortier et al., 2017b; Felber et al., 2015).

4.2. *BELGIAN BLUE CH_4 EMISISONS*

The second objective was to estimate methane emissions for the Belgian Blue breed on a typical Belgian commercial farm and to compare these values with existing estimates. When averaging all four campaigns, estimated emissions were 220 ±35 g CH_4 LU^{-1} day^{-1} or 80 ±13 kg CH_4 LU^{-1} yr^{-1}. These values are very close to tier 2 IPCC emission estimates (IPCC, 2006) of 205 ±41 g CH_4 LU^{-1} day^{-1}, considering a measured average dry matter ingestion of 9.5 kg per day (Gourlez de la Motte et al., 2016), a default raw energy content of 18.45 MJ kg^{-1}, a default methane conversion factor of 6.5% and a default uncertainty range of 20%. The values are also very close to a previous measurement of 223 ±16 g CH_4 LU^{-1} day^{-1} obtained by De Mulder et al. (2018) on the same breed using metabolic chambers (indoor-housed Belgian Blue heifers). On the whole, the random error associated with f_{CH4} estimates was 16% (35 g CH_4 LU^{-1} day^{-1}).

The random error associated with emission estimates does not give any information about the measurement accuracy. Our best estimate of this accuracy is obtained from the artificial source experiment run on the same site (Dumortier et al., 2019). A recovery rate between 90% and 113% was obtained, according to the distance between the source and the mast. For comparison, a 13% systematic error on f_{CH4} estimates would translate to approximately 30 g CH_4 LU^{-1} day^{-1}.

4.3. *IMPACT OF CATTLE BEHAVIOR ON CH_4 EMISSIONS*

The third objective was to investigate the relation between methane emissions and cattle behavior. The 95% confidence interval of f_{CH4} estimates depends on the number of observations. Therefore, when the dataset was subdivided, uncertainty on binned estimations increased, making it difficult to demonstrate the dependency of emissions on the cattle's behavior. For instance, when averaged over 4-hour periods, f_{CH4} uncertainty ranges were estimated between 20 to 60% according to the time of the day and the campaign. The confidence interval was thus simply too large to detect any link between f_{CH4} and cattle behavior. This high uncertainty might be due to the fact that we were working with relatively low stocking densities (1.9 to 6 LU ha^{-1}) in a real production environment where cattle do not always exhibit the same behavior simultaneously. In these conditions about 480 valid half-hours were needed in order to limit the 95% relative uncertainty range to 20%.

No significant differences in f_{CH4} appeared between campaigns, with 95% confidence intervals largely overlapping. Therefore, no impact of the season or of grass intake, both in terms of quantity or quality, can be inferred from the present dataset. We can say that the impact of the season on cattle methane emissions at our site was lower than the uncertainty range associated with our measurements. Moreover, cattle methane emissions might be relatively stable as the farmer adjusts cattle stocking density according to grass availability and quality variations throughout the year.

Cattle positions in the pasture as well as micro-meteorological variables like the minimal distance from the mast, atmospheric stability, u_* or wind direction variation had no significant impact on estimated methane emissions. This means that the precision associated with the measures was insufficient for their detection. Filters (u_* and z/L) were nevertheless applied to reduce the variability associated with f_{CH4} as these filters were theoretically justified.

5. CONCLUSIONS

Estimated methane emissions from cattle raised at the BE-Dor site were 220 ±35 g CH_4 LU^{-1} day^{-1}, where the uncertainty corresponds to the random error and does not include any possible systematic error. This figure corresponds to previous estimates and should be representative of common rearing practices in south Belgium.

The present technique is not limited to methane and, provided the appropriate analyzers are available, can be used to estimate other gaseous animal emissions like CO_2 (Felber et al., 2016b; Gourlez de la Motte et al., 2019). Some European pastures are already monitored using eddy covariance (Flechard et al., 2007; Hörtnagl et al., 2018), most of them without tracking the cattle's location on the pasture. However, measured fluxes on a pasture (CO_2, CH_4, volatile organic compounds, N_2O, etc.) are intrinsically biased as these fluxes are impacted by cattle. As cattle distribution on the pasture is fundamentally heterogeneous, the use of geolocation can greatly help in the interpretation of the measurements. Alternatively, CH_4 fluxes could be used as proxies of cattle presence in the footprint (Gourlez de la Motte et al., 2019). Altogether, the combination of eddy covariance with a footprint model has the advantages of working outdoors with minimal impacts on cattle raising conditions, but is costly and labor intensive.

Several improvements could be brought to the technique. The most labor-intensive step of the work was to equip cattle with GPS trackers in order to obtain their positions. More easily automatable solutions could be developed with the help of active RFID tags or infra-red cameras. Eddy covariance footprint models could also be improved by considering source height using a 3D footprint model or by working with backward stochastic Lagrangian models. Additionally, individual fluxes measured through eddy covariance are often discarded due to stationarity issues. The use of recently explored alternative flux calculation methods such as a wavelet transform (Göckede et al., 2019; Schaller et al., 2017) could increase methane flux measurement accuracy in non-stationary conditions, which is of great importance at the half-hour scale. In conclusion, the combination of a methane flux quantification method with cattle geolocation is a promising way to measure cattle methane emissions on the field in real commercial conditions, but substantial improvements are still required for optimal efficiency.

6. Acknowledgments

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CHAPTER 5

HERD POSITION HABITS CAN BIAS NET CO_2 ECOSYSTEM EXCHANGE ESTIMATES IN FREE RANGE GRAZED PASTURES

Chapter 5. Herd position habits can bias net CO_2 ecosystem exchange estimates in free range grazed pastures

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Abstract

The eddy covariance (EC) technique has been widely used to quantify the net CO_2 ecosystem exchange (NEE) of grasslands, which is an important component of grassland carbon and greenhouse gas budgets. In free range grazed pastures, NEE estimations are supposed to also include cattle respiration. However, cattle respiration measurement by an EC system is challenging as animals act as moving points emitting CO_2 that are more or less captured by the EC tower depending on their presence in the footprint. Often it is supposed that, over the long term, cattle distribution in the pasture is homogeneous so that fluctuations due to moving sources are averaged and NEE estimates are reasonably representative of cattle respiration.

In this study, we test this hypothesis by comparing daily cow respiration rate per livestock unit (LU) estimated by postulating a homogeneous cow repartition over the whole pasture with three other estimates based on animal localization data, animal scale carbon budget and confinement experiments.

We applied these methods to an intensively managed free range grassland and showed that the NEE estimate based on a homogeneous cow repartition was systematically lower than the three other estimates. The bias was about 60 gC m^{-2} yr^{-1}, which corresponded to around 40% of the annual NEE. The sign and the importance of this bias is site specific, as it depends on cow location habits in relation to the footprint of the EC measurements which highlight the importance of testing the hypothesis of homogeneity of cattle distribution on each site.

Consequently, in order to allow estimating the validity of this hypothesis but also to improve inter site comparisons, we advocate to compute separately pasture NEE and grazer's respiration. For the former we propose a method based on cattle presence detection using CH_4 fluxes, elimination of data with cattle and gap filling on the basis of data without cattle. For the second we present and discuss three independent methods (animal localization with GPS, animal scale carbon budget, confinement experiments) to estimate the cattle respiration rate.

Keywords
Eddy covariance; Grassland; Grazing; Cow respiration; Methane; CO_2; Net ecosysteme exchange.

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; Polley et al., 2008; Rutledge et al., 2017a, 2017b), 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):

$$\mathrm{NEE_{tot}} = \mathrm{NEE_{past}} + \mathrm{R_{cows}} \qquad \textbf{Equation 5.1}$$

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

$$\mathrm{NBP} = \mathrm{NEE_{tot}} - \mathrm{C_{exports}} + \mathrm{C_{imports}} \qquad \textbf{Equation 5.2}$$

However, as cattle act as moving CO_2 sources their emissions either will or won't be captured by the measuring system, depending on the presence of the cattle in the footprint area. Although R_{cows} is a small flux compared to gross primary productivity (GPP) and the total ecosystem respiration (TER), it can be of the same order of magnitude as NEE_{tot}. Even if its magnitude may vary from site to site, R_{cows} around 200 g C m^{-2} yr^{-1} may be expected in pastures with a high stocking rate (Jérôme et al., 2014). Therefore, an under- or overestimation of this flux could lead to a non-negligible systematic bias in annual NEE_{tot} values and therefore in annual NBP.

Historically, most of the studies on grazed sites assumed (explicitly or not) that, averaged over a grazing season, cattle were spread evenly over the field so that their respiration signals become a part of NEE_{tot} and are correctly estimated by EC. Although most often not verified, this hypothesis was commonly (sometimes implicitly) used for free range grazed pastures where the presence or not of cattle within the footprint at a given time is not easy to assess (Byrne et al., 2007; Gourlez de la Motte et al., 2016; Jaksic et al., 2006; Klumpp et al., 2011; Zeeman et al., 2010) When the pasture is divided into several paddocks for rotational grazing this hypothesis is not met, but the presence of cattle in the footprint is much easier to assess so that the computation of NEE_{past} is possible by filtering fluxes affected by cattle respiration. In an intensively rotationally grazed site with multiple paddocks, Skinner (2008) advocated that fluxes affected by cattle respiration should be removed as CO_2 fluxes were very erratic in the presence of a high stocking density within the footprint. He proposed to filter out the fluxes from paddocks affected by cattle respiration, compute NEE_{past}, and account for the biomass ingested by the animals as C exports and the animal excretions as C imports, thereby considering cattle to be external to the system. More recently, several studies also identified this problem and adapted their methodology to exclude grazer respiration and thus, compute NEE_{past} (Felber et al., 2016a; Hunt et al., 2016; Rutledge et al., 2017a, 2017b). Kirschbaum et al., (2015) also highlighted the need to filter fluxes in the presence of high stocking density in the footprint in order to obtain good agreement between modelled and measured CO_2 fluxes in a rotationally grazed pasture.

Alternatively, Felber et al. (2016b) used GPS trackers on cows in combination with a footprint model to separate fluxes with and without cattle respiration. Animal positions were then used to estimate a reference respiration rate per animal. In order to verify the hypothesis that NEE_{tot} includes R_{cows} in a representative way, they compared this respiration rate value to the respiration rate calculated considering a homogeneous cattle distribution on the pasture. For their site, a rotationally grazed multi-paddock pasture, they found that on a yearly basis animal respiration was included in NEE_{tot} in a representative way suggesting that there were no correlations between the animal positions and the wind direction. However, this result is site specific and such observations has yet to be verified for continuously grazed pastures (Felber et al., 2016b). In those sites the animals are allowed to move freely in the pasture so that, if cattle are more likely to remain grouped in specific areas of the pasture such as shade areas or near water/feed supplies, which is very probable, NEE_{tot} would be biased in a way and to an extent that depends on the position of these specific areas relative to the footprint.

The aim of the present study is to test different methods to verify if the contribution of grazing animal respiration is adequately represented in the NEE measured in a continuously grazed pasture. The methods were applied at the Dorinne Terrestrial Observatory (DTO), an intensively managed pasture with a high annual stocking rate (>2 livestock units (LU) per hectare). A solution is also proposed to correct cow respiration values if not estimated properly. Conclusions and consequences regarding the computation of the carbon budget of the pasture are also discussed. Advantages and drawbacks of the different methods proposed in the paper are discussed and more general guidelines are provided for researchers who aim to measure consistent NEE and cow respiration rates in grazed pastures.

2. MATERIAL 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 5-1** 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., 2017a) 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.

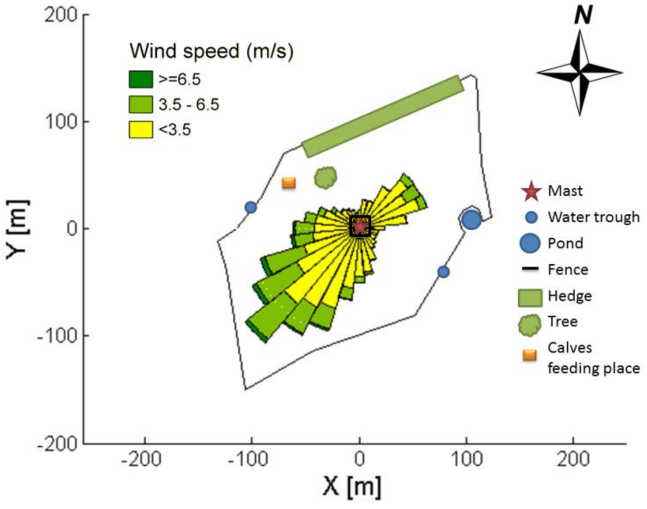

Figure 5-1: Schematic map of the site. During confinements, internal fences were closed and the cattle were confined in the south-west part of the pasture. Figure taken from Dumortier et al. (2017a).

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 CO_2/H_2O 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 tube (6.85 m long, 6 mm inner diameter). A more detailed description can be found in Dumortier et al. (2017a).

Half hourly CO_2 and CH_4 fluxes were computed following the standard procedure defined by the CarboEurope IP network (Aubinet et al., 2012, 2000). CO_2 fluxes were calculated as the sum of the turbulent flux and of the storage term (Foken et al., 2012b) using the EDDYSOFT software package (EDDY Software, Jena, Germany, (Kolle and Rebmann, 2010)). They were corrected for high frequency loss following the procedure proposed by Mamadou et al. (2016). They were later filtered for stationarity using a selection criteria of 30%, according to Foken et al. (2012b). CH_4 fluxes were calculated using the EddyPro® (LI-COR Inc, Lincoln, NE, USE) open source software (Version 6). A double rotation was applied to wind velocity for both fluxes (Rebmann et al., 2012). Both CO_2 and CH_4 fluxes were filtered for low turbulence using a friction velocity (u_*) threshold of 0.13 m s^{-1}. This threshold was determined as the u_* value where the relationship between u_* and the temperature normalized nighttime CO_2 flux flattens. A more detailed description of CO_2 and CH_4 flux computation can be found in Gourlez de la Motte et al. (2016) and Dumortier et al. (2017a), respectively. Note that, in this study, the requirement for the CH_4 flux quality is low as the fluxes are only used as a tool to assess the presence or absence of cows in the footprint (binary test).

2.3. *METEOROLOGICAL MEASUREMENTS*

Meteorological 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).

2.4. *GENERAL DESCRIPTION OF THE METHODOLOGY*

A methodology was developed to assess if cow respiration is included in a representative way in annual NEE_{tot} estimates and, if needed, to make the necessary corrections. The main steps of this methodology are:

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). 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 (2016, 2018).

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.

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

Both the homogeneous and the GPS approaches rely on stocking density estimates. The homogeneous approach (average stocking density, SD_p) rely on the average number of LU on the whole field (n_{avg}), which was carefully monitored by the farmer during the whole grazing season, and corrected (factor φ) to take into account the average pasture contribution to the footprint:

$$SD_p = \frac{n_{avg} \times \varphi}{A} \qquad \textbf{Equation 5.3}$$

where A is the total pasture area. The average pasture contribution to the footprint φ was computed for every half hour, using an analytical footprint model (Kormann and Meixner, 2001) designated hereafter as the KM model. This correction was necessary as, very often, the footprint area was bigger than the pasture. It supposes there are no cattle in the footprint area outside of the experimental area, which is the case in the main wind direction (SW) where the pasture is bordered by a crop field.

In the other directions, the pasture is surrounded by other pastures where some cows may be present from time to time. As a result, around 80% of the cumulated footprint is coming from the pasture and from the crop. The remaining contribution is coming from pastures that may, sporadically, be polluted by other cows. To take this into account, an uncertainty of 10% was accounted for SD_p.
The second estimate (geolocation-based stocking density, SD_f) is based on geolocation tracking. The individual contribution of each animal was estimated half-hourly using the KM model and was summed as (Felber et al., 2016b):

$$SD_f = \sum_i \sum_j n_{ij} \phi_{ij} \frac{n_{avg}}{n_{detected}} \qquad \textbf{Equation 5.4}$$

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, 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 specific half hour. For each half hour, the position of some animals was unknown (calves were not tracked and not all geolocation devices were always operational), the calculated SD_f was thus corrected in order to also include undetected or unaccounted animals. The resulting average correction factor ($\frac{n_{avg}}{n_{detected}}$) was of 1.47.

Both SD_p and SD_f depend on the model used to compute the footprint function and its associated uncertainties. The footprint model used in this study was thus carefully selected through an artificial source experiment run by (Dumortier et al., 2019) at the same site.

2.6. *HOMOGENEOUS APPROACH FOR E_{COW}*

In the homogeneous approach (**Figure 5-2**), annual R_{cows} were computed using **Equation 5.1**. For the determination of NEE_{past}, CH_4 fluxes were used as a cow detection tool, considering that CH_4 fluxes emitted by the cattle were much higher than those exchanged by the soil and the vegetation (Dumortier et al., 2017a). The advantage of this CH_4 flux filtering approach is that it can be used throughout the year, even outside GPS tracking campaigns. Annual CO_2 flux data series were filtered in order to only keep data when net ecosystem exchange was unaffected by cow respiration (NEE_{past}).

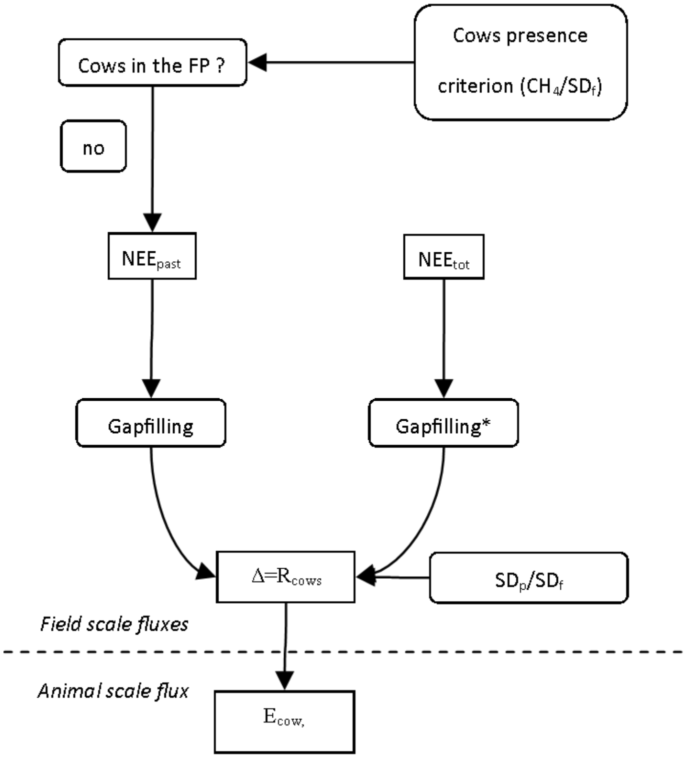

Figure 5-2: Flow chart of the procedure used to estimate cow respiration rates per livestock unit (E_{cow}) using either GPS campaigns or assuming a homogeneous cow repartition in the field (CH_4 approach). Both procedures are similar, differing in their way of assessing the presence of cows in the footprint (FP) and of assessing the stocking density (stocking density in the pasture (SD_P) for the CH_4 filtering approach, or stocking density in the footprint (SD_f) for the GPS method). Gaps in total net ecosystem exchange (NEE_{tot}) were filled only for the CH_4 approach. Gaps in pasture net ecosystem exchange (NEE_{past}) were filled for both approaches. Figure modified after Felber et al., (2016b).

The CH_4 flux threshold used for filtering was calibrated during the GPS tracker campaigns: cows were considered to be absent when SD_f was lower than 2×10^{-5} LU m^{-2}. The CH_4 flux threshold was then fixed in order to keep a maximum of events without cows and a minimum of events with cows. The best compromise (>85% of events without; <10% of events with cows) was obtained for a value of 25 nmol CH_4 m^{-2} s^{-1}.

Missing NEE data were filled for both NEE_{past} and total NEE_{tot} data sets using the online REddyProc gap filling and flux partitioning tool (https://www.bgc-jena.mpg.de/bgi/index.php/Services/REddyProcWeb, (Reichstein et al., 2005)). This algorithm uses time-moving look up tables and finds fluxes measured in similar meteorological conditions to fill the data. Meteorological variables used by the algorithm are the air temperature (T_{air}), the vapor pressure deficit (VPD), and the global radiation (R_g). R_{cows} was then obtained by subtracting filled NEE_{tot} and NEE_{past}

data series, and average monthly/annual respiration rates per LU ($E_{cow,hom}$) were obtained by dividing this result by monthly/annual average SD_p.
The uncertainties on $E_{cow,hom}$, besides those affecting SD_p, are due to uncertainties affecting R_{cows} estimation, which itself depends on NEE_{tot} and NEE_{past} estimates during grazing periods. To be complete, the uncertainties on NEE_{tot} and NEE_{past} were computed for the whole year but were combined only during grazing periods to estimate uncertainties on R_{cows}.
Annual NEE estimates are typically affected by different sources of random and systematic errors:

1) Random errors affecting both the measured fluxes and the gap filling procedure (Dragoni et al., 2007; Richardson et al., 2006).
2) Error associated with the additional gaps in NEE_{past} due to cow presence.
3) A residual uncertainty associated with the choice of the u_* threshold used to filter fluxes under low turbulence conditions (Aubinet et al., 2018).
4) A residual uncertainty associated with the choice of the cut-off frequency for the high frequency loss corrections (Gourlez de la Motte et al., 2016; Mamadou et al., 2016).

Each sources of error were computed separately:
(1) The random error on half-hourly fluxes was computed using the successive days approach developed by Hollinger and Richardson, (2007). In this approach, half hourly errors on measured fluxes (ε_m) were computed as the absolute difference between two valid successive day fluxes with similar weather. A regression between bin-averaged NEE (same number of observations per bin) and the standard deviation of the error ($\sigma(\varepsilon_m)$) was established separately for positive and negative flux values for NEE_{tot} (Felber et al., 2016b; Gourlez de la Motte et al., 2016) :

$$\begin{cases} \sigma(\varepsilon_m) = -0.11 \times NEE + 1.47 \quad \text{for } NEE \le 0 \quad (R^2 = 0.90) \\ \sigma(\varepsilon_m) = \quad 0.30 \times NEE + 0.08 \quad \text{for } NEE > 0 \quad (R^2 = 0.97) \end{cases}$$ **Equation 5.5**

and for NEE_{past} :

$$\begin{cases} \sigma(\varepsilon_m) = -0.1 \times NEE + 1.02 \quad \text{for } NEE \le 0 \quad (R^2 = 0.84) \\ \sigma(\varepsilon_m) = \quad 0.21 \times NEE + 0.22 \quad \text{for } NEE > 0 \quad (R^2 = 0.94) \end{cases}$$ **Equation 5.6**

For both data sets, random noise was then added to half-hourly NEE assuming an exponential distribution (Richardson and Hollinger, 2007) with zero mean and a standard deviation $\sigma(\varepsilon_m)$ (Monte Carlo simulation (Dragoni et al., 2007)). Data were then filled and annual NEE values were computed. The operation was repeated 100 times and the random error was computed as 2σ (standard deviation) of the 100 annual NEE values.

(2) The error due to additional gaps in NEE_{past} was estimated using the following procedure. First, missing data in the NEE_{past} data set were filled. Then, gaps initially present in NEE_{past} except those due to cow presence were re-added. Noise was also added to the gap filled data using **Equation 5.6**. By doing so, we obtain a data set without cow respiration influence but with the same number of gaps as the NEE_{tot} data

set. Then, a number of gaps corresponding to the amount of additional gaps due to cow presence in the footprint were randomly added to the data set only during grazing periods. The operation was repeated 100 times and the annual NEE_{past} were computed. The error was computed as 2σ of the 100 annual NEE values.
(3) The uncertainty associated with the choice of the u_* threshold was estimated by computing annual NEE values by varying the u_* threshold within a plausible range of 0.13 ± 0.5 m s^{-1} (Gourlez de la Motte et al., 2016). The error was computed as 2σ of the computed values.
(4) The uncertainty associated with the choice of the cut-off frequency amounted to only 2 g C m^{-2} yr^{-1} on average at our site and was therefore neglected (Gourlez de la Motte et al., 2016).
The different sources of uncertainties were combined following Gaussian propagation rules to estimate annual uncertainties on NEE_{tot} and NEE_{past}.
Finally the uncertainty on R_{cows} was computed. As R_{cows} is computed as the difference between NEE_{tot} and NEE_{past} which are computed from the same data sets (with additional gaps for NEE_{past}), the last two sources of errors nullify. The error on R_{cows} is therefore the combination of (1) the random error affecting both NEE_{tot} and NEE_{past} during grazing events only and (2) the error due the presence of additional gaps in NEE_{past} (also only during grazing events). The resulting uncertainty on R_{cows} was computed by combining these terms following Gaussian error propagation rules. The magnitude of each error term during grazing periods is computed for both years in **Table 5-1**. The uncertainty on E_{cow}, hom was computed by adding the relative errors on R_{cows} with the relative error of 10% on SD_p.

Table 5-1: 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		Gap filling	
	NEE_{past}	NEE_{tot}	NEE_{past}	R_{cows}
2013	14	12	8	20
2015	17	15	9	24

2.7. *HETEROGENEOUS APPROACHES FOR E_{COW}*

2.7.1. GPS approach

Four cattle geolocalization campaigns were organized (**Table 5-2**). 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 $SD_f > 2×10–5$ 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)).

Table 5-2: 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 Automn 2015	19 Oct 2015 - 2 Nov 2015	15	8/0	S-E

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 well as the use of the KM footprint function to weight the animals' contribution. It however does not include uncertainties associated with the choice of the footprint model as stated at section 2.5.

2.7.2. Confinements approach

Confinement experiments specifically designed to estimate the cattle respiration rate per LU were carried out at DTO. The methodology and the results are fully described and discussed in a previous paper (Jérôme et al., 2014). Briefly, the method consists of confining the entire herd for one day on a small part of the pasture located in the main wind direction. By confining the cows in the main wind direction area (**Figure 5-1**) and by filtering the fluxes according to wind direction, the probability that the cows are in the footprint area is greatly increased. The designated paddock was not grazed the day before or the day after the confinement. Fluxes measured during the confinement periods were then compared to the fluxes measured one day before and after:

$$R_{cows,conf} = \frac{\sum(NEE_i - NEE,_{i\pm 24h})}{n_{obs}}$$ **Equation 5.7**

Where $R_{cows,conf}$ is the average respiration of all the cows in the confinement area, NEEi is the NEE at a given hour during the confinement, NEEi±24h is the NEE at the same hour 24 h before and after the confinement, and nobs the number of valid paired NEE observations. To make sure that these differences were due to cow respiration and not to micrometeorological variability, only data pairs with similar conditions were kept (soil and air temperature within 3°C, wind speed 3 m s^{-1} and photon photosynthetic flux density (PPFD) within 75 µmol m^{-2} s^{-1}). The experiment was repeated four times. The average livestock respiration rate ($E_{cow,conf}$) during the confinement was then obtained by converting the average difference in terms of kg C LU^{-1} d^{-1} by dividing R_{cows},conf by SDc (stocking density during confinements), computed using **Equation 5.3** considering φ as the average contribution of the confinement area to the footprint, A the confinement area and navg the number of animals in this area. By doing so, we consider a homogeneous repartition of the cows in the confinement area which is more realistic as cattle are confined in a smaller area that is within the footprint extent, ensuring that cows are contributing to the measured flux. In the present study, the results obtained from this former study were used but note that this latter footprint correction was not implemented in Jérôme et al. (2014) (i.e. φ was considered equal to 1).

The uncertainty on $E_{cow,conf}$ was computed as 2 times standard error of the average $E_{cow,conf}$. Note that, again, this uncertainty estimate does not account for uncertainties associated with the choice of the footprint model.

2.7.3. Animal carbon budget approach

Another possibility to estimate the cow respiration rate per LU is to compute a complete carbon budget at the animal scale when the animal is on the pasture (C fluxes at the barn are not included). This carbon budget was computed from ingested biomass estimates, combined with their C content and digestibility. The methodology and the results are fully described and discussed in a former paper (Gourlez de la Motte et al., 2016). **Figure 5-3** describes the C fluxes involved in the C budget of an animal. Briefly, to build this C budget, the C ingested in dry matter (C_{intake}) was estimated using biomass measurements combined with laboratory dry matter C content measurements.

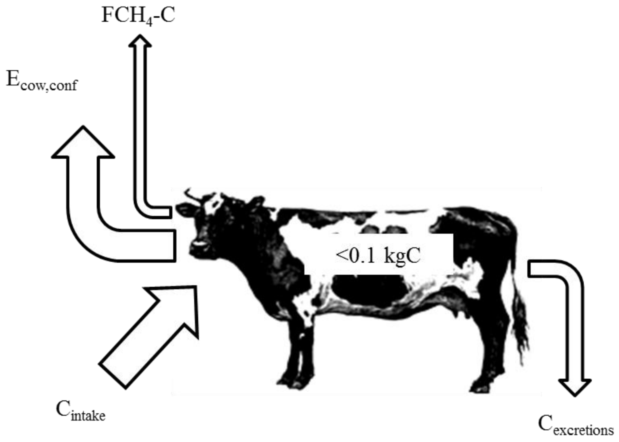

Figure 5-3: Illustration of the fluxes involved in the carbon (C) budget of a cow. $E_{cow,budg}$ corresponds to the respiration of a cow estimated from the carbon budget, F CH_4-C the methane emitted by the cow, $C_{excretions}$ the C lost in excretions, and C_{intake} the C ingested through biomass consumption.

To do so, herbage heights were measured almost once a week during the grazing season using a 0.25 m^2 rising plate herbometer over 60 points covering the whole field. Previously, an allometric equation between the herbage height and the herbage mass (HM, dry matter) was calibrated in order to convert herbage heights into HM (Gourlez de la Motte et al., 2016). For this, samples were directly harvested in the field and protected enclosures with a 0.25 m^2 quadrat. Herbage heights were measured right before and after being sampled. The samples were then dried using a forced-air oven to obtain their dry matter content. A relationship between grass height differences and harvested dry matter content was then established. Biomass C content was determined by laboratory measurements of samples following the dumas method (Dumas, 1831). Three secured enclosures were used to obtain grass growth rates during grazing periods ($HM_{gr,i}$). Cattle C intake through biomass consumption for a given period i was computed as:

$$C_{intake,i} = C_{content,grass}(HM_{beg,i} - HM_{end,i} + HM_{gr,i}) + C_{content,feeds}F_{import,i}$$ **Equation 5.8**

where $HM_{beg,i}$ and $HM_{end,i}$ are the herbage mass at the beginning and at the end of the period i (weekly), Ccontent,grass the C content of grass in the field, Ccontent,feeds the C content of feeds supplements and $F_{import,i}$ the dry matter ingested in form of feed supplements. This equation was used on a weekly basis and the annual Cintake was computed by summing all the periods. Note that, when $HM_{beg,i}$>$HM_{end,I}$, this biomass is accounted negatively and is therefore considered uneaten.

The C lost by the animal through excretions ($C_{excretions}$) was computed as the fraction of non-digestible ingested carbon. Digestible and non-digestible organic matter contents were obtained by analyzing the biomass samples collected almost every week in the field using near infrared reflectance spectrometry analysis (Decruyenaere et al., 2009). Cow CH_4-C emissions were estimated using a constant fraction of the ingested biomass, which was 6% (Lassey, 2007). The meat production term (Fproduct) was estimated from live weight gain measurements but was negligible compared to other fluxes. Finally the CO_2 cow respiration ($E_{cow,budg}$) was computed by closing the C budget of the animal. The results obtained from this former study were directly used in the present paper.

In lack of a suitable method to evaluate the uncertainty associated with this method, no error bound was computed for $E_{cow,budg}$. Note that the main factor influencing $E_{cow,budg}$ uncertainty should be the uncertainty on dry biomass intake which is especially challenging to estimate in continuously grazed pastures.

2.8. *Alternative NEE_{TOT} determination*

As direct NEE_{tot} estimates rely on the homogeneity hypothesis assuming an even distribution of the grazing animals, significant biases may appear if this hypothesis is not met. An alternative annual NEE_{tot} may then be provided by computing NEE_{past} (using CH_4 filter, see section 2.6) and R_{cows} independently and by summing them using **Equation 5.1**. R_{cows} can be obtained by combining the cow respiration rate per LU obtained by one of the three methods detailed above (Section 2.7) with the average stocking density (SD_p). The uncertainty on the up scaled R_{cows} was computed by adding the relative errors on both the concerned E_{cow} and SD_p. The choice of the used respiration rate depends on 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 5-4**, a) and nighttime (**Figure 5-4**, 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 5-3**). 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.

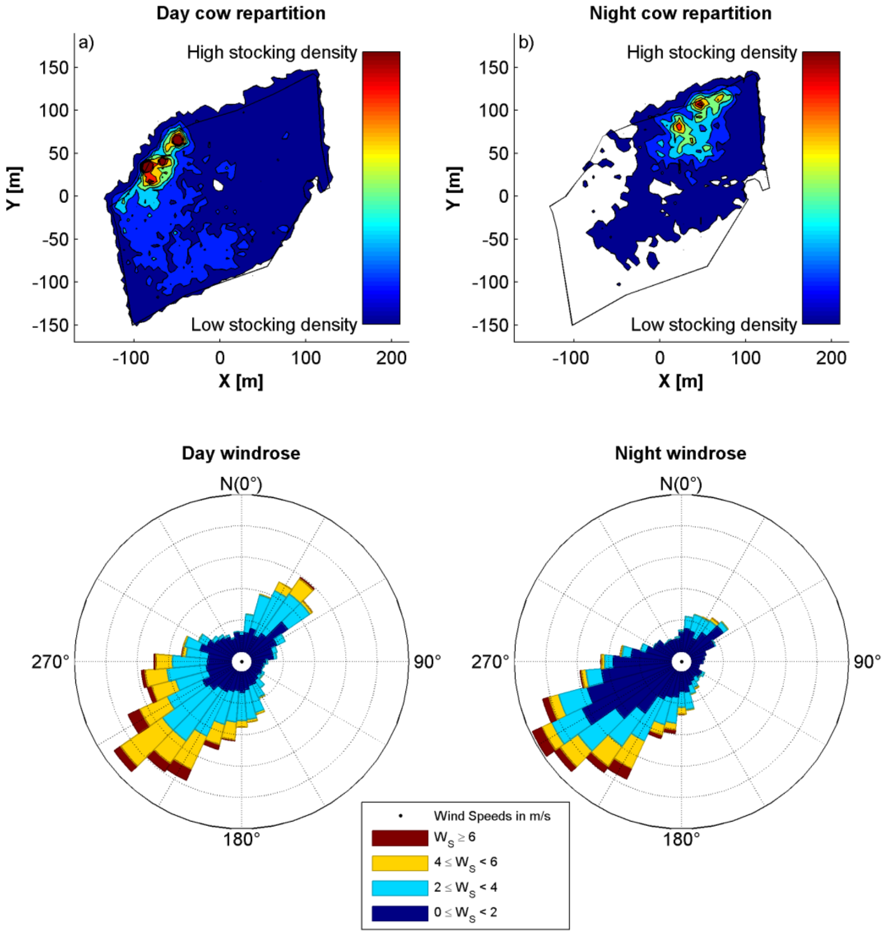

Figure 5-4: Cow distribution maps during the GPS campaigns for both days (a) and nights (b). The same scale is used for both maps. The numeric scale of the color map is given for a comparison purpose. One unit corresponds to the presence of one animal in a pixel of 5×5m^2 during 5 minutes. Areas colored in white are areas that are never visited by the herd. The average wind rose for the year 2015 is also presented both during the day (c) and during the night (d). For interpretation of the colors in this figure, the reader is referred to the electronic version of this article.

Table 5-3: 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**

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 shows 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.

On average, SD_f was 25% lower than SD_p during the campaigns. This result however cannot be directly extrapolated to the entire year in terms of cow respiration, as the north-east wind conditions were over represented in the data when compared to yearly wind direction statistics (data not shown).

Nevertheless, the cow distribution maps clearly show that the cows are not evenly distributed on the pasture, especially during the night.

3.2. *COW RESPIRATION RATE PER LU CONSIDERING A HOMOGENEOUS COW REPARTITION*

3.2.1. Validation of the CH_4 flux filtering approach

In order to validate the CH_4 flux filtering approach, NEE_{past} was computed during GPS tracking campaigns by using both the CH_4 and the cow presence (GPS) criterion. The results show that, after gap filling, very similar NEE_{past} were obtained when using both partitioning methods for each campaign (**Table 5-4**) with differences in NEE_{past} that varied only from 0 to 4 g C m^{-2}. Identical differences between R_{cows} were observed, as they were computed as the difference between NEE_{tot} (which was the same for both methods) and NEE_{past}.

Table 5-4: Gap filled net ecosystem exchange of the pasture without cow influence (NEE_{past}) using the CH_4 cow presence filtering criterion and the GPS criterion for each GPS campaign.

Campain 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

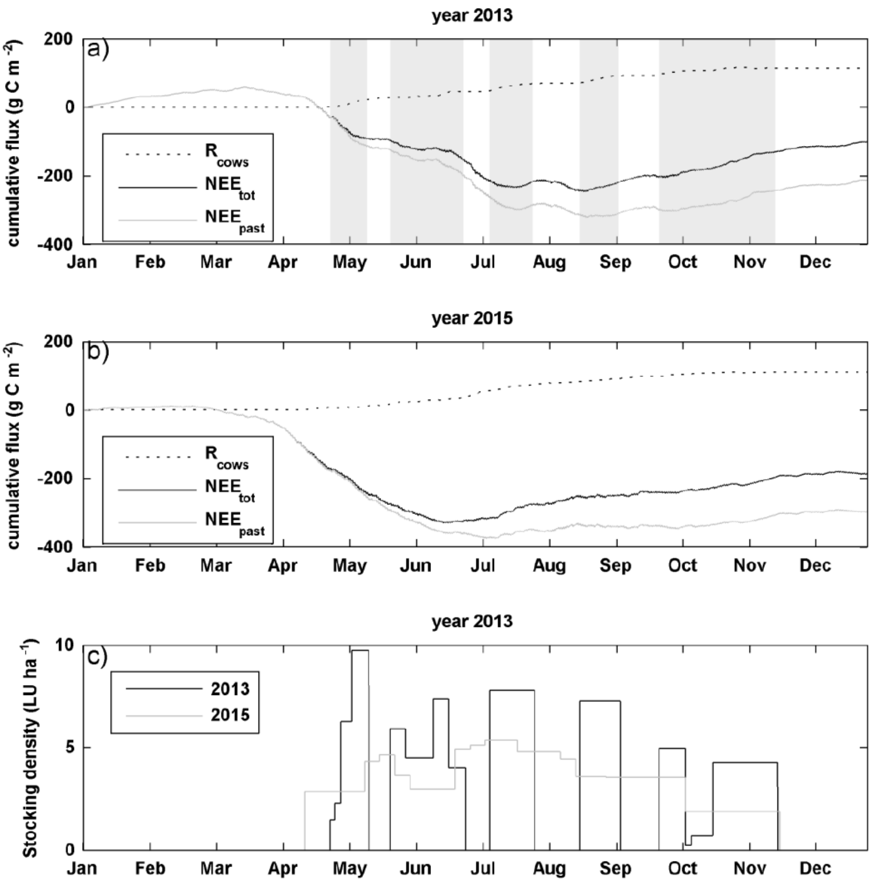

Figure 5-5: Evolution of the gap filled total cow respiration (R_{cows}), the net ecosystem exchange including cow respiration (NEE_{tot}) and the net ecosystem exchange excluding cow respiration NEE_{past} for both 2013 (a) and 2015 (b). Grazing periods are indicated in grey. (c) Evolution of stocking densities on the field for both years.

3.2.2. Discriminating NEE_{tot} into NEE_{past} and R_{cows}

The CH_4 flux filtering approach was then applied to two years of measurements. After filtering, the NEE_{tot} data set consisted of 8579 (49%) and 8432 (48%) valid fluxes (**Table 5-5**) in 2013 and 2015 respectively, while the NEE_{past} data set consisted of 6911 (39%) and 6325 (36%) valid fluxes. Cumulative NEE_{tot}, NEE_{past}, R_{cows} and stocking densities are shown in **Figure 5-5** for 2013 and 2015. The same trend can be observed for both years. At the beginning of the year, NEE_{tot} and NEE_{past} were identical as there were no animals on the pasture. Then, the curves start to deviate from each other because of the animal. At the end of the year, when no animals were on the pasture, the curves evolve again in parallel. The total annual R_{cows} amounted to very similar values of 112 ± 20 and 111 ± 24 g C m^{-2} yr^{-1} in 2013 and 2015 respectively.

Table 5-5: Number of valid net ecosystem exchange measurements, including the cow respiration rate (NEE_{tot}) and excluding it (NEE_{past}), annual gap filled sums of both net ecosystem exchange and the total gap filled annual respiration R_{cows} for both 2013 and 2015. Note that error bar on R_{cows} are not the 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} (gC m^{-2})	NEE_{past} (gC m^{-2})	R_{cows} (gC m^{-2})
2013	8579	6911	-102	−214	112
2015	8432	6325	-188	−299	111

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 amounted to 2.0 ± 0.6 and 2.0 ± 0.6 kg C LU^{-1} d^{-1} for both years (**Figure 5-6**, a, **Table 5-6**) 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 5-6**, b) and from night fluxes (**Figure 5-6**, 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.

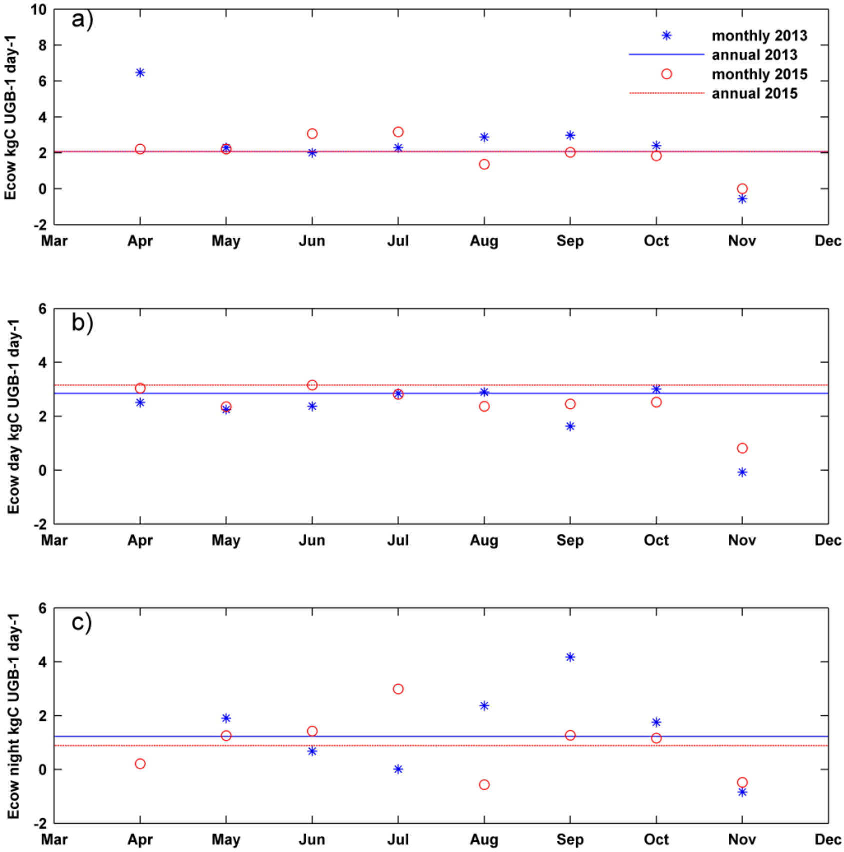

Figure 5-6: Mean cow respiration rates per LU in 2013 and 2015 computed from (a) all the data ($E_{cow,hom}$), (b) daylight data ($E_{cow,hom,day}$, global radiation >2.5 W m^{-2}), and (c) night data ($E_{cow,hom,night}$) considering a homogeneous cow repartition. Average monthly/annual respiration rates per LU were obtained by dividing total annual/monthly cow respiration (R_{cows}) by monthly/annual average SD_p. Annual values are marked by lines while circle markers correspond to the monthly values.

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 5-7**). 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).

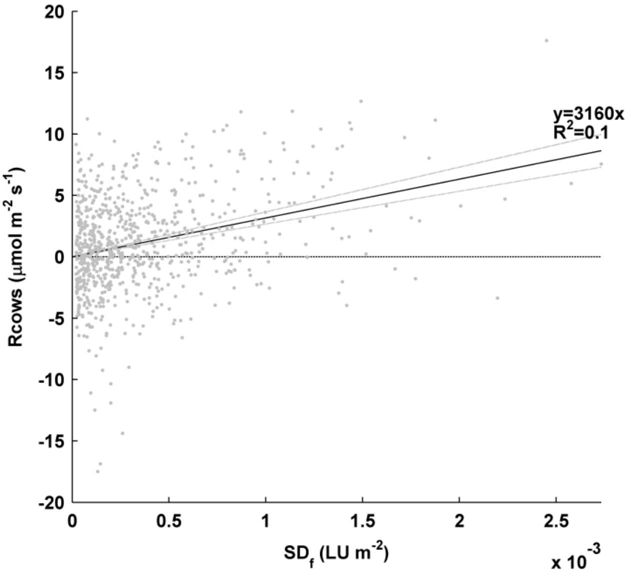

Figure 5-7: Linear regression between the total respiration of the cows in the footprint (R_{cows}) on a half-hourly time scale and the weighted stocking density in the footprint (SD_f). The fitted line (y = 3160x SE = 245, R_2 = 0.1) corresponds to a daily cow respiration rate of 3.2 ± 0.5 kg C LU^{-1} d^{-1}. The uncertainty bound is given as 2SE.

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 5-8**). 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 Cintake 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.

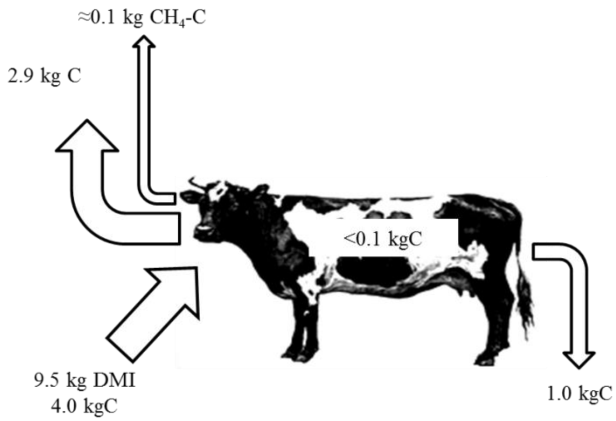

Figure 5-8: Average daily carbon budget of a Belgian Blue beef cow.

3.4. *BIAS INDUCED BY A NON-HOMOGENEOUS COW DISTRIBUTION*

As shown in **Table 5-6**, $E_{cow,hom}$ 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 5-4**). 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.

Table 5-6: Average footprint contribution of the pasture and stocking density on the pasture (SDp), daily average cow respiration rates per livestock unit (LU) computed from a) annual gap filled data sets assuming a homogeneous cow repartition on the field from day (global radiation > 2.5 W m^{-2}, $E_{cow,hom,day}$), night ($E_{cow,hom,night}$), and all the data ($E_{cow,hom}$) and b) without assuming this cow repartition and using GPS trackers ($E_{cow,GPS}$), confinement experiments ($E_{cow,conf}$), and the carbon budget of the animal ($E_{cow,\ budg}$). Field scale cow respiration rates are also given when computed from the CH_4 partitioning (R_{cows}) and when upscaled using $E_{cow,GPS}$ ($R_{cows,GPS}$). The footprint is expressed as the 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		
$E_{cow,hom}$	2.1	2.1
$E_{cow,hom,day}$	2.8	3.2
$E_{cow,hom,night}$	1.2	0.9
b) No homogeneous cow repartition hypothesis		
$E_{cow,GPS}$	3.2±0.5	
$E_{cow,conf}$	2.6±0.6	
$E_{cow,budg}$	2.9	
Field scale fluxes (g C m^{-2})		
$R_{cows,hom}$	112	111
$R_{cows,GPS}$	164±26	175±27
Bias (absolute value)	52	64

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 5-6**), 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., (2017, 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., 2017a; 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 g C m^{-2} yr^{-1} because of non-homogeneous cow repartition resulting in an underestimation of R_{cows}. This underestimation implies that the carbon sink activity of the pasture was considerably overestimated when using NEE_{tot} values to compute its net biome productivity. The NBP (including cow respiration, **Equation 5.2**) of the pasture was computed for 5 years (2010-2014) in a previously published paper using NEE_{tot} estimates and other non CO_2 carbon fluxes (Gourlez de la Motte et al., 2016). Those results showed that the pasture acted as a C sink every year with an average

NBP value of –161 g C m^{-2} yr^{-1} (lowest absolute in 2013: –87 g C m^{-2}, highest absolute value in 2014: –176 g C m^{-2}) and an average annual stocking rate of 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 37% of NBP) every year because of cow respiration underestimation, the corrected average NBP is reduced (in absolute values) to ≈ –100 g C m^{-2} yr^{-1}. The magnitude and sign of this bias is of course site specific so that, depending on the site configuration, the wind direction, and the gregarious behavior of the animals, it can lead to either positive or negative systematic errors. This must therefore be verified on a case by case basis. It is important to highlight the fact that gregarious behaviors of the animals on free range pastures are expected, at least for cows (Hassoun, 2002) and sheeps (Dumont and Boissy, 2000). The methodology presented in this paper may be used at each site to detect and, if necessary, estimate this bias and correct C budgets accordingly.

4.3. *METHOD TO MEASURE A REFERENCE COW RESPIRATION RATE PER LU*

In this paper, three methods were proposed and tested at DTO to estimate a reference E_{cow} that does not assume a homogeneous cow repartition in the pasture and that can be used as a basis of comparison to check if R_{cows} is measured in a representative way. This respiration rate per LU can also be used to correct R_{cows} if necessary.

The GPS tracker method appeared to be very useful as it provided an improved understanding of animal location habits. The distribution maps have proven to be a useful tool to detect heterogeneous cattle distributions. The use of GPS devices combined with footprint models also provides a more realistic stocking density in the footprint (Felber et al., 2016b, 2015). This footprint function is however also the subject of several uncertainties (Dumortier et al., 2019). Finally, the GPS tracking method has the advantage of not disturbing the behavior of the cows when compared, for example, to 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 Cintake 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 Cintake is to estimate the energy requirements of the animals for maintenance, activity, and grazing and convert this energy into dry matter intake (and then C_{intake}) (IPCC, 2006) or, for dairy cows, using equations based on milk yields and the lactation week of the cows, as proposed by Felber et al. (2016).

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 6-5, 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. (2017). 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.

6. Acknowledgments

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CHAPTER 6

GENERAL DISCUSSION, PERSPECTIVES & CONCLUSIONS

Chapter 6. General discussion, perspectives & conclusions

We have come a long way since the setup of a fast methane analyzer at the Be-Dor site in 2012. Eight years of data helped us getting a better understanding about how to measure fluxes on a pasture, how to make a proper carbon budget of a pasture, how to infer cattle methane emissions and what drives cattle emissions. Each article, presented in chapters 2 to 5, helped us answering these questions and address the objectives of the thesis (**Figure 6-1**).

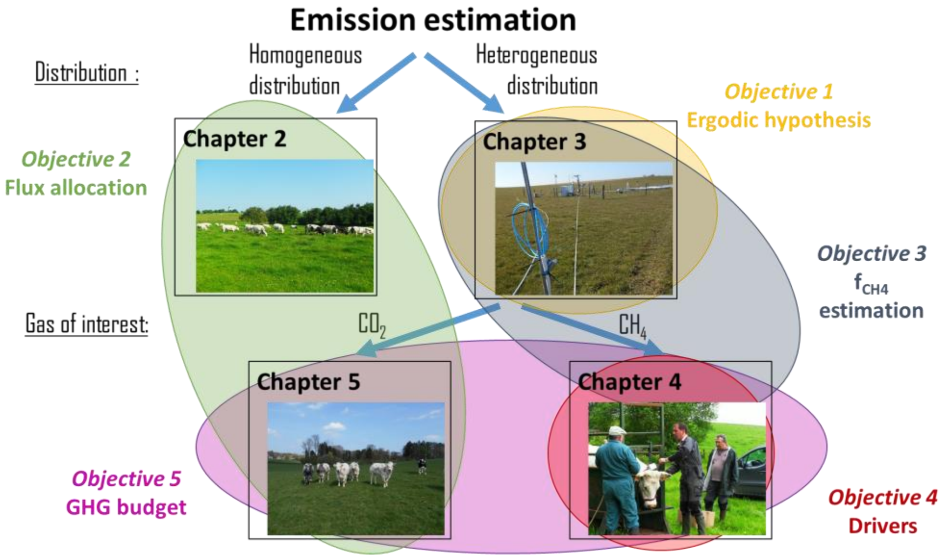

Figure 6-1 Schematic structure of the thesis.

Two hypothesis could be considered when estimating cattle emissions using EC: a homogeneous cattle distribution on the pasture, over long periods and on average (Chapter 2) or a heterogeneous cattle distribution on the pasture (Chapter 3, 4 and 5). The heterogeneous cattle distribution hypothesis is of course more representative of the real situation but requires recording animal locations. Moreover, if animals are not distributed homogeneously in the pasture, the ergodic hypothesis is breached, which requires additional attention (Objective 1). Moreover, two gases of interest were considered: CH_4 (Chapter 4) and CO_2 (Chapter 5). In the case of CO_2, disentangling cattle and soil/plant exchanges was not straightforward (Objective 2). Therefore, computing cattle emissions was easier to develop for CH_4 exchanges (Objective 3), although the same technique was used on CO_2 later on in order to provide an unbiased pasture GHG budget (Objective 5). Finally, cattle CH_4 emissions drivers were looked for (Objective 4). Each objective is hereunder discussed.

1. ERGODIC HYPOTHESIS

Our first objective was to adapt EC to deal with situations where mobile and intermittent emission sources are found inside the target area. This objective is mainly related to the ergodic hypothesis. However, other challenges like the impact of cattle on turbulence structure or roughness length are discussed by Felber et al. (2015) but will not be discussed further here.

1.1. *ISSUE*

EC requires the measurement point to be representative of all points at the same height above the whole pasture (ergodic hypothesis), as described by Foken et al. (2012a). However, this hypothesis is only fulfilled when the mast is placed above a totally homogeneous area which emissions are constant over time. This is never the case when dealing with ecosystems. EC should always be submitted to quality tests in order to decide whether or not each measurement fulfils enough the ergodic hypothesis to be used (Foken and Wichura, 1996).

One of our main challenges was thus to deal with cattle as they behave as mobile and intermittent point sources. Their presence in the FP of the flux measurements has therefore the potential to greatly increase the probability of breaching the ergodic hypothesis, leading to erratic flux measurements and the potential removal of many measurements through application of quality filters.

The idea of using EC to quantify point source emissions only recently emerged (Harper et al., 2011; McGinn, 2013). Since then, some authors who measured fluxes associated with point sources simply overlooked the impact of the ergodic hypothesis breach (Arriga et al., 2017; Heidbach et al., 2017; Prajapati and Santos, 2017) while others grounded some quality filters in order to avoid too large data rejection (Felber et al., 2015). However, in our opinion, both approaches fail to properly address the issue, as explained in section 1.2.

1.2. *CONTRIBUTION*

The stationarity issue hides two potential problems. Firstly, quality filters are generally used to remove remaining unstationary data. However, as shown in chapter 3, this approach may remove a large part of the dataset, while still failing to remove unstationary data. For example, one of the most commonly used stationarity test, the one developed by Foken & Wichura (1996) for ecosystem CO_2 fluxes monitoring, dives each half-hour into six 5 minutes periods and flags periods associated with wind velocity, concentrations or fluxes relative mean variations above a specific threshold (generally 15 %). Therefore, this test often flags fluxes close to zero and fails to flag data associated with elevated fluxes which do generally correspond to cattle presence in the FP. This would result in biased budget as almost only measurement without cattle in the FP would be affected. Application of the Foken & Wichura (1996) stationarity test is thus not advised when working with point sources emissions. Secondly, if mean CH_4 concentration varies during an averaging period, the instantaneous mean is not representative of the average mean. Therefore, the use of a block averaging method tends to over-estimate deviations form the mean. This problem was addressed in Chapter 2 (Dumortier et al., 2017a) by working with a detrending method (use of a running mean instead of a block averaging method). This approach, though theoretically sounded, broke Reynod's averaging rules and thus required validation in the field. Therefore, different calculation options were tested and compared in Chapter 3 with the use of an artificial known source to benchmark our computed fluxes (Dumortier et al., 2019) and the running mean was always associated with a higher performance score than the block average (see Chapter 3 for more information).

1.3. *OUTLOOK*

The use of a running mean instead of a block averaging method when computing EC fluxes could be extended to other gases (CO_2, N_2O) when strong point sources are present in the FP. However, a new flux computation method addressing this stationarity issue has been developed; the wavelet analysis method. The main theoretical advantage of this method is that stationarity of the time series is not required anymore (Schaller et al., 2017). However, according to our knowledge, this method has never been applied to cattle yet and the potential improvements brought by wavelet analysis are still quite speculative. Wavelet analysis was in its infancy when this thesis was initiated (Detto et al., 2011; Varadharajan and Hemond, 2012). Progress has been made very recently on the application of the method and its usefulness has been highlighted in the context of CH_4 sporadic and localized outbursts in a wetland (Göckede et al., 2019; Schaller et al., 2019). Cattle CH_4 emissions are a textbook case in terms of flux event and we believe that a study that would compare the classical EC, our adapted method (detrending and grounding of stationarity filtering tests) and the wavelet-computed fluxes would be highly desirable. Moreover, wavelet analysis does not require any additional data. Therefore, previous data dating from several years could be reprocessed in order to compute unbiased fluxes.

2. FLUX ALLOCATION

Our second objective was to identify the respective contribution of cattle and soil / plants to the CH_4 and CO_2 exchanges measured above a grazed pasture.

2.1. *ISSUE*

Fluxes measured above a pasture result from the mix of at least three components: (1) fluxes associated with the soil-plant continuum (including cow excreta), (2) fluxes associated with cattle, (3) fluxes associated with contamination originating from outside the pasture. EC measurements do not discriminate the fluxes between these three different origins. We wanted to identify the respective contribution of soil / plant, cattle and contamination sources to the CH_4 and CO_2 exchanges as this is required to establish a sound carbon budget of the pasture.

The main challenge is that fluxes measured above a pasture are representative of emissions originating from the FP area, which seldom equals the pasture. The FP is always larger than the pasture, ending in a contribution from (contaminating) sources like manure heaps, barns or cattle from adjacent pastures, whose emissions bias the carbon budget. However, the FP area does never cover the entire pasture. In this case, inhomogeneous cattle distribution on the pasture may cause a second bias. Both biases are strongly site dependent as they depend on the locations of the contaminating sources and where the herd gathers . Moreover, varying cattle distribution in the pasture at different time scales can definitely hamper the interpretation of flux daily/seasonal/annual variability. Until now, most of the studies measuring CO_2 fluxes above a pasture considered the FP area as representative of the whole pasture as reviewed by (Gourlez de la Motte et al., 2019) thus neglecting this potential bias. However, Chapter 3 and 5 along with other studies (Felber et al., 2016a; Hunt et al., 2016; Rutledge et al., 2017a, 2017b) showed that the homogeneous cattle distribution hypothesis can no longer be assumed and that pasture budgets should consider this bias.

2.2. *CONTRIBUTION*

While each component varying contribution to the FP constitutes a challenge, it also offers opportunities as it allows flux allocation according to their origins. Tools are however needed to identify the respective contribution of each component to the measured fluxes. The following approach was developed during this thesis.

For CH_4, it was hypothesized that fluxes coming from the pasture were almost exclusively associated with cattle. All fluxes measured in the absence of cattle in the FP could thus be associated with contamination sources. This hypothesis was confirmed in Chapter 2 by field observations; in the absence of cattle in the FP, elevated fluxes were associated with very specific wind directions where plausible contamination sources were found (barn or manure heap). For other wind directions, fluxes were very small, showing that the soil/plant continuum only represents a minor contribution to CH_4 exchanges. These two sources being filtered/neglected, remaining fluxes were associated with enteric emissions.

For CO_2, the situation was more intricate as soil/plant and cattle emissions are of similar magnitude during the night and can cancel each other during the day. A way to overcome this issue is to measure soil/plant exchange when no cattle are present in the FP (e.g. by using CH_4 fluxes as a cattle presence in the FP proxy). Soil/plant exchanges could then be calculated over long periods by using a gap filling tool like REddyProc (Reichstein et al., 2005). Fluxes associated with cattle thus correspond to the difference between the measured flux and the simulated flux without cattle. Cattle emissions could then be computed by dividing the fluxes associated with cattle by the stocking density. This partitioning method is described in Chapter 5, §2.7.1. (Gourlez de la Motte et al., 2019). The issue of contamination sources is much more limited for this GHG on our study site. Neighboring pastures (grazed or not) present a similar exchange pattern as the area undergoing the carbon budget. The potential bias is thus limited. This issue should however be considered in study areas containing potential contaminating sources for CO_2 (e.g. major roads, urbanized areas etc.).

2.3. *OUTLOOK*

Knowledge of cattle presence in the FP is necessary for flux allocation which allows computation of pastures' carbon budget (Chapter 5) and identification of carbon fluxes drivers. Measuring methane fluxes in the pasture is therefore very useful, even beyond the scope of methane. Methane fluxes can indeed be considered as indicators of cattle presence in the FP and can thus help give sense to other measurements (e.g. CO_2, N_2O, VOC) on the same mast. However, as adding another measurement to existing masts is costly, alternatives to methane fluxes as a proxy for cattle presence were searched for. For instance, identifying proxies of cattle presence in the FP on the basis of slower (and therefore less financially demanding) CH_4, or even better on the basis of already available CO_2, concentration measurements rather than fluxes would be very attractive. Statistical quantities like raw data spike counts, skewness or kurtosis have been tested but without much success. Other source partitioning methods based on high frequency eddy covariance data (Klosterhalfen et al., 2019; Scanlon and Kustas, 2010) have not been considered in this thesis and remain speculative. Therefore, CH_4 fluxes still seems to be the better proxy of cattle presence in the footprint.

While 17 % of the ICOS ecosystem stations do correspond to grasslands (ICOS handbook, 2019), very few of them are grazed (up to our knowledge, only two stations: Dorinne (Belgium) and Laqueille (France)). One of the reason for this low proportion of grazed pastures might be that flux allocation between cattle and the soil-plant continuum still causes discussion when analyzing those fluxes. In these conditions, the CO_2 flux allocation method proposed in Chapter 5 might be helpful. We therefore strongly advise to generalize CH_4 fluxes measurement to all EC stations monitoring fluxes above a pasture.

3. EMISSION ESTIMATION

Our third objective was to develop a method allowing estimation of cattle CH_4 emissions per LU (f_{CH4}) on a pasture using EC. This method is applied to quantify Belgian Blue CH_4 emissions at typical Walloon cow-calf operation and the associated error.

3.1. *ISSUE*

Even after obtaining robust fluxes (Chapter6-§1. Ergodic hypothesis) and attribution of these fluxes to cows (Chapter6-§2. Flux allocation), a method is needed to deduce emission per livestock unit from measured fluxes. Before the beginning of this thesis, when using EC to measure CH_4 fluxes above a pasture, the obvious way to calculate CH_4 emission per livestock unit (f_{CH4}) was to divide the measured flux by the stocking density in the pasture (Chapter 2; (Dengel et al., 2011)). This method is easy to implement and does not require any animal handling. However, it is biased for several reasons as detailed on point 2 “Flux allocation” of this discussion.

3.2. *CONTRIBUTION*

Once fluxes are adequately measured, two challenges remained when computing f_{CH4}; the first one was to compute source densities in the FP (SD_f) and the second one was to propose a computation method allowing to estimate f_{CH4}. This method was then applied to the Be-Dor ecosystem station.

3.2.1. Source density in the footprint

Each source contribution to the FP can then be computed using an adequate model, i.e. a set of functions weighting the respective contribution of each element of the surface to the measured vertical flux (Rannik et al., 2012). Among available models, the Kormann & Meixner (2001) model and the FFP tool developed by Kljun (2015) were applied to our dataset. The correspondence of both models with our observations was assessed in Chapter 3 and a higher performance score was systematically associated with the KM model.

Additionally, although critical when working with cattle, source height is rarely considered in models. Models were therefore run by our team in order to estimate source height impact at different distances from the mast (De Cock et al., 2019). As a result, in Chapter 4, filters were used to eliminate data when the source height impact on the estimated SD_f was suspected to be larger than 15 %. However, artificial source experiments involving elevated sources are still needed in order to improve or validate existing models.

3.2.2. Cattle emission estimation method

We developed a f_{CH4} estimation method which requires to compute the stocking density in the FP for each flux measurement interval (Chapters 3 and 4). Then, cattle CH_4 emission per LU (f_{CH4}) were computed by dividing the measured CH_4 flux by the source density in the FP (SD_f). However, estimated f_{CH4} were more robust to outliers when f_{CH4} was computed as a regression slope rather than a simple ratio. Several variations of this method were tested at the Be-Dor station using an artificial source. The best performing method, in terms of precision, accuracy and reproducibility, was selected and led to methane emission recovery rates between 90 of 113% (Chapter 3).

Cattle f_{CH4} estimation was either based on 15-minutes (Chapter 3) or 30 minutes averaging intervals (Chapter 4 & 5). The selection of an averaging interval was a choice between the highest performance score (15 minutes) or the interval on which most of the figures from the literature are based (30 minutes). However, this choice had a very limited impact on the associated results (**Table 3-2**).

3.2.3. Measurements at the Be-Dor ecosystem station

Cattle methane emissions were measured at the Be-Dor station on a typical Walloon Belgian Blue cow-calf operation, resulting in estimated emissions of 220 ± 35 g CH_4 LU^{-1} day^{-1} (Chapter 4). This value corresponds to what would be expected for this type of cattle in these conditions (estimated tier 2 IPCC emissions were of 205 ± 41 gCH_4 $LU^{-1}day^{-1}$). The same method was adapted to cattle CO_2 emissions in Chapter 5, resulting in estimated respiration of 3.2 ± 0.5 kg C LU^{-1} day^{-1} which also corresponds to what would be expected for this type of cattle in these conditions (2.9 kg C LU^{-1} day^{-1} according to an animal scale carbon budget).

3.2.4. Comparison with existing methods

In comparison with other methods commonly used to measure cattle methane emissions, the combination of EC with geolocation has advantages and drawbacks. The preference of one methane emission measurement method over another largely depends on the research objectives.

If the objective is to correctly estimate cattle methane emissions, the measurement accuracy (closeness to the actual value) is more critical than the precision (closeness of the measurements to each other). The best way to estimate the accuracy of a measurement method is to work with an artificial source and to estimate a recovery rate. For this purpose, the respiration chamber method (RC) is very efficient, with a typical recovery yield of 100±3 % (Hristov et al., 2018), which is far more accurate than any other measurement method. However, this method requires studied animals to be placed inside a close chamber which affect cattle behaviors and probably their emissions.

If the objective is the ranking of animals according to their emission potential, the precision is more important than the measurement accuracy and the measurement should be preferably run at animal scale. Among the available measurement methods RC is particularly well adapted when cattle are raised indoor while the SF_6 and Greenfeed (C-Lock Inc., South Dakota) methods are well adapted when cattle are raised outdoor, thereby leaving the cattle in their natural environment.

Finally, if the objective is to assess the impact of various treatments/management practices on emissions, the precision is again more important than the measurement accuracy and the measurement should be preferably monitored at herd scale to integrate inter-animal variability, in conditions as close as possible from commercial practices. For this purpose, methods like Greenfeed, SF_6 or micro-meteorological methods like EC are well adapted.

Moreover, the micro-meteorological methods have the theoretical advantage of being able to measure methane emissions variation throughout the day and independently of cattle activity (Laubach et al., 2014, 2013), which is not the case for the Greenfeed solution. However, EC has the major drawback of being subject to unsolved methodological issues (source height is never known, FP prediction methods have a limited accuracy, different slope calculation methods provide different results, external contamination sources may always be sporadically present…). Despite these issues, recovery rates obtained using an artificial source indicate that this method accurately estimate point source emissions (Chapter 3) and led to plausible results when applied on the field (Chapter 5). Moreover, this measurement method is very appealing as it would allow continuous measurement of CH_4 emissions from a whole herd without affecting animal behavior.

3.3. *OUTLOOK*

Animal location and, ideally, muzzle height, must be known, using specific tools (GPS, RFID, classic or thermographic camera…). Each geolocation method has its advantages and disadvantages. GPS are very accurate but requires lots of animal handling when installing devices or replacing batteries and can lead to animal injuries if improperly fixed. On the other hand, GPS can easily be accompanied by accelerometers or other devices in order to track animal activities. Active RFID (radio frequency identification) are very promising but still require some animal handling and installation of an associated receiver network throughout the pasture. Cattle geolocation techniques could also be automated by using conventional or thermographic cameras to locate cattle. Ideally, those cameras would be placed at different locations at an important height above the pasture so that animals could be triangulated and no animal could be hidden behind another one. This technique would result in the absence of animal handling and offers opportunities for continuous, non-invasive, cattle emissions monitoring. Moreover, this technique could be used for any hot blooded animal and would be especially useful when monitoring wild herbivores methane emissions (Stoy et al., 2020). However, location using cameras requires a challenging data treatment process and associated precision can be insufficient.

FP models are ill adapted for cattle FP contribution estimation. Most of these methods consider a source placed at ground height (and not at mouth height) and do not take into account cattle movement during an averaging interval. The use of 3D Lagrangian stochastic models which consider real time cattle position could substantially improve FP model precision (Coates et al., 2018, 2017). However, the use of such models require a better description of turbulence characteristics.

The combination of EC with a FP model as presented in this thesis allowed estimation of cattle methane emissions on a pasture, with minimal animal handling and minimal impacts on animal behavior. Chapter 5 extended this method to cattle CO_2 emission estimation. Moreover, this method could be extended to other target gases showing important source distribution heterogeneities (e.g. N_2O, NH_3, or VOC). As an example, our team is currently investigating the opportunity to transfer this technique to VOC exchanges on the pasture. Sources are multiple, VOCs being potentially emitted by cattle through direct gas exhausts, by excreta and by grass, recently grazed grass being in addition more prone to emit large quantities of wound-induced coumpounds. Therefore, measured fluxes should be partitioned first and then grass/soil fluxes can be related to cattle grazing activity history in the FP. The intensity and duration of this relation is currently investigated separately for each compound. Finally, this method is not limited to cattle and could be used to estimate emissions from other herbivores or from geologic sources, provided information about sources distribution in the FP are available.

4. DRIVERS

Our fourth objective was to characterize diel and seasonal variations in cattle CH_4 emissions and its underlying drivers.

4.1. *ISSUE*

EC allows continuous measurements of ecosystem exchanges during long periods, with a half-hour resolution. This method should thus be particularly adequate to characterize diel and seasonal variations in GHG emissions. One of the goals of this thesis was to identify drivers underlying variations in cattle CH_4 emissions. Cows were therefore equipped with accelerometers so that their diel activity pattern could be monitored and correlated to the methane emissions patterns. Moreover, monitoring behaviors offer possibilities to test the coherence and precision of emission estimates.

Previous studies showed that cattle methane emissions follow a diel cycle in connection to the feeding pattern and, to a lesser extent, cattle behavior (Blaise et al., 2018; Hammond et al., 2016; Hegarty, 2013). Moreover, cattle emissions are known to be impacted by forage quality which varies seasonally (Elgersma and Søegaard, 2016; Saha et al., 2014).

4.2. *CONTRIBUTION*

In this work, despite monitoring cattle methane emissions for 85 days, we observed only a very weak relation between methane emissions and feeding events (whole herd grazing simultaneously). The only significant correlation was a drop in emissions 4 hours after the meal, which was identified in one of our four observation campaigns (Chapter 4). However, the continuous availability of forage caused individual variations in the meal time even if a common pattern was observed for the herd. Moreover, these feeding pattern showed day to day temporal shifts, potentially due to weather and daylight variations. Overall this variability of the cattle behavior, led to large day to day methane emissions variations. As a consequence, large errors bars were associated with our data (30 to 75 % when aggregating data over four hour periods), hampering the identification of significant correlations even when pooling data over the entire campaign. Moreover, although campaigns were organized at different times of the year, no seasonal variation was observed. Additional studies are required in order to properly investigate diel and seasonal variations in cattle emissions.

We also produced cattle density maps which allows better understanding of cattle behaviors on the pasture. Those figures indicate that cattle distribution on the pasture is almost homogeneous when cattle are grazing. And we know when cattle are grazing: at dawn and at dusk. This information might be precious when working under the homogeneous average cattle distribution assumption. Moreover, these density maps could give us additional information about soil C stocks, N_2O hotspot or plant functional groups distribution on the pasture.

4.3. *OUTLOOK*

The precision of the measurement was too low to measure the impact of the tested drivers (relation between f_{CH4} and season, time of the day, cattle behavior or time since the last mass grazing event). Increasing the measurement precision could help with the identification of drivers. However, the key information here is that the observed drivers impact is low and that increasing the measurement precision in order to measure significant impacts might be futile. Another explanation might be that cattle behaviors are not synchronized and that an analysis at herd scale could be not adapted to analyze the animal's response to drivers.

5. GHG BUDGET

Our fifth and latest objective was to contribute to the Be-Dor GHG budget by estimating the pasture CO_2 and CH_4 exchanges.

5.1. *ISSUE*

Gaseous exchange measurements can then be integrated into an ecosystem budget which compiles all in- and out-going ecosystem exchanges. However, as stated in Chapter 6, § 2, delivering such a budget for a pasture is tricky as cattle distribution on the pasture is heterogenous and varies over time. Until recently, according to Felber et al. (2016a) the main options to present such a budget was either to assume a homogeneous cattle distribution on the pasture (e.g. Flechard et al. (2007) or Soussana et al. (2007)) or to limit measurements to periods without cattle on the field (e.g. Skinner (2008)). Both options were unsatisfactory, leading to an underrepresentation of pastures in measurement networks. In consequence, very few articles presenting grazed pasture budgets are available, limiting the potential to analyze mitigation options.

5.2. *CONTRIBUTION*

During this thesis, we measured CO_2 and CH_4 fluxes on the Be-Dor site for the year 2015 (Chapters 2, 4 & 5). Moreover, N_2O fluxes were monitored from March 2018 to February 2019 at the Be-Dor site (Lognoul, 2020). These data, while not being obtained during the same years, can contribute to GHG budget of this pasture. CO_2 and CH_4 and N_2O exchanges by the soil/plant continuum and by cattle (when present on the pasture) were integrated into a GHG budget (**Table 6-1**) whose boundaries are detailed in **Figure 6-2**. In this budget, sources are associated with a positive sign and sinks with a negative sign. Uncertainty ranges associated with each figures were computed separately, using different methods which are described in the corresponding papers. If uncertainty ranges were not available (cattle respiration), a default uncertainty range of 20% was considered.

CO_2 fluxes were computed in Chapter 5. Our analysis indicated that the two main factors contributing to this balance are the plant-soil continuum (−256 $gCO_2\ m^{-2}\ yr^{-1}$ or −940±92 $gCO_2\ m^{-2}\ yr^{-1}$) and cattle respiration (2.9 kg C $LU^{-1}\ d^{-1}$ or 854 $gCO_2\ m^{-2}\ yr^{-1}$ considering an average SD_p of 2.2 LU ha^{-1}). Details on this analysis can be found in Chapter 5. There is however a difference between this analysis and the one presented in Chapter 5: we computed the total NEE of the pasture by considering the SD_p (2.2 LU ha^{-1}) instead of computing the NEE of the footprint by considering the SD_f (1.5 LU ha^{-1}).

For CH_4, the balance will be calculated here. Assuming that methane emissions of the soil-plant continuum in 2015 are similar to those observed in 2013 (Chapter 2), surface methane emissions would be of 0.548 ± 0.073 $gCH_4\ m^{-2}\ year^{-1}$. It corresponds to 15 ± 2.0 $gCO_{2éq.}\ m^{-2}\ year^{-1}$, considering a CH_4 global warming potential of 28 (IPCC, 2014). During 2015, cattle methane emissions on the pasture can be computed using a mean yearly stocking density of 2.2 LU ha^{-1} and assuming a methane emission of 220 ± 35 $gCH_4\ LU^{-1}\ day^{-1}$. This gives 491± 77 $gCO_{2éq.}\ m^{-2}$ grazing $season^{-1,}$ considering a CH_4 global warming potential of 28 (IPCC, 2014).

For N_2O, fluxes measured at the Be-Dor site between March 2018 to February 2019 constitute a source of 1.55±0.04 nmol $N_2O\ m^{-2}\ s^{-1}$ or 570±15 $gCO_{2éq.}\ m^{-2}\ yr^{-1}$. Additional details about these measurements can be found in the thesis of Margaux Lognoul (2020). Cattle indirectly contribute to these fluxes via the degradation of urine. However, the plant soil/ continuum can also emit NO_2 (e.g. degradation of fertilizer or clover presence). The available data do not separate these different drivers.

If we combine the balance obtained for CO_2, CH_4 and N_2O fluxes, we obtain a total GHG source of 990±357 $gCO_{2éq.}\ m^{-2}\ yr^{-1}$. From these figures, we can conclude that at the Be-Dor ecosystem station the pasture act as a GHG source, though a large part of the emissions are offset by plant-soil exchanges.

Table 6-1 Pasture GHG budget for the Be-Dor ecosystem station. Figures are relative to the years 2013 to 2019 according to the considered GHG. Budget boundaries are described in **Figure 6-2**.

	Plant/soil exchanges $gCO_{2éq.}\ m^{-2}\ yr^{-1}$	Cattle exchanges $gCO_{2éq.}\ m^{-2}$ grazing $season^{-1}$	Total $gCO_{2éq.}\ m^{-2}\ year^{-1}$
CO_2	−940 ±92	854 ±171	-86±263
CH_4	15 ±2	491 ±77	506±79
N_2O	570 ±15	/	570±15
Total	-355 ±109	1345 ±248	990±357

However, it must be noted that this is a partial GHG balance whose boundaries are described in **Figure 6-2**. Year round soil-plant exchanges are considered, while cattle emissions are only considered when in the pasture (barn emissions are not included). Measurements were not done simultaneously for all gases, leading to potential bias associated with year-to-year variations. In addition, this work focused on CO_2, CH_4 and N_2O, thus other GHG or compounds interacting with the GHG atmospheric chemistry are not considered (i.e. O_3, VOC…). This type of budget can be misleading as it is not the complete pasture GHG budget nor the cattle or farm GHG budget. As an outlook for our work, a life cycle assessment could be done to obtain a full GHG balance related to cattle rearing on the Be-Dor site. Our data represent a first step in this considerable work. Moreover, our data can be integrated into other models, meta-studies and life cycle assessments.

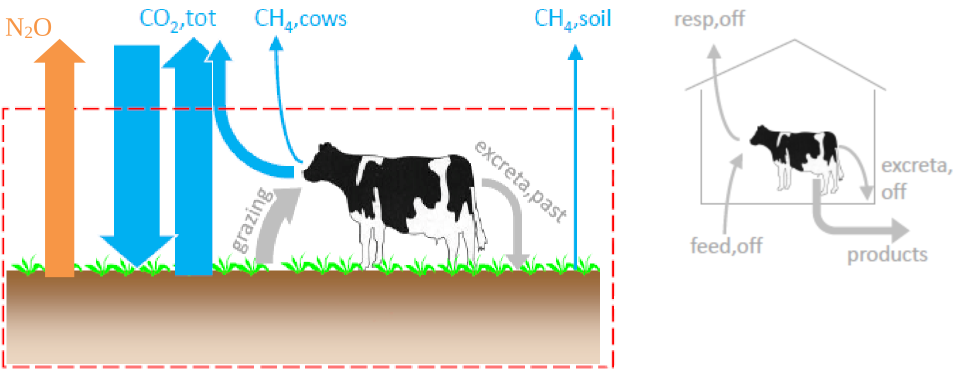

Figure 6-2 Boundaries of the partial GHG budget of the pasture are represented by the red dashed line. Year round soil / plant exchanges are considered, while cattle emissions are only considered when in the pasture. Adapted from Felber et al. (2016a)

5.3. *Outlook*

The allocation method presented in Chapter 6, §2 allows disentangling soil/plant and cattle CO_2 emissions and to increase the accuracy of pasture GHG budget. Our method could be generalized to other EC sites and would allow more pastures to be integrated into ecosystem monitoring networks. These networks are essential in order to widen our knowledge about ecosystem exchanges. Moreover, complete GHG budgets are necessary when assessing the impact of a mitigation option in order to avoid “pollution swapping” (decreasing the exchanges of one GHG while increasing another or causing an upstream or downstream increase in the exchange of the same GHG) (Hristov et al., 2013).

6. Conclusions

All five objectives presented in the introduction where responded to hereabove. Moreover, to put it shortly, the main take home messages gathered through this thesis are the following:

- EC can be used to measure fluxes above a heterogeneous ecosystem like a pasture, provided some adaptations are applied.
- Measuring gaseous fluxes above a pasture does make sense. However, cattle distribution in the FP cannot be overseen. Therefore, measurements above a pasture should always be accompanied by a method allowing discrimination of surface exchanges from cattle emissions.
- Measuring methane fluxes above pastures is useful per se. Moreover, methane fluxes can be considered as an adequate tool to estimate the stocking density in the FP, which can help discriminate CO_2 or VOC surface exchanges from cattle emissions.
- Estimated source densities in the FP were reliable. Moreover, if the source height is variable, data filtering may be used to reduce the model sensitivity to source height.
- EC can be used to estimate source-averaged emissions but not to discriminate individual sources emissions.
- EC is an adequate tool when computing a pasture GHG budget. However, soil/plant and animal exchanges must be accounted for separately before being integrated in a budget.

VII

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