Comments to manuscript revision

We thank the two referees for the very careful reading of the manuscript and the many helpful and interesting comments. We followed them for the most part to improve the revised manuscript. Our detailed responses to the referees comments are listed below (referee comments are printed in *italic*, author responses are printed in blue) and the changes are indicated in the attached version with markups.

As suggested by referee #2 we removed Fig. 4 in the revised version. The figure numbering is changed accordingly in the markup version and in the revised manuscript.

Author response to comments of Referee #1

I wondered why the paper considers only CH4. Surely the same kind of analysis could be undertaken for CO2 and water vapor? The analytical problem would be the same, but the weights of "soil" (ecosystem) and animal contributions would be different. Because of the different weights for the different gas species, it might then be possible to arrive at conclusions how the weights affect achievable accuracy.

We fully agree with the reviewer, that a similar evaluation can be done for other trace gases. The CO_2 topic will be presented in another paper, which is under review in Agricultural and Forest Meteorology at the moment. Presenting both gas species in one paper would end in a very long paper. Additionally the calculation of the background is more complex for CO_2 than for CH_4. Water vapour respired or transpired by animals represents a very small contribution to the total pasture evapotranspiration (typical magnitude 4 mm/day = 5 litres/m2/day). For an instantaneous stocking density of 20 animals on a 0.6 ha paddock area (= 33 heads/ha) this corresponds to a flux of 1500 litres/head/day, thus about two orders of magnitude more than the possible animal water respiration/transpiration. Thus the animal contribution would not be detectable in the EC flux.

A question not addressed is: were there differences in the performance of the footprint model (and, hence, the animal vs soil partitioning of fluxes) between stable and unstable stratification? I would hope that it was not too hard to separate the data in Tables 1 and 2 into two classes according to stratification.

Emissions for stable situation were on average higher than under unstable conditions. However this effect is difficult to interpret because it strongly coincides with the observed diurnal cycle (new Fig. 10). Given the general scatter of individual flux values, it was not possible to separate a potential stability-dependent bias in the footprint model from real diurnal variations of the animal emission rates. Therefore we consider it not meaningful (or potentially misleading) to list just stability separated values in Tables 1 and 2. However, the issue of stability is added in the discussion of the diurnal cycle (Sect. 4.4).

1

A point for the Discussion: the footprint model assumes that the cows emit the CH4 at ground level. However, that is not strictly true in reality, with some fraction of the gas being emitted higher up. What would be, qualitatively, the effect of the idealized groundlevel assumption on the total emission estimate: an overestimate or an underestimate? The question is relevant because the authors select the "near cows" class (where any such height effect would matter most) as their "most reliable" data.

With the analytical FP function of KM01, the effect of elevated sources could (unfortunately) not be evaluated. However it was recently reported by McGinn et al. (2015, J. Environ. Qual. 44:97–102) that for a bLS dispersion modelling application (with concentration measurements) they found no significant difference between sources at the surface and at 0.5 m height. It needs to be investigated in the future whether this result is also valid for the EC flux footprint weight.

A short discussion including the reference mentioned above are included in the revised version at the end of Sect. 4.2.

Specific Comments
Title: "eddy covariance" implies that a "flux" is measured, so one word can be dropped to avoid redundancy

It is true that for people familiar with EC measurement the term eddy covariance already implies that a flux is measured. To mention the technique but also to state that fluxes are measured for an audience not familiar with EC measurement, we'd like to use both words.

Abstract L 13 replace "guess of" by "estimate from"
Is changed accordingly.

P 3423 The site, climate and management details are perhaps too comprehensive for a study that is mainly focused on the effects of position-time information, and not on the greenhouse gas budgets per se. For example, I do not see the relevance of the site's history (L 16) or of whether this was a climatically unusual year (L 11-14) when the final budgets presented are only for half a year anyway.

We shortened the section by removing dispensable information that is not needed for context of this paper from the section describing climatic and management details. The climatically unusual year is indicated because we expected that the cows would spend more time on the paddocks measured by the EC system.

P 3424 L 11 Are paddocks 2 and 5 those later labelled "near cows" and the other four "far cows"? It would help to clearly state that here already.
The following sentence was added: "In the following the term 'near cows' refers to grazing in PAD2 or PAD5, whereas the term 'far cows' refers to situations when one of the other four paddocks was under grazing."

2

P 3426 L 4: Should "bi-passed" be "bypassed"?
Yes, it's corrected.

P 3426 bottom: It would be interesting to compare the CH4 time series (Fig. 2a) to that of temperature or water vapor for the same period, to get an idea what part of the variability is due to the passing of turbulent eddies and what part to the emissions from moving point sources.
We forgot to indicate that the examples in panels (a) and (b) represent midday intervals that are only separated by 1 hour and mainly differ by the presence of cow in the footprint. This information was added in the Figure caption and the text (first paragraph Sect. 2.2.2) was slightly adjusted.
To better illustrate the effect of the cows on the concentration measurements the Figure was adapted by using the same y-axis-scale for both panels (with a close-up plot as insert). In this way it gets very obvious that the much higher variability range in panel (a) is caused by the presence of the cows. We can state, that no big difference was observed for other scalars for these intervals. However plotting them would add little information to the manuscript and would unnecessarily increase its length.

P 3428 bottom: Why is the "plausible range" for tilt angle not symmetric around zero?
We rephrased this sentence to: "small vertical vector rotation angle (tilt angle) within ±6° to exclude cases with distorted wind field". The original non-symmetric range may be misleading. It was indicated, because there were practically no cases between -6 and -2°.

P 3429 bottom and Table 1. It is not clear to me why the GPS and PAD method end up with different numbers of runs. That introduces the possibility of bias because the datasets are not matched. If outliers were removed for one method, the same periods should be removed for the other method also. However, why were "outliers" removed at this stage anyway? Is it not the nature of the beast (pun intended) that a single emitter in a location with high footprint contribution could cause high fluxes, and would the explicit point-source modeling not capture this?
The two methods represent two levels of information to discern fluxes with and without cow contribution. Therefore the selection criteria are different, because we aimed to show the difference/uncertainty of calculated emissions, which are induced by different levels of information.

P 3438 L 5 Why is Fig 11 only for the "near cows" class? Did the "far cows" follow the same pattern? If not, that might give clues why the mean emissions differed between these two classes.
The quantitative analysis of the diel cycle of the *far cows* case is difficult. Only 63 emission values were available for this analysis which results in very few data per hourly bin. However qualitatively the pattern over the day was similar as for the *near cows* case.

3

P 3439 L 16 "Obviously... possible only due to the GPS" does not seem correct. Surely, knowledge of the paddock being grazed and wind direction would suffice to identify the majority of runs with "uncontaminated" soil fluxes.

We agree that this sentence is not fully adequate in the context. It can therefore be omitted without affecting the statement in this paragraph. The sentence is removed.

P 3440-3441 In Section 4.2, it is not easy to follow the argument. The first paragraph seems mainly concerned with random errors, first of flux and footprint model, then of roughness length (which is a separate issue). The second and third paragraphs deal with the observed discrepancy between "near cows" and "far cows" (which requires a bias for explanation, not random error). It would help to subdivide the first paragraph further, and to state early in each paragraph what its subject will be.

We agree that the arguments in Section 4.2 were not fully consistent. Overall this Section was intended to discuss systematic errors (z_0 and FP related errors are mainly systematic), but some statements concerned random flux errors (without clear declaration).
We removed the random-error related parts from this Section.

P 3440 bottom: "Additionally [insert comma] variations of the wind direction... amplify the effect of moving." I do not understand this sentence.

This sentence is removed from the text.

P 3441 L 22 "Hence the over-/underestimation tended to be balanced for the near cows cases". Was that actually tested, by picking example runs for different footprint-maximum locations and analyzing the cow position data for these? Or is the statement just qualitative arm-waving? Since the authors argue later that the near-cows GPS method was the "most reliable" one, it is important to show that bias was indeed small.

This statement cannot be tested by the use of actual cow positions. The assumed over- or underestimation of the FP weight at varying distance from the EC tower is purely a FP model problem. We will rephrase the text to clarify that our argumentation is based on the findings of Kljun et al. (2003) using the bLS FP model as a reference.

P 3441 bottom. Could it be that emissions at elevated level (from standing cows) contribute to a bias of the "near-cows" results, but less so for the "far-cows" class? With a measurement height of 2 m only, it may matter whether the sources are at ground level or at up to 1.5 m height. A good tool to assess this would be a Lagrangian model.

See our response to the third general comment above.

P 3444 L 13 Can the observed overall inhomogeneity of the cow density distribution be related to the locations of drinking-water supplies?

Indeed there was a water supply on the field (open drinking trough), but the location did not correlate to the cow density distribution. The trough was usually placed in a corner of the paddock.

4

P 3444 bottom: The animals in Laubach et al. were not "grazing", they were fed silage, and the locations of the silage and water supplies go a long way to explain why the animal distribution was uneven. This should be clarified.
This is clarified in the text.

Table 2 It would seem fair to include columns of "near cows" and "far cows" combined, to show how much the authors' preference for "near cows" affects the result.
This is in our view not necessary (and could even be misleading). The 'combination' effect directly follows from the difference between the 'near cows' and 'far cows' means and the corresponding number of data (n) in each class also given in the table. We intentionally did not include the 'combination' result, because we argue that the 'far cows' result suffers from a systematic underestimation, and thus a combination makes not meaningful.

Table 2, caption. The passage "for different distances… (near, far)" should be placed before "and without cow position information", because it applies only to the first two methods
Changed as suggested.

Table 2: On first reading, I was confused by the two entries in the top row under "FIELD", each with its own footnote and no connection stated between the two. Perhaps it would be better to have only one footnote stating "The first number is... The second number is...".
We don't consider this as a better solution, because the footnote "b" is also used for other entries, and it clearly indicates which entries are related to each other. We kept the original footnote structure but added a reference to the parallel footnote.

Table 3: Include the numbers from the present study for comparison (so the reader does not need to search for them in the text).
We included the number of our study directly in the text and also added a reference to the respective Table 2 were all results of the present study are listed. We consider a repetition of the result in two different Tables unnecessary.

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Author response to comments of referee B. Heinesch

1. I would appreciate the addition of one or two sentences in a visible part of the paper stating clearly that authors are lacking information on cows' activity in their study. The consequences being that they are not able to discuss meaningfully the diel CH_4 cow emission cycle and to investigate how much of the 30-min variability is coming from the variation in cow's activity. In addition, their use of the term "grazing" for all moments when cows were in the paddocks is misleading, cows spending part of their time ruminating/idling, especially during the night.

Actually, we did record the cow activity by the mean of pressure noseband sensors (RumiWatch, Itin+Hoch, Switzerland). Originally we considered the corresponding information not conclusive enough and thus did not use it in the original manuscript version. But motivated by the referee comment, we analyzed the data again more thoroughly. The new analysis showed that there is indeed a daily pattern of cow activity, which only to minor degree is correlated to the emissions. Cow activity data was added to Fig. 11 (new Fig. 10) and the methods (2.1), results (3.3.2) and discussion (4.4) sections were enhanced accordingly.
In addition, we agree with the referee that the term 'grazing' can lead to confusion if used to generally indicate the periods when cows were present on the pasture. We changed the wording where necessary.

2. I'm wondering about the best strategy for computation of the 30 min FP weight (Eq3). You chose to combine your positions with the footprint at a time step of 5s in order to optimize the use of your position information. In doing so, you compute a FP over an interval of only 5s. What is the physical meaning of this 5s footprint and how is it linked to a cow position taken simultaneously? For example, with a wind blowing from the South at a wind speed of 2 m s-1 and a cow located 100m away South of the mast, methane emitted by the cow will take 50s to reach the mast. If there is a wind direction shift during these 50s, your 5s FP weight will be totally wrong. On the other hand, making a 30 min average of a cow positions and combining it with the 30 min average footprint will also raise this type of questions. So pragmatically, my question is: was the computed flux per cow sensitive to the computation strategy? Might be useful for other teams.

This is probably some kind of misunderstanding. As stated in the text, we always used the footprint (FP) weight function determined for 30 min intervals; and even if this is combined with a set of 5s-position data, the result is still an (average) property of the 30 min interval (i.e. the temporal sequence of the 5 s data is not taken into account).
The issue here is, whether it would be meaningful to first average the position data to 30 min values before combining it with the FP function. Since the footprint function is very non-linear, a position averaging is generally problematic, e.g. one cow on the right side of the main FP and another on the left side could average to two cows at the center of the FP. So the calculation with 5 s position data is just a simple way to avoid unwanted effects of position averaging. This method is fully equivalent to the determination of a 30-min. two-dimensional cow density distribution, which is then combined with the 30-min. FP weight function.

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Through modification of Eq. 3 (acc. to comment *P3432Eq3* below) and the surrounding sentences, the FP averaging procedure was clarified in the revised version and should prevent misunderstandings.

3. The immediate vicinity of the studied pasture should be better described, especially in the wind sectors that were not filtered out. Was it crops or pastures? If it was pastures, do cows were present in these nearby pastures during the experiment? The measured signal could have been significantly polluted by the presence of cows on these possible nearby pastures, amplified by herd behavior at times when cows were also present on the principal pasture.

The neighboring fields of our experimental pasture and their use are indicated in Fig. 1. Concerning possible footprint (FP) interference, the fields in the main wind directions (North-East and South-West) are of main interest. The meadow in the East was under mowing, the pastures in the South-West were managed very similarly to the experimental field, most of the time they were alternatingly grazed by the same cow herd due to the lower than expected growth on the study field. Thus the influence of cows on the neighboring fields was mostly limited to 'background' conditions without cows on the study field. Although the calculated FP contributions of these neighboring areas where typically below 5%, cases with cows in the far FP have been removed for the determination of the CH_4 soil flux.

We adjusted the text (Sect. 2.1, 3.1 and 4.1) to clarify this point.

4. Removal of outliers is always questionable for data showing a huge variability. In this case significant and natural flux variability can arise for important cow footprint weight events due to the cow movement or changing wind direction. The authors should precise how they define exactly an outlier (P3429L23: How is this R boxplot function working?) and how they can distinguish between an outlier and natural variability?

We agree that the removal of outliers is critical for data with a large natural variability. Therefore we did not apply the outlier determination to the entire flux dataset, but only to the subset of 'soil fluxes' for which a very small value range was expected and observed. For the cases influenced by cows, we did not apply the outlier test to the measured flux data, but to the derived E_{cow} values, because they are expected to be much less variable.

We must admit that the introduction of the outlier removal already at the beginning of Sect. 2.3 was not appropriate and may have been misleading. We therefore moved this content to the end of Sect. 2.3.3. There we also explained the used outlier definition (according to the standard boxplot definition).

The resulting limits for the E_{cow} outlier determination correspond to the upper and lower limit of values shown in Fig. 13 (new Fig. 12). This range is much larger than the range of ('natural') systematic diurnal and seasonal variability of E_{cow} shown in Figs. 11 (new Fig. 10) and 12b (new Fig. 11b). See also discussion in Sect. 4.4.

5. "In 92% of the cases when cow fluxes could be measured more than 70% of all GPS devices delivered usable data" (P3430L28). Meaning that among these 92%, you often have several cows (0 to 6 over 20) that are not localized. What did you do with these "missing" cows? Did

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you simply ignore them in the cow footprint weight calculation or did you position them at the mean of measured cows positions for this 5s data? In all cases, rather than simply concluding that "it was considered as sufficient for the quantification of cow FP contribution", you should recognize that this is also a significant source of (random) uncertainty in the CH4 emissions/cow estimation.

We agree that this sentence (together with the previous one) was not very conclusive and rephrased them. We also added a sentence at the end of Sect. 2.3.2 explaining that (according to Eq. 3) it was assumed that the FP weight of cows with missing GPS data corresponded to the average of the FP weight of cows with available GPS data.

6. Authors do not make use of the traditional u* filtering for exclusion of low turbulence events where turbulent fluxes do not represent the true exchange anymore. Probably some of their data filtering steps overlap with the u* filtering but they should make it more clear to which extend.

As mentioned by the reviewer, the applied data filtering overlaps to a large degree with a u_* filtering. Therefore, the additional application of a u_* threshold would not have significantly changed the mean CH_4 emission (u_* thresh = 0.07 m s^{-1} → 426 gCH4 head^{-1} d^{-1} or u_* thresh = 0.1 m s^{-1} → 429 gCH4 head^{-1} d^{-1}, in comparison to 423 gCH4 head^{-1} d^{-1} without specific u_* threshold filter). Thus the application of a u_* filter has an effect of less than 2% on cow emissions.

We added a comment about the negligible effect of additional u_* filtering in the manuscript at the end of Sect. 2.2.3.

Specific comments:
P3422L21-29: Objectives formulation involves non-trivial concepts like "compensation for heterogeneous distribution" and "footprint weight" not yet introduced and therefore difficult to understand for non-experts. Please make it more explicit.

We rephrased the objectives in a more explicit way without the mentioned terms.

P3426L5-7: Meaning that the calibration was strongly affected the first half of August, when cows were back on the pasture. What did you do with the data?

First we have to say that the formulation was not fully appropriate here: 'accuracy' has to be replaced by 'instrument sensitivity'. We used the individual calibration (sensitivity) for this phase.

P3425L22: What do you mean by "the noise level was determined as minimum of the SD of the 10Hz data". On which time window?

For each 30 min interval the SD of the 10 Hz time series was calculated. The weekly minimum of the SD was then used to estimate the noise level and its temporal development. We rephrased this statement in the revised text (Sect. 2.2.1).

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P3427L4: Why did you use linear detrending and not block averaging? Did it have significant influence on the computed fluxes?

Both linear detrending (for concentration only) and block averaging are commonly used methods for EC flux calculation. The question, which method is more appropriate is a basic question of EC flux measurement theory and cannot be assessed to a satisfying degree within the specific scope of this paper. The application of a linear detrending for the concentration time series did have a general systematic influence on the computed fluxes but could avoid non-stationarity effects for some cases in the transition phases of the diurnal cycle.

P3427L26-29: I agree that CO2 can usefully be used for analyses of high-frequency losses. However, elsewhere you mention that many CH4 fluxes were well above the detection limit. So why these CH4 data were not used for spectral analyses? If this is because spectra have some specificity for cows related fluxes, please comment.

For the fully empirical ogive method applied here, a preferably large number of ogive ratios (trace gas vs. temperature) for each wind speed and stability class is needed. It was found that for CH4 the cow respiration signals led to generally higher (random-like) scatter in the cospectra and ogives, which complicated the quantitative determination (regression) of the damping factor as a function of wind speed and stability. Therefore, the CO2 flux ogives determined with the same setup and analyzer were mainly used for this purpose.
We modified the text to clarify this explanation.

P3428: Why "around"? You can give the precise value.

We do not understand this comment, the precise value is given at the end of the sentence (L17).

P3427L21: Why "statistically" more representative?

The sentence was clarified to "… is more representative on statistical average, because it is not biased by the choice of the maximum".

P3428L14-21: Please add a reference for this definition of the flux detection limit.

We do not know about a literature reference for this detection limit determination. However, it is based on the flux error estimation from the variation of the 'baseline' of the covariance function. We added a reference about this error estimation method.

P3428L26: How was this range of acceptable tilt angles defined?

We rephrased this sentence to: "small vertical vector rotation angle (tilt angle) within ±6° to exclude cases with distorted wind field". The original non-symmetric range may be misleading. It was indicated, because there were practically no cases between -6 and -2°.

P3430L4: Precise on which part of the cow and with what kind of fixations the GPS were installed and if the selected position was efficient to avoid damages on the GPS. It may be a useful info for other teams.

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The GPS was attached to the nylon web halter on the cow's neck mainly to optimize satellite signal reception. This information is added to the text.

P3430L13: Our own experience with the dilution of precision information given by the GPS systems is that the time evolution of this variable shows from time to time abrupt changes not correlated to the error in the localization. It therefore makes it difficult to simply define a threshold on DOP above which data should be discarded. Did you observe the same behavior?
We did not evaluate the PDOP behavior of the GPS in this respect.

P3430L14: Which criteria were used for identifying visually a "bad data"?
This were obviously implausible data showing erratic changes in position (e.g. faster than a cow is able to run…).

P3430L26: How do you know the spatial accuracy of your EC footprint model? Please add at least a pertinent reference.
We changed this sentence to: "We assessed an accuracy of 4.5m as sufficient for the present experiment because it is much smaller than the typical flux FP extension and also smaller than the typical cow movement range within a 30 min interval."

P3431Eq2: This equation has two unknowns: z0 and d. What about the displacement height d? You probably equated it to a fraction of the vegetation height z. But did you have a dynamic evolution of z based on field measurements? I guess this is extremely difficult due to non-uniform grazing within your different paddocks.
Indeed we considered the displacement height d as a fraction (2/3) of the canopy height. Since the latter varied between about 5 and 25 cm, the aerodynamic measurement height (z-d) varied between 184 and 197 cm corresponding to only 7%. This is much lower than the relative variability of z_0 (see Fig. 8) and therefore the temporal variation of d was found to be negligible.
Besides, we measured the canopy height of the main paddocks each week by means of low-weight plates (see Ammann et al., 2009) as well as by a medium-weight rising-plate herbometer at multiple spatially distributed points. Because of the intensive rotational grazing, we found distinct time series for the vegetation height (not difficult to measure but just a lot of work …). The corresponding results will be presented in another paper on CO2 exchange.

P3432Eq3: I fully understand this average FP weight quantity but I think you should rather use the total footprint weight of the herd when you plot a dependent variable like the flux or z0 in function of the footprint weight. This remark holds at least for fig 7, 8, 9. Of course, in your case, the number of cows stays constant during the whole experiment so it will not change the figures but fundamentally, your dependent variable depends on the total footprint weight and not on the mean footprint weight. If you agree with this comment, introduce the total footprint weight in LSU m-2 (the denominator of Eq4) and change the text and the figures accordingly.
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We agree with the referee that the total footprint weight of the herd is a more useful quantity in the mentioned Figures, also for comparison with other studies. We therefore introduced the quantity $\bar{\varphi}_{herd} = n_{cow} \cdot \bar{\varphi}_{cow}$ in Equation (3) and used it in the corresponding Figures and also adjusted the thresholds and the text accordingly. As mentioned by the referee, this mainly changed the scale of the x-axis by a factor of 20 (= the usual number of cows).

However we did not change the units/normalization from 'head' (animal) to LSU as suggested. In our opinion this could make sense for beef cattle but not so much for dairy cows. The CH_4 emission is strongly correlated with the amount of feed intake (energy demand) of the animal and for dairy cows this mainly depends on the milk yield (and only to a minor extent on the body weight). Therefore a normalization to LSU using the animal live weight would not lead to meaningfully comparable values for dairy cows.

P3432L15-17: What is the quantitative impact of this "blurring procedure" on the final flux per head estimation? Is it really a useful step?

The blurring procedure had no significant effect on the (statistical) mean results presented here. However, we also used the same data for other more detailed evaluations (not presented in this manuscript), for which the uncertainty of the cow positions (and FP function) for individual 30-min- intervals was more important. Therefore we used the 'blurring' as a general procedure for our data. It represents and illustrates the uncertainty of individual GPS position data.

P3439L10: Baldocchi et al. 2012 do not define how their detection limit was computed, making the comparison difficult.

The calculation of the uncertainty can be found in Detto et al. (2011). The reference was changed accordingly.

P3440L15-19: There you discuss random uncertainties. Please separate more clearly the discussion about random and systematic uncertainties.

We agree that the statement about random uncertainty here was not adequately separated from the systematic uncertainties mainly treated in this Section. The random-error related part was removed from this Paragraph.

P3445L24-26: I found this sentence confusing, please re-formulate.

We agree that the sentence is not fitting into the text flow here. Since it is not crucial, we removed it from the Conclusions section.

Fig4: It took me some time to understand the meaning of the blue line. It's indeed useful to show that successive positions are correlated but it should be commented in the main text or the legend. However, given the high number of figures in your paper, I would suggest to remove this one, information in the text being self-explaining.

We followed the suggestion and removed this Figure from the manuscript.

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Fig7: This important plot is a bit confusing. Probably due to the expression ("most of the diagram") used in the legend when describing the zero FP weight case. Use rather something like "left panel containing most of the points". Or you could group all "soil" cases and label this group "FP weight <= 10-7"? Also I do not understand why you have so many gray points in the same y-axis range as colored points. According to your legend, gray points that are within panels containing also colored points should be outliers. And an outlier should be by definition "out of the range".

We agree that the plot was somewhat complicated in the original version. Therefore we followed the referee's suggestion and grouped all cases with zero FP contribution into one boxplot. This also illustrates much better that the large majority of the data is within a very small range between 0-10 nmol m-2 s-1. The number of gray points in the original Figure denoted as 'undefined' also included cases without cow GPS information and led to some misunderstanding concerning the outlier removal. Actually, the outlier test for soil fluxes was applied only on cases, which had a defined $\bar{\varphi}_{cow}$ (i.e., GPS data was available). Only these cases are shown in the updated Figure as gray dots and have been renamed to 'others'.

Technical corrections:

P3420L20-21: I prefer: "Methane is after carbon dioxide the second most important human induced greenhouse gas, contributing about 17% ..." making it more clear that it is not two separate information.

Changed as suggested.

P3421L2: "to assess their effect on global scale".

Corrected accordingly

P3422L27: Comparable to what?

Is rephrased to "... comparable results to detailed cow GPS positions"

P3431L20: typo: replace z by z0.

This error was introduced during typesetting and overseen during proof-read, we will check that in the final version.

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Revised Manuscript with marked changes

Eddy covariance methane flux measurements over a grazed pasture: Effect of cows as moving point sources

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Gelöscht: for Animal

Abstract

Methane (CH_4) from ruminants contributes one third to global agricultural greenhouse gas emissions. Eddy covariance (EC) technique has been extensively used at various flux sites to investigate carbon dioxide exchange of ecosystems. Since the development of fast CH_4 analysers the instrumentation at many flux sites have been amended for these gases. However the application of EC over pastures is challenging due to the spatial and temporal uneven distribution of CH_4 point sources induced by the grazing animals. We applied EC measurements during one grazing season over a pasture with 20 dairy cows (mean milk yield: 22.7 kg d^{-1}) managed in a rotational grazing system. Individual cow positions were recorded by GPS trackers to attribute fluxes to animal emissions using a footprint model. Methane fluxes with cows in the footprint were up to two orders of magnitude higher than ecosystem fluxes without cows. Mean cow emissions of 423 ± 24 gCH_4 head^{-1} d^{-1} (best estimate from this study) correspond well to animal respiration chamber measurements reported in the literature. However a systematic effect of the distance between source and EC tower on cow emissions was found which is attributed to the analytical footprint model used. We show that the EC method allows to determine CH_4 emissions of cows on a pasture if the data evaluation is adjusted for this purpose and if some cow distribution information is available.

Gelöscht: grazing

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1   Introduction

Methane (CH_4) is after carbon dioxide (CO_2) the second most important human induced greenhouse gas (GHG), contributing about 17% to the global anthropogenic radiative forcing (Myhre et al., 2013). Agriculture is estimated to contribute about 50% of total anthropogenic emissions of CH_4 while enteric fermentation of livestock alone accounts for about one third (Smith et al., 2007). For Switzerland these numbers are even higher, with 85% total agricultural contribution and 67% from enteric fermentation alone, but still afflicted with considerable uncertainty (Hiller et al., 2014). Measurements of these emissions are therefore important for national GHG inventories and to assess their effect on global scale.

Direct measurements of enteric CH_4 emissions are commonly made on individual animals using open-circuit respiration chambers (Münger and Kreuzer, 2006, 2008) or the SF_6 tracer technique (Lassey, 2007; Pinares-Patiño et al., 2007). Both methods are labor-intensive and thus are usually applied only for rather short time intervals (several days). Although the respiration chamber method needs a costly infrastructure and investigates animals in a constrained situation, it presently is the reference technique to estimate animal breed and diet related differences in CH_4 emissions.

Recently also micrometeorological measurement techniques have been tested to estimate ruminant CH_4 emissions on the plot scale and compare animal scale emissions to field scale emissions. These approaches are based on average concentration measurements: backward Lagrangian stochastic dispersion, mass balance for entire paddocks, and gradient methods (Harper et al., 1999; Laubach et al., 2008; Leuning et al., 1999; McGinn et al., 2011). They have in common that they integrate over a group of animals and are usually applied over specifically designed relatively small fenced plots.

Among the micrometeorological methods, the eddy covariance (EC) approach is considered as the most direct to measure the trace gas exchange of ecosystems (Dabberdt et al., 1993), and it is used as standard method for CO_2 flux monitoring in regional and global networks (e.g. Aubinet et al., 2000; Baldocchi, 2003). Advances in the commercial availability of tunable diode laser spectrometers (Peltola et al., 2013) that measure CH_4 (and N_2O) concentrations at sampling rates of 10 to 20 Hz have steadily increased the number of ecosystem monitoring sites also measuring the exchange of these GHG. However the number of studies made over grazed pastures is still low although such measurements are of importance to assess the full agricultural GHG budget. Baldocchi et al. (2012) showed the challenge of measuring CH_4 fluxes affected by cattle and stressed the importance of position information of these point sources. Dengel et al. (2011) used EC measurements of CH_4 fluxes over a pasture with sheep. But the interpretation

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67 of the fluxes had to be based on rough assumptions because the distribution of animals on the

68 (large) pasture was not known.

69 An ideal requirement for micrometeorological measurements is a spatially homogeneous source

70 area around the measurement tower (Munger et al., 2012), which is often hard to achieve in

71 reality. Although EC fluxes are supposed to average over a certain upwind 'footprint' area

72 (Kormann and Meixner, 2001), the effect of stronger inhomogeneity in the flux footprint (FP),

73 like ruminating animals contributing to the CH_4 flux, have not been studied in detail. These

74 animals are not always on the pasture (e.g., away for milking) and move around during grazing.

75 They are in changing numbers up- or downwind of the measurement tower and represent non-

76 uniformly distributed point sources. In addition cows are relatively large obstacles and may

77 distort the wind and turbulence field making the application of EC measurement disputable.

78 The main goal of the present study was to test the applicability of EC measurement for in-situ

79 CH_4 emission measurements over a pasture with a dairy cow herd under realistic grazing

80 situations. GPS position data of the individual cows were recorded to know the distribution of

81 the animals and to distinguish contributions of direct animal CH_4 release (enteric fermentation)

82 and of CH_4 exchange at the soil surface to measured fluxes. Cow attributed fluxes were

83 converted to animal related emissions using a flux FP model in order to test the EC method in

84 comparison to literature data. Additionally the following questions were addressed in the study:

85 • Are animal emissions derived from EC fluxes consistent and independent of the distance

86   of the source?

87 • How detailed has the cow position information to be for the calculation of animal

88   emissions? Does the information about the occupied paddock area reveal comparable

89   results to detailed cow GPS positions?

90 • Do cows influence the aerodynamic roughness length used by footprint models?

91 **2   Material and methods**

92 **2.1   Study site and grazing management**

93 The experiment was conducted on a pasture at the Agroscope research farm near Posieux on

94 the Swiss western plateau (46°46'04"N 7°06'28"E). The pasture vegetation consists of a 85/15%

95 grass-clover mixture (mainly *Lolium perenne* and *Trifolium repens*) and the soil is classified as

96 stagnic Anthrosol with a loam texture. The vegetation growth was retarded at the beginning of

97 the grazing season due to the colder spring and the wetter conditions during April and May

98 compared to long-term averages. The dry summer (June and July) also led to shortage of fodder

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on the study field. Therefore additional neighboring pasture areas were needed to feed the animals.

The staff and facilities at the research farm provided the herd management and automated individual measurements of milk yield and body weight at each milking. Milk was sampled individually on one day per week and analyzed for main components. Monthly energy-corrected milk (ECM) yield of the cows was calculated from daily milk yield and the contents of fat, protein and lactose (Arrigo et al., 1999). Monthly ECM yield decreased over the first three months but overall was fairly constant in time with a mean value of 22.7 ± 5.5 (SD) kg. The average live weight of 640 ± 70 (SD) kg slightly increased by around 6% over the grazing season.

The field (3.6 ha) was divided into six equal paddocks (PAD1 to PAD6) of 0.6 ha each (Fig. 1). The arrangement of the paddocks was chosen to create situations with the herd confined in

differing distances to the EC tower. Mainly two distance classes are used in the following: *near cows* denotes cases with animals in PAD2 or PAD5, *far cows* denotes cases with animals in one of the other four paddocks. The present study covers one full grazing season 9 April – 4 November 2013. 20 dairy cows were managed in a rotational grazing system during day and night. Depending on initial herbage height the cows typically grazed for 1 to 2 days on a paddock. The herd consisted of Holstein and Red Holstein x Simmental crossbred dairy cows and was managed with an objective to keep the productivity of the herd relatively constant in time. The cows left the pasture twice a day for milking in the barn where they were also offered

concentrate supplement (usually <10% of total diet dry matter) according to their milk production level. The paddock leaving time was around 4 am and 3 pm but varied slightly depending on workload in the barn and air temperature. If there was risk of frost, the cows stayed in the barn overnight (58 nights), and if the daytime air temperature exceeded about 28°C before noon, the cows were moved into the barn for shade (19 days). Waterlogged soil condition entirely prohibited grazing on the pasture between 12 and 13 April. In total the cows were grazing on the study field for 198 half-days and for another 157 half-days on nearby pastures not measured by the EC tower.

The management of the neighboring fields is also indicated in Fig. 1. The pastures in the South-West are the additionally used areas due to fodder shortage of the experimental site (see above) and were only used with cows participating in the experiment. The feeding behavior of each cow was monitored by RumiWatch (Itin+Hoch GmbH, CH) halters with a noseband sensor. From the pressure signal time series induced by the jaw movement of the cow (Zehner et al.,

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162 2012) the relative duration of three activity classes (eating, ruminating, and idling) was
163 determined using the converter software V0.7.3.2.

2.2 Eddy covariance measurements

2.2.1 Instruments and set up

166 The EC measurement tower was placed in the middle of the pasture and was enclosed by a 2-
167 wire electric fence to avoid animal interference with the instruments (Fig. 1). The 3D wind
168 vector components u, v (horizontal) and w (vertical), as well as temperature were measured by
169 an ultra-sonic anemometer (Solent HS-50, Gill Instruments Ltd., UK) mounted on a horizontal
170 arm on the tower, 2 m above ground level. Methane, CO_2, and water vapor concentrations were
171 measured by cavity-enhanced laser absorption technique (Baer et al., 2002) by a fast greenhouse
172 gas analyzer (FGGA; Los Gatos Research Inc., US). The FGGA was placed in a temperature-
173 conditioned trailer in 20 m distance (NNE) from the EC tower and was operated in high flow
174 mode at 10 Hz. A vacuum pump (XDS35i Scroll Pump, Edwards Ltd., UK) pulled the sample
175 air through a 30 m long PVC tube (8 mm ID) and through the analyzer at a flow rate of about
176 45 sL min^{-1}. The inlet of the tube was placed slightly below the center of the sonic anemometer
177 head at a horizontal distance of 20 cm. Two particle filters with liquid water traps (AF30 and
178 AFM30, SMC Corp., JP) were included in the sample line. The 5 µm air-filter (AF30), installed
179 1 m away from the inlet, avoided contamination of the tube walls. The micro air-filter (AFM30;
180 0.3 µm) was installed at the analyzer inlet.

181 The noise level of the FGGA for fast CH_4 measurements depended on the cleanness of the
182 cavity mirrors. It was determined as the (weekly) minimum of the half-hourly standard
183 deviation of the 10 Hz signal. At the beginning the noise levels was at 15 ppb but gradually
184 increased to 38 ppb over time due to progressive contamination. In July 2013 the noise abruptly
185 increased without any explanation but the cleaning had to be postponed until mid of August.
186 During this period the noise level was 230 to 400 ppb. After the cleaning the noise was even
187 lower (around 7 ppb) than at the beginning.

188 The gas analyzer was calibrated at intervals of approximately two months with two certified
189 standard gas mixtures (1.5 ppm CH_4/350 ppm CO_2 and 2 ppm CH_4/500 ppm CO_2; Messer
190 Schweiz AG, CH). An excess of the standard gas was bypassed by a T-fitting to the device
191 which was set into low measurement mode at 1 Hz using the internal pump. The calibration
192 showed that the instrument sensitivity did not vary significantly over time, except for the period
193 when the measurement cell was very strongly contaminated.

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Gelöscht: interaction with

Gelöscht: concentration measurements depended on the cleanness of the cavity mirrors. It was determined as minimum of the standard deviation of the 10 Hz data

Gelöscht: accuracy

The data streams of the sonic anemometer and the dry air mixing ratios from the FGGA instrument were synchronized in real-time by a customized LabView (LabView 2009, National Instruments, US) program and stored as raw data in daily files for offline analysis.

Standard weather parameters were measured by a customized automated weather station (Campbell Scientific Ltd., UK).

2.2.2 Flux calculation

Fluxes were calculated for 30 min intervals by a customized program in the R software (R Core Team, 2014). First, each raw 10 Hz time series was filtered for values outside the physically plausible range ('hard flags') and the sonic data (wind and temperature) were subject to a de-spiking ('soft flags') routine according to Schmid et al., (2000); replacing values that exceed 3.5 times the standard deviation within a running time window of 50 s. Filtered values were counted and replaced by a running mean over 500 data points. No de-spiking was applied for the CH_4 mixing ratio because a potentially large effect on resulting fluxes was found. For cases with cows in the FP the CH_4 concentration showed many large peaks as illustrated in Fig. 2a, whereas for situations without cows the variability range was much lower (Fig. 2b). If the de-spiking routine is applied to the time series, this has a strong effect in the case with cows in the FP (Fig. 2a). 454 data points are replaced in this 30 min interval and the remaining concentration data are limited to 3500 ppb. The corresponding flux is reduced from 1322 to 981 nmol m^{-2} s^{-1} (-26%). The second time series not influenced by cows shows no distinct spikes and only 5 data points are removed by the de-spiking routine without significant effect on the resulting flux. Prior to the covariance calculation the wind components were rotated by the double rotation method (Kaimal and Finnigan, 1994) to align the wind coordinate system into the mean wind direction, and the scalar variables were linearly detrended.

The EC flux is defined as the covariance between the vertical wind speed and the trace gas mixing ratio (Foken et al., 2012b). Due to the tube sampling of the FGGA instrument there is a lag time between the recording of the two quantities. Therefore, the CH_4 flux was determined in a three-stage procedure: i) For all 30 min intervals the maximum absolute value (positive or negative) of the cross-covariance function and its lag position ('dynamic lag') was searched within a lag time window of ±50 s. ii) The 'fixed lag' was determined as the mode (most frequent value) of observed dynamic lags over several days allowing for longer-term temporal changes due to the FGGA operational conditions. iii) For the final data set, the flux at the fixed lag was taken, if the deviation between the dynamic and the fixed lag was larger than 0.36 s, else the flux at the dynamic lag was taken. The fixed lag for the CH_4 flux in this study was around 2 s.

Gelöscht: as illustrated in Fig. 2

233   For large emission fluxes with cows in the FP a pronounced and well determined peak in the
234   cross-covariance function could be found close to the expected lag time (Fig. 3a). For small
235   fluxes the peak can be hidden in the random-like noise of the cross-covariance function and the
236   maximum value may be found at an unplausible dynamic lag position (Fig. 3b). In this case the
237   flux at the fixed lag is more representative on statistical average, because it is not biased by the
238   maximum search.

239   The air transportation through the long inlet tube (30 m) and the filters led to high-frequency
240   loss in the signal (Foken et al., 2012a). To determine the damping factor, sufficient flux
241   intervals with good conditions are needed, i.e., cases with a large significant flux and very
242   stationary conditions resulting in a well-defined cospectrum and ogive with a low noise level.
243   These requirements were generally better fulfilled for CO_2 than for CH_4 fluxes. Because both
244   quantities were measured by the same device, we assumed that CH_4 fluxes had the same high-
245   frequency loss as determined for the more significant CO_2 fluxes. High-frequency loss was
246   calculated by the 'ogive'-method as described in Ammann et al. (2006). In short, the damping
247   factor was calculated by fitting the normalized cumulative co-spectrum of the trace gas flux to
248   the normalized sensible heat flux co-spectrum at the cut-off frequency of 0.065 Hz. The minor
249   high-frequency damping of the sensible heat flux itself was calculated according to Moore
250   (1986). A total damping of 10 to 30% depending mainly on wind speed was found for the
251   presented setup, and the fluxes were corrected for this effect.

252   The mixing ratios measured by the FGGA were internally corrected for the amount of water
253   vapor (at 10 Hz) and stored as 'dry air' values. Since also temperature fluctuations are supposed
254   to be fully damped by the turbulent flow (Reynold number = 10'000) in the long inlet line, no
255   further correction for correlated water vapor and temperature fluctuations (WPL density
256   correction, Webb et al., 1980) had to be applied.

2.2.3   Detection limit and flux quality selection

258   The flux detection limit was determined by analyzing the cross-covariance function of fluxes
259   dominated by general noise, i.e., fixed lag cases without significant covariance peak.
260   Additionally, the selection was limited to smaller fluxes (range around zero for which more
261   fixed lag than dynamic lag cases were found: here ± 26 nmol m^{-2} s^{-1}) in order to exclude cases
262   with unusually high non-stationarity effects. The uncertainty of the noise dominated fluxes was
263   determined from the variability (standard deviation) of two 50-s windows on the left and the
264   right side of the covariance function (Fig. 3) similar to Spirig et al. (2005). The detection limit
265   was determined as 3 times the average of these standard deviations.

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271 All measured EC fluxes were selected using basic quality criteria. The applied limits were

272 chosen based on theoretical principles and statistical distributions of the tested quantities. Only

273 cases which fulfilled the following criteria were used for calculations:

274 • less than 10 hard flags in wind and concentration time series

275 • small vertical vector rotation angle (tilt angle) within ±6° to exclude cases with non-

276 horizontal wind field

277 • wind direction within sectors 25 to 135° and 195 to 265° to exclude cases that are

278 affected by the farm facilities in the north and in the south of the study field (by non-

279 negligible flux contribution, non-stationary advection, distortion of wind field and

280 turbulence structure).

281 • fluxes above the detection limit need a significant covariance peak (dynamic lag

282 determination)

283 Moving sources in the FP lead to strong flux variations which are normally identified by the

284 stationarity criterion (Foken et al., 2012a). We did not apply a stationarity test, because it would

285 have potentially removed cases with high cow contributions. We also did not apply a u_*

286 threshold filter that is often used for CO_2 flux measurements (Aubinet et al., 2012), because it

287 would have been largely redundant with the other applied quality selection criteria (with a

288 negligible effect of < 2% on mean emission). Table 1 shows the reduction in number of fluxes

289 due to the quality selection criteria.

2.3 GPS method for deriving animal CH₄ emission

291 To assess the reliability of EC flux measurements of CH_4 emissions by cows on the pasture, the

292 measured fluxes (F_{EC}) had to be converted to average cow emissions (E) per animal and time.

293 This was done using three different information levels about animal position and distribution

294 on the pasture:

295   i. 'GPS method': use of time-resolved position for each animal from GPS cow sensors

296   (this section)

297 ii. 'PAD method': use of detailed paddock stocking time schedule (Sect. 2.4)

298 iii. 'FIELD method': using only the seasonal average stocking rate on the measurement field

299   without stocking schedule details (Sect. 2.5).

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2.3.1 Animal position tracking

For the animal position tracking each cow was equipped with a commercial hiking GPS device (BT-Q1000XT, Qstarz Ltd., TW) attached to a nylon web halter at the cows neck to optimize satellite signal reception. The GPS loggers using the WAAS, EGNOS and MSAS correction (Witte and Wilson, 2005) continuously recorded the position at a rate of 0.2 Hz. Each GPS device was connected to a modified battery pack with 3 x 3.6 V lithium batteries to extend the battery lifetime up to 10 days. GPS data was collected from the cow sensors weekly during milking time, and at the same occasion also the batteries were exchanged. GPS coordinates were transformed from World Geodetic System (WGS84) to the metric Swiss national grid (CH1903 LV95) coordination system. GPS data was filtered for cases with low quality depending on satellite constellation (positional dilution of precision PDOP ≤ 5). Each track was visually inspected for malfunction to exclude additional bad data not excluded by the PDOP criterion. Smaller gaps (<1 min) in the GPS data of individual cow tracks were linearly interpolated. The total coverage of available GPS data was used as quality indicator for each 30 min interval. The position data were used to distinguish between 30 min intervals when the cows were on the study field or elsewhere (barn or other pasture), or moved between the barn and the pasture.

The accuracy of the GPS devices was assessed by a fixed point test with six devices placed directly side by side for five days. Each device showed an individual variability in time not correlated to other devices and some systematic deviation from the overall mean position (determined from very good data with PDOP < 2 of all devices). The accuracy of each device was calculated as the 95% quantile of deviations. It ranged from 1.9 to 4.3 m for the six devices. We assessed this accuracy as sufficient for the present experiment because it is much smaller than the typical flux FP extension and also smaller than the typical cow movement range within a 30 min interval. Although there occurred some sensor malfunctions and data losses for individual GPS sensors during the continuous operation, the overall data coverage was satisfying for sensors attached to animals. Time intervals with less than 70% of cow GPS positions available, were discarded from the data evaluation. This occurred in only 8% of the cases.

2.3.2 Footprint calculations

An EC flux measurement represents a weighted spatial average over a certain upwind surface area called flux FP. The FP weighting function can be estimated by dispersion models. Kormann & Meixner (2001) published a FP model (KM01) based on an analytical solution of

355 the advection-dispersion equation using power-functions to describe the vertical profiles. The

356 basic Eq. (1) describes the weight function φ of the relative contribution of each upwind location

357 to the observed flux with the x-coordinate for longitudinal and y-coordinate for lateral distance.

$$\varphi(x,y) = \frac{1}{\sqrt{2\,\pi} \cdot D \cdot x^E} e^{\frac{-y^2}{2 \cdot (D \cdot x^E)^2}} \cdot C \cdot x^{-A} \cdot e^{\frac{-B}{x}} \tag{1}$$

358 The terms A to E are functions of the necessary micrometeorological input parameters ($z - d$:

359 aerodynamic height of the flux measurement; u_*: friction velocity; L: Monin-Obukhov length;

360 σ_v: standard deviation of the lateral wind component; wd: wind direction; $\bar{u}$: mean wind speed)

361 which were all measured by the EC system.

362 The FP weight function also needs the aerodynamic roughness length (z_0) as input parameter.

363 It can be calculated as described in Neftel et al. (2008) from the other input parameters $z - d$,

364 u_*, L, and $\bar{u}$ by solving the following wind-profile relationship:

$$\bar{u}(z - d) = \frac{u_*}{k}\left[\ln\left(\frac{z - d}{z_0}\right) - \psi_H\left(\frac{z - d}{L}\right)\right] \tag{2}$$

365 However, the determination of z_0 by this equation is sensitive to the quality of the other

366 parameters and especially problematic in low-wind conditions with relatively high uncertainty

367 in the measured u_*. Because z_0 is considered approximately constant for given grass canopy

368 conditions, its average seasonal course for the measurement field was parameterized by fitting

369 a polynomial to individual results of Eq. (2) which fulfilled the following criteria: $\bar{u} > 1.5$ m s⁻

370 ¹ (see e.g., Graf et al., 2014), days without snow cover, and mean wind direction in the

371 undisturbed sectors 25 to 135° and 195 to 265° (other wind direction showed relatively large

372 variation of z_0).

373 Because of short-term variability in the vegetation cover and because of the potential impact of

374 cows on z_0, a range of factor 3 to both sides of the fitted parameterization (see Fig. 7) was

375 defined. If the individual 30 min z_0 value (derived by Eq. 2) was within this range it was directly

376 used for the FP calculation. If z_0 exceeded this range it was restricted to the upper/lower bound

377 of the range.

378 Assuming that each cow represents a (moving) point source of CH₄, the FP contribution of each

379 5s-cow-position (Fig. 4a) was calculated according to Eq. (1). The individual values were then

380 averaged for each 30 min interval to the mean FP weight of a cow $\bar{\varphi}_{cow}$ and of the entire cow

381 herd $\bar{\varphi}_{herd}$:

$$\bar{\varphi}_{herd} = n_{cow} \cdot \bar{\varphi}_{cow} = n_{cow} \cdot \left[\frac{1}{N}\sum_{i=1}^{N}\varphi(x_i, y_i)\right] \tag{3}$$

Gelöscht: For each 30 min interval the average FP weight of the cow herd was calculated as

Gelöscht: $\bar{\varphi}_{cow} = \frac{1}{n_{cow} \cdot N}\sum_{k=1}^{n_{cow}}\sum_{i=1}^{N}\varphi(x_{i,k}, y_{i,k})$

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with n_{cow} denoting the number of cows in the herd, and N the total number of available GPS data points within the 30 min interval. To account for the uncertainty of the GPS position, each data point was blurred by adding 4 m in each direction from the original point. $\varphi(x_i, y_i)$ was calculated as the mean of the five $\varphi(x, y)$. $\bar{\varphi}_{herd}$ values were accepted only for 30 min intervals where >70% of the GPS data was available and the input parameters L, u_*, and σ_v were of sufficient quality. According to Eq. (3) it was assumed implicitly that the FP weight of the cows with missing GPS data corresponded to the mean weight of the cows with available position data.

2.3.3 Calculation of average cow emission

The measured flux (F_{EC}) cannot be entirely attributed to the contribution of direct cow emissions within the FP. It also includes the CH_4 exchange flux of the pasture soil (including the excreta patches). This contribution is denoted as 'soil flux' (F_{soil}) in the following. F_{soil} had to be quantified by selecting fluxes with no or negligible influence of cows based on the GPS FP evaluation and other selection criteria (Table 1).

The GPS data allows the calculation of emissions based on actual observed cow distribution and the use of the average cow FP weights (Eq. 3). The average emission per cow (E_{cow}) for a 30 min interval is determined as:

$$E_{cow} = \frac{(F_{EC} - F_{soil})}{\bar{\varphi}_{herd}} \tag{4}$$

In addition to the quality selection criteria for the EC fluxes mentioned in Sect. 2.2.3, the E_{cow} and the F_{soil} datasets were subject to an outlier test and removal. Outliers were identified using the boxplot function of R (R Core Team, 2014) as values farther away from the box (inter-quartile rage) than 1.5 times the length of the box. The effect of the outlier removal on the number of available data is indicated in Table 1.

2.4 PAD method for deriving animal CH_4 emission

To assess the effect of the precision of cow position information on the determination of the average cow emission, an option with less detailed but easier to obtain position information was also applied and compared to the GPS approach. In the PAD method, no individual cow position information is used, but it is assumed, that the animal CH_4 source is evenly distributed over the occupied paddock area. For this approach, an accurate paddock stocking time schedule is needed.

23

2.4.1 Footprint calculation for paddocks

Neftel et al. (2008) developed a FP tool based on Eq. (1) that calculates the FP weights of quadrangular areas upwind of an EC tower. The source code was adapted and transferred to an R-routine in order to allow more complex polygons instead of quadrangles for the different sub-areas of interest (here paddocks).

Under the assumption that an observed flux originates from a known source and that the source is uniformly distributed over a defined paddock area, the measured fluxes can be corrected with the integrated FP weight (Neftel et al., 2008):

$$\Phi_{\text{PAD}} = \iint\limits_{\text{PAD area}} \varphi(x,y)\,dx\,dy \tag{5}$$

In the FP tool the domain which covers 99% of the FP is divided into a grid of 200 (along-wind) times 100 (crosswind) cells, and for each cell the FP weight is calculated. The sum over all cells lying in the area of interest is the FP weight of the area (Eq. 5 and Fig. 4b). The FP model was already validated in a field experiment with a grid of artificial CH_4 sources and two EC flux systems (Tuzson et al., 2010).

2.4.2 Determination of average cow emission

With the information on pasture time and occupied paddock number, average cow emission for each 30 min interval is calculated as:

$$E_{\text{cow}} = \frac{(F_{\text{EC}} - F_{\text{soil}}) \cdot A_{\text{PAD}}}{\Phi_{\text{PAD}}} \cdot \frac{1}{n_{\text{cow}}} \tag{6}$$

with n_{cow} denoting the number of cows in the occupied paddock, A_{PAD} the area and Φ_{PAD} the FP fraction of the corresponding paddock. Emissions are calculated only for 30 min intervals where the cows were on the pasture, the FP weight of the grazed paddock Φ_{PAD} exceeds 0.1, and FP input parameters are of sufficient quality.

2.5 FIELD method for deriving animal CH_4 emission without position information

EC measurements are frequently performed over pastures, but usually no detailed information on the position and exact number of animals and specific occupation times are available. If at least the average stocking rate over the grazing period is available and under the assumption that the cows are uniformly distributed over the entire pasture the time averaged cow emission can be calculated as:

24

$$\langle E_{\mathrm{cow}} \rangle = (\langle F_{\mathrm{EC}} \rangle - \langle F_{\mathrm{soil}} \rangle) \cdot A_{\mathrm{field}} \cdot \frac{1}{\langle n_{\mathrm{cow}} \rangle} \qquad (7)$$

with $\langle F_{\mathrm{EC}} \rangle$ denoting the mean observed CH_4 flux of the grazing period, A_{field} the total pasture area, and $\langle n_{\mathrm{cow}} \rangle$ the mean number of cows on the study field over the grazing season. $\langle n_{\mathrm{cow}} \rangle$ = 6.6 heads is calculated as the total number of cows of each 30 min interval with cows on the study field plus ½ of the number of cows when the cows were moved between barn and pasture divided by the total number of 30 min intervals of the grazing period. For comparison reasons, the cow flux is calculated by subtraction of the average soil flux. This is of course only possible because the GPS data was available.

3 Results

3.1 Methane fluxes with and without cows

Observed 30 min CH_4 fluxes varied between -150 and 2801 nmol m^{-2} s^{-1} during the grazing season. Situation with cows close to the sensor revealed strong fluxes (Fig. 5b and c). For situations with no cows in the FP (Fig. 5a) or with cows further away measured fluxes were very small. For the cow emission calculations with FP consideration, fluxes were divided into situations with *near cows* (Fig. 5 white paddocks) and *far cows* (Fig. 5 gray paddocks).

For a systematic assessment of the relation between CH_4 flux and cow position and for the separation of cases representing pure soil fluxes, all quality selected fluxes were plotted against $\bar{\varphi}_{\mathrm{herd}}$ in Fig. 6. It shows a clear relationship with a strong increase of fluxes only in the highest $\bar{\varphi}_{\mathrm{herd}}$ range. Situations with *near cows* led to generally higher FP weights and fluxes than for the *far cows* situations. Based on Fig. 6, a threshold of $2 \cdot 10^{-4}$ m^{-2} ($\varphi_{\mathrm{crit,herd}}$) was determined as the lower cut off for cow affected fluxes to be used for the calculation of E_{cow}. Cases with $\bar{\varphi}_{\mathrm{herd}}$ below $\varphi_{\mathrm{crit,soil}} = 2 \cdot 10^{-6}$ m^{-2} were classified as soil fluxes. The exclusion of cases with $\bar{\varphi}_{\mathrm{herd}}$ between the two critical limits ensured that fluxes with potential influence by the cows grazing on the neighboring pasture were removed.

The soil flux values were found to be generally small but mostly positive in sign (typically in the range 0 to 15 nmol m^{-2} s^{-1} Fig. 6) indicating a continuous small emission by the soil and surface processes. The accuracy of these fluxes was difficult to quantify because they mostly had no well-defined peak in the covariance function and thus 92% had to be calculated at the fixed lag. Even though temporal variations in median diurnal and seasonal cycles were observed (in the range of 1 to 7 nmol m^{-2} s^{-1}), it was unclear whether these can be attributed to effects of environmental drivers or whether they result from non-ideal statistics and selection procedures. Also varying small contributions from cows on neighboring upwind fields could not be

25

484   excluded. Therefore we used a conservative overall average estimate for the soil flux of 4 ± 3

485   nmol m^{-2} s^{-1} with the uncertainty range of $\pm50\%$ covering the temporal variation of medians

486   indicated above.

487   3.2   Footprints and cow influence

488   3.2.1   Roughness length

489   The 30 min values of the roughness length z_0 determined for wind speeds > 1.5 m s^{-1} showed a

490   systematic variation over the year peaking in summer (Fig. 7) when the vegetation height

491   ranged between 5 and 15 cm. Bi-weekly medians for situations with no cows in the FP ranged

492   from 0.16 to 1.6 cm and corresponded well to the parameterized z_0. Cows in the FP (withers

493   height c. 150 cm) slightly influenced z_0. The effect was distance dependent (Fig. 8). For cases

494   with high FP weights of the cows (i.e., cows closer to the EC tower), z_0 was systematically up

495   to 2 cm higher than the average parameterized z_0. However there was still a considerable scatter

496   of individual values and variation with time. The range limits for z_0 (grey range in Fig. 7) were

497   necessary to filter implausible individual values under low wind or otherwise disturbed

498   conditions. However, they were sufficiently large to include most of the cases influenced by

499   cows. While for soil fluxes not influenced by cows 16% (5% below/11% above) of the

500   calculated z_0 values lay outside the accepted z_0-range, the respective portion was only slightly

501   higher (2% below/18% above) for situations with cows in the FP.

502   3.2.2   Footprint weights of cows and paddocks

503   Average cow FP weights (Eq. 3) ranged up to $2.9 \cdot 10^{-4}$ and $0.7 \cdot 10^{-4}$ m^{-2} for the *near* and *far cows*

504   situations (Fig. 9a). On the lower end they were limited by the cut-off value $\varphi_{crit,herd}$. The

505   distribution of the *near cows* cases showed a pronounced right tail whereas the *far cows* cases

506   were more left skewed. Figure 9b shows the FP fraction of the paddock in which the cows were

507   present and which were used to calculate the emissions with the PAD method (Eq. 6). FP

508   fractions for *far cows* were always lower than 25% of the total FP area. For the majority of the

509   *near cows* cases the contribution to the measured flux was more than 40%.

<div style="float:right; border:1px solid #c00; padding:2px; font-size:90%">**Gelöscht:** grazing</div>

510   3.3   Methane emission per cow

511   3.3.1   Overall statistics

512   The discrimination of fluxes into the classes *near* and *far cows* resulted in 194 and 63 30 min

513   GPS based cow emission values, respectively. Using the PAD method, the corresponding

    26

515   numbers were only slightly higher (Table 1). Table 2 shows the estimated cow emissions for

516   the three emission calculation schemes and for the two distance classes (*near cows*, *far cows*)

517   if applicable. Emissions calculated for the *near cows* cases were significantly larger than

518   emissions calculated for the *far cows* cases. The uncertainty of the mean (2·SE, calculated

519   according to Gaussian error propagation) was lowest for the *near cows* of the GPS method.

520   Emission results calculated with the PAD method were comparable to those of the GPS method

521   considering the distance classes. The difference between median and mean values for GPS and

522   PAD method were relatively small indicating symmetric distribution of individual values.

523   Because the result of the FIELD method was calculated as temporal mean over the entire

524   grazing period (with many small soil fluxes and few large cow influenced fluxes, see Fig. 6),

525   the uncertainty could not be quantified from the variability of the individual 30 min data.

526   Therefore we applied the FIELD method also to monthly periods and estimated the uncertainty

527   ($\pm$184 gCH_4 head^{-1} d^{-1}) from those results (n = 7). It is much larger than for the two other

528   methods and there exists also a considerable difference between the two different mean values.

529   **3.3.2 Diurnal variations**

530   Average diurnal cycle analysis for the *near cows* cases (Fig. 10a) showed persistent CH_4

531   emission by the cows over the entire course of the day. For four hours of the day less than five

532   values per hour were found, mainly around the two milking periods or during nighttime. Mean

533   emissions per hour ranged from 288 to 560 gCH_4 head^{-1} d^{-1} with highest values in the evening

534   and lowest in the late morning (disregarding hours with n < 5). Although the two grazing

535   periods (evening/night: 5 pm to 3 am and morning/noon: 8 am to 2 pm) between the milking

536   phases were not equally long, comparable numbers of values were available (n = 91 vs. 103).

537   After the morning milking, the emissions decreased slightly for the first three hours followed

538   by a slight increase. An almost opposite pattern could be found after the second milking in the

539   afternoon.

540   The temporal pattern of cow activity classes (Fig. 10b) mainly followed the daylight cycle with

541   grazing activity dominating during daytime and ruminating during darkness. Highest grazing

542   time shares were observed right after the milking in the morning and in the later afternoon.

543   While grazing and ruminating show clear opposing patterns, there is no distinct overall relation

544   to the CH_4 emission cycle in Fig. 10a. Yet maximum emissions in the evening hours coincide

545   with maximum grazing activity.

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4 Discussion

4.1 Flux data availability and selection

Fluxes used for cow emission calculations were less than 3% of the total number of 30 min intervals (Table 1). In average years 3.6 ha of pasture are approximately sufficient to feed 20 dairy cows by rotational grazing during the early season. The cold and wet spring in 2013 negatively influenced the productivity of the pasture. Therefore, more than expected additional pasture time outside the study field was needed to feed the animals. These neighboring pastures were used for 44% of the time but contributed typically less than 5% to the EC footprint, which was too low for a sufficient cow emission signal. Hence the data coverage to measure cow emissions was lower than expected. The selection of acceptable wind directions and the limited probability that the wind came from the direction where the cows were actually present further reduced the number of cases selected as cow fluxes. Cow emissions with sufficient FP contribution mostly induced well defined peaks in the cross-covariance function (Fig. 3) and were well above the flux detection limit (similar as found by Detto et al., 2011). Even if the cows were present in the far paddocks 94% of the fluxes already filtered by the other quality criteria were determined at dynamic lag times. This shows that a further quality filtering by a stationarity test was not needed.

Individual soil exchange fluxes were mostly below the (3σ) detection limit of 20 nmol m^{-2} s^{-1} and more than 92% were determined at the fixed lag time. Detto et al. (2011) reported a detectable limit of ± 3.78 nmol m^{-2} s^{-1} for a similar set up. The higher detection limit in this study has to be attributed to a different set-up but also to the stronger polluted region with various agricultural CH$_4$ sources (farm facilities). The uncertainty of the soil flux was of minor importance for the calculations of the cow emissions by the GPS and PAD methods (Eqs. 4 and 6), because the selected cow fluxes with significant FP contribution were about two orders of magnitude higher than $F_{soil} = 4 \pm 3$ nmol m^{-2} s^{-1} (Fig. 6). Soil fluxes observed here are of similar magnitude like fluxes measured in other studies: CH$_4$ fluxes in the order of 0 to 10 nmol m^{-2} s^{-1} are reported from a drained and grazed peatland pasture (Baldocchi et al., 2012), fluxes around zero seldomly larger than 25 nmol m^{-2} s^{-1} for a grassland in Switzerland after renovation (Merbold et al., 2014), and fluxes between -1.3 and 9.6 nmol m^{-2} s^{-1} from a sheep grazed grassland measured by chambers (Dengel et al., 2011).

Methane fluxes from pasture always include fluxes from animal droppings (dung and urine). Therefore the soil fluxes referred to here are the combination of fluxes from the soil microbial community and fluxes from dung/urine which normally dominate over the pure soil fluxes

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(Flessa et al., 1996). Emissions from cattle dung are estimated to 0.778 gCH4 head^{-1} (Flessa et al., 1996) and from finish dairy cows to 470 gCH$_4$ ha^{-1} over a 110 day grazing period (Maljanen et al., 2012). The soil flux in the present study (16 g ha^{-1} d^{-1}) is around three times higher than the corresponding flux calculated with the literature numbers (Flessa et al. (1996): 5 g ha^{-1} d^{-1} and Maljanen et al. (2013): 4.3 g ha^{-1} d^{-1}) but in the same order of magnitude. Hence, the soil in the present study was a source of CH$_4$. Factors which may explain differences in the present study and the literature are different animal breeds/types, soil and vegetation types, and soil and weather conditions. Additionally the rotational grazing lead to measurements of mixed fluxes from old and new dung patches.

4.2 Source distance effect and footprint uncertainty

In the GPS and PAD method, cow emissions were derived from the measured fluxes (corrected for soil exchange) with the help of the KM01 footprint model (Eqs. 4 and 6). Although it can be assumed that the cows emitted the same amount of CH$_4$ whether they grazed in the far or the near paddocks, a systematic effect of their distance from the EC tower was found (cf. *near cows* vs. *far cows* results in Table 2). The accuracy of the emissions depends on the accuracy of the flux measurement and on the accuracy of the FP model. The FP weight gets smaller and thus its relative accuracy decreases further away from the EC tower. This led to larger systematic uncertainties for calculations in the *far cows* case compared to the *near cows* case.

One potential error source in the FP calculation could be the choice of z_0. The observed course of z_0 over the year (Fig. 7) coincides with the herbage productivity during the season and corresponds to around 1/10 of the grass height. The presence of the cows (in *near* paddocks) only slightly increased z_0 but the values remained in the expected range of 8 mm to 6 cm for short to long grass terrains (Wieringa, 1993). For occasional large obstacles (separated by at least 20 times the obstacle height) rather a value of 10 cm and larger is expected (WMO, 2008). Cows were moving obstacles in the FP, which obviously damped the enhancement of z_0. For the FP calculation we therefore generally limited z_0 to a certain range around the mean seasonal course. For the majority of the cases, individually calculated z_0 values lay within this range, but in a minor fraction (18%) of the cases with cows, they exceeded the range (see Fig. 7) and were truncated to the upper range limit. We tested the effect of a doubling of the parameterized z_0 on Φ_{PAD} for the *near cows* case, as typically observed in Fig. 8, and found a moderate increase of around 17% which would lower the calculated cow emissions proportionally. Because the truncation effect was small and only applied to few cases, we consider the uncertainty in z_0 as

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Gelöscht: In general fluxes induced from cows further away were smaller () and therefore tended to have a higher relative uncertainty than fluxes closer to the EC tower. Additionally the relative FP accuracy is assumed to be lower further away from the EC tower. This led to systematic larger

Gelöscht: Larger effects seen for a fixed obstacle were obviously blurred if the obstacle moves. Additionally variations of the wind direction in a 30 min interval amplify the effect of moving.

623 not important for our cow emission results. In particular it cannot explain the observed mean

624 difference between *near* and *far cows* situations.

625 We chose the KM01 footprint model because the model uses an analytical solution and the

626 calculation is fast compared to numerical particle models (e.g. backward Lagrangian stochastic

627 models; bLS) which describe turbulence structure in a more complex way. Kljun et al., (2003)

628 compared the KM01 model to a bLS model and found in general good agreements. However,

629 the KM01 model underestimates the FP weight compared to the bLS model around the

630 maximum of the FP function φ_{max} and overestimates the FP weight further downwind (see

631 figures in Kljun et al., 2003). Integration over larger parts of the FP extension may balance this

632 over-/underestimation. In the present study, the position of φ_{max} typically lay within 30 m of the

633 EC tower (in PAD2 or PAD5). Thus for the *near cows* cases with animals typically within 60

634 m distance, such a balancing effect can be assumed. For the *far cows* case the KM01 model

635 generally tends to overestimate the FP weights and thus the resulting emissions were

636 underestimated on average. According to Kljun et al. (2003) the KM01 model also

637 underestimates the FP weights in the direct vicinity of the EC tower (few meters). A detailed

638 analysis of the cow positions (data not shown) revealed that in 68% of the *near cows* cases

639 animals were present in distances $< 2/3 \, \varphi_{max}$ from the tower. But in less than 5% of the cases

640 more than a tenth of the 30 min was affected. Hence the influence on the $\bar{\varphi}_{herd}$ was generally

641 small.

642 The analytical model solution by KM01 was developed for ground level sources. Yet, while the

643 cow's mouth and nose (respiration source) are close to the surface during grazing, they may be

644 elevated up to c. 1 m during other activities. Unfortunately, this effect could not be evaluated

645 with the KM01 model. However, very recently McGinn et al. (2015) investigated the effect of

646 elevated cow emissions for a micrometeorological flux method that also uses turbulent

647 dispersion modelling. They found no significant difference in their results between simulations

648 with sources at the surface and at 0.5 m height. It needs to be investigated in the future whether

649 this finding is also valid for the EC flux footprint weight.

650 4.3 Comparison to published respiration chamber results

651 While measured methane EC fluxes depend on site and environmental conditions and are

652 therefore not directly comparable to other studies, this is much better feasible for the average

653 cow emissions derived by the GPS method and the two alternative methods (PAD and FIELD)

654 described in Sect. 2.3-2.5. It can be assumed that dairy cows of similar breed and weight and

655 with comparable productivity (milk yield) have a similar gross energy consumption and CH_4

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emission. We therefore collected literature results from Swiss respiration chamber studies selected for a mean milk yield in the range of 20 to 25 kg d^{-1} around the mean milk yield of the present study (22.7 kg d^{-1}). Most of those studies aimed to find diets that reduce CH_4 emission based on different forage types and supplements. Cow diets therefore varied between all studies but always fulfilled animal nutrient requirements. One value from van Dorland et al. (2006) which showed very low CH_4 emissions due to special diet supplements was excluded from Table 3. Mean body weight of cows in the present study (640 kg) was in the upper range of body weight in the selected chamber measurements.

Mean CH_4 emission over all selected studies of 404 gCH$_4$ head^{-1} d^{-1} agrees very well with emission measured by EC for the *near cows* cases of 423 gCH$_4$ head^{-1} d^{-1} (difference of only 5%, within uncertainty range, see Table 2). The deviation for the PAD *near cows* results is about twice as large. The *far cows* results for GPS and PAD methods show even larger but negative deviations from the literature mean. The result of the FIELD method applied to the entire grazing period also shows a good agreement but we consider that as rather coincidental, because the estimated uncertainty of monthly values as well as the deviation of their mean and median is much larger.

Based on the FP uncertainty considerations in Section 4.2 and the agreement with the recent literature values, we consider the GPS *near cows* results as the most reliable in this study. They were derived from only large fluxes with relatively low uncertainty. Therefore, the following discussion focusses on the GPS *near cows* results and uses them as reference for the comparison with the other results.

4.4 Systematic and random-like variations of cow emission

Our result show only a moderate diel cycle (Fig. 10a) with highest emissions in the evening and lowest before noon (hourly means ±30% around overall mean). Although the timing of maximum emissions coincides with maximum grazing activity, the general diel variation cannot be explained satisfyingly by the observed cow activities (Fig. 10b). On the other hand the emission pattern shows some correlation to the stability conditions, which were also subject to a distinct diel cycle (predominantly unstable conditions from daybreak till early evening and stable conditions during evening and night). Therefore a methodology induced effect of stability (e.g. via FP calculation) on the observed diel emission cycle cannot be fully excluded.

Increasing emission fluxes during daytime hours were also found over a sheep pasture by Dengel et al. (2011). But their nighttime fluxes were much smaller (close to zero) compared to daytime. Laubach et al. (2013) observed maximum CH_4 emissions within two hours after

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Gelöscht: of EC results

697 maximum feeding activity of cattle. Those cattle were fed before noon with imported fodder
698 (i.e. all animals fed at the same time) whereas the cows in the present study were free in
699 choosing their grazing activity time over the entire day. Obviously this is reflected in the less
700 pronounced diel cycle.

701 To assess and interpret potential systematic effects of variations in cow performance (among
702 animals in the herd and with time over the grazing season) we used published emission models
703 based on observed productivity parameters (see Ellis et al., 2010). Figure 11 compares the
704 results of two models (Corré, 2002; Kirchgessner et al., 1995) estimating cow emission from
705 recorded milk yield and body weight with results of this study. Although milk yield showed a
706 general decrease over the first three months and a considerable variability within the herd, the
707 effect on CH_4 emissions according to the models was relatively small. The observed monthly
708 emissions showed a larger variability which cannot be explained by the variability of the cow
709 performance.

710 Although the mean emissions observed in this study agree well with literature values the
711 variation of the individual 30 min emissions is large (relative SD of 41% for GPS *near cows*,
712 see Table 2). It is a combination of various effects with major contributions of the discussed
713 diel variation, the stochastic uncertainty (short term variability) of turbulence, and the changing
714 source distribution (various numbers of cows in the FP and moving). Very similar relative
715 variability of 30 min fluxes was reported in a study using the micrometeorological bLS method
716 (Laubach et al., 2014). Similar to Laubach et al., the large scatter of our individual emission
717 values showed a fairly random-like (normal) distribution (Fig. 12) with only minor deviation
718 between mean and median. This distribution is clearly more symmetric than the corresponding
719 distribution of cow FP weights (Fig. 9a). Based on this behavior, the estimated uncertainty
720 range of the overall mean cow emission calculated according to Gaussian error propagation
721 rules is considered as representative.

722 **4.5   Relevance of cow position information**

723 In an intensive rotational grazing system the cows are expected to effectively graze the entire
724 paddock area. On shorter timescales of 30 minutes (Fig. 5) this assumption is often not fulfilled.
725 For a grazing rotation phase of two days the example in Fig. 13a shows that the cows indeed
726 visited the entire paddock, but their position distribution was not uniform with higher densities
727 in the central part of the paddock. Even over the entire grazing season some inhomogeneity in
728 the cow density distribution persisted (Fig. 13b). Despite this inhomogeneity the mean emission
729 calculated with the PAD method (implicitly assuming homogeneous cow distribution within

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730 the paddock) was comparable to the emission based on GPS data (Table 2), yet with a larger
731 uncertainty range. Thus the hypothesis that more detailed information lead to better results was
732 not clearly verified in this case. Apparently the limited size and the geometric arrangement of
733 the paddocks in relation to typical extension of the FP area in the main wind sectors limited the
734 value of the more detailed GPS information.
735 The PAD method uses a similar level of cow position information as other micrometeorological
736 experiments applying the bLS approach (Laubach et al., 2008, 2013; Laubach and Kelliher,
737 2005; McGinn et al., 2011). The bLS models use the geometry of the fenced grazing area and
738 perform a concentration FP calculation (instead of the flux FP used here). The size of the animal
739 containing fenced areas in those experiments (0.1 to 2 ha) were of the same order of magnitude
740 as the paddock size in this study. Although the density of grazing animals in Laubach et al.
741 (2013) was five times higher than the average density of 33 heads ha^{-1} in this study, they
742 reported systematic effects of uneven cow distribution within the paddock on derived mean cow

743 emissions, which was associated to the location where the fodder was offered. They found a
744 discrepancy of up to +68% between their reference SF_6 technique and the bLS model using
745 concentration profile measurements at a single mast. The bLS experiments with line-averaging
746 concentration measurements yielded generally better results because they are less sensitive to
747 the source distribution. The corresponding uncertainties were similar to uncertainties found in
748 this study.
749 Although some inhomogeneity of the animal density was found within the paddocks, the
750 rotational grazing system prevented major differences among them on the long term (Fig. 13b).
751 This may not be the case for a free range grazing system without subdivision of the field into
752 paddocks, like e.g. in the study by Dengel et al. (2011). In such a case, a larger scale
753 inhomogeneity may develop leading to a systematic under- or overrepresentation of the animals
754 in the flux FP (in the main wind sectors), and the FIELD method without cow position
755 information would yield biased results. As an alternative to the use of GPS sensors on individual
756 animals, their position could be monitored by the use of digital cameras and animal detection
757 software (Baldocchi et al., 2012).
758 The problem discussed so far for CH_4 also exists for the investigation of CO_2 flux measurements
759 at pasture sites, because of the considerable contribution of animal respiration to the net
760 ecosystem exchange. If joint CO_2 and CH_4 fluxes are available at the site CH_4 can be used as a
761 tracer for ruminant induced CO_2 fluxes by using typical CH_4/CO_2 ratios of exhaled air found in
762 respiration chamber measurements.

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5 Conclusions

EC flux and GPS data were combined using an analytical FP model to derive animal related CH_4 emissions. A systematic effect of the distance from the EC tower to the source (cows) was found, which has to be attributed to the applied analytical FP model. It overestimates the FP weight of sources in large distances (> 25 times the measurement height). The problem may be avoided by using a more sophisticated Lagrangian dispersion model. The roughness length z_0 used as input for the FP model was moderately but systematically increased by the cows which should be taken into account.

The position information allowed a reliable distinction of fluxes representing soil exchange without direct influence of cows. Although these fluxes were very low with marginal effect on the determination of cow emissions (using cow position information), they are potentially more important for the annual CH_4 and full GHG budget of the pasture. In our rotational grazing set up, the simple information on paddock occupation times led to comparable estimates of mean cow emissions like the more detailed GPS information. For other pasture flux sites with a different grazing system, cow position information may be more crucial to determine representative animal emissions and soil exchange fluxes. We conclude that EC measurements over pasture are sufficiently accurate to estimate mean CH_4 emissions of animals on the pasture. Although the uncertainty makes it difficult to detect small differences in animal CH_4 emissions during short-term experiments, the EC method is well suitable for assessing longer-term ecosystem GHG budgets that are necessary to improve national inventories.

Acknowledgements

Gelöscht: With an adjusted evaluation procedure (no de-spiking nor stationarity selection) an underestimation or rejection of cases with strong cow signals could be avoided.

Gelöscht: grazing

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975   Eng. - CIGR-AgEng 2012 Agric. Eng. Heal. Life Valencia Spain 8-12 July 2012, C–0438,

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978 Table 1. Number of available 30 min CH$_4$ fluxes in this study after the application of selection
979 criteria for the three calculation methods (FIELD, GPS, and PAD method). Bold numbers
980 were used for final calculations.

	all/FIELD	GPS			PAD	
		soil	*near cows*	*far cows*	*near cows*	*far cows*
grazing season[1]	10 080					
quality operation[2]	9856					
quality turbulence[3]	7093					
wind direction[4]	4645					
flux error/LoD[5]	**3630**					
soil/cow attrib.[6]		2076	205	64	216	74
outliers removed[7]		**1917**	**194**	**63**	**198**	**74**

981 [1] total number of 30 min intervals in grazing season (09.04.2013 – 04.11.2013)

982 [2] available data with proper instrument operation (hard flags < 10)

983 [3] acceptable quality of turbulence parameters and vertical tilt angle within ±6°

984 [4] accepted (undisturbed) wind direction: 25 to 135° and 195 to 265°

985 [5] no fluxes at fixed lag if flux larger than flux detection limit (LoD)

986 [6] split fluxes based on GPS data; exclusion of intervals with low GPS data coverage;
987 exclusion of intervals (730) when cows were moved between barn and pasture; discarding
988 of cases with intermediate mean cow FP weights

989 [7] outliers for cow cases determined based on emission (E_{cow})

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997 Table 2. Methane emissions calculated with known cow position (GPS) or occupied paddock
998 area (PAD) for different distances of the cow herd to the EC tower (near, far), and calculated
999 without using cow position information (FIELD). All values, except n, are in units gCH$_4$ head$^-$
1000 ^{1} d^{-1}.

	GPS		PAD		FIELD
	near cows	*far cows*	*near cows*	*far cows*	
Mean	423	282	443	319	389[a] / 470[b]
± 2 SE	±24	±32	±32	±40	±184[b]
Median	408	296	405	323	348[b]
SD	168	124	226	173	243[b]
n	194	63	198	74	7[b]

1001 [a] mean of all available 30 min data over the entire grazing period (in contrast to the second
1002 value[b])

1003 [b] statistical values calculated based on monthly results (April – October)

1004

1011 Table 3. Methane emissions from open-circuit respiration chamber measurements of Holstein

1012 and Swiss Brown breeds selected for milk yields and body weights comparable to cows in the

1013 present study. Hindrichsen et al., (2006a) used Swiss Brown breeds only.

Reference	Emission	Body weight	ECM[1]
	[gCH$_4$ head^{-1} d^{-1}]	[kg]	[kg d^{-1}]
van Dorland et al. (2006)	428	669	23.5
van Dorland et al. (2006)	413	669	24.4
van Dorland et al. (2007)	424	641	24.5
Hindrichsen et al. (2006a)	415	586	20.0
Hindrichsen et al. (2006a)	379	583	20.0
Hindrichsen et al. (2006a)	374	594	21.0
Hindrichsen et al. (2006b)	414	619	22.8
Münger and Kreuzer (2006)[2]	387	593	22.9
mean	404	619	22.4
SD	21	36	1.8

1014 [1] ECM: energy-corrected milk yield

1015 [2] mean values of lactation week 8, 15, and 23

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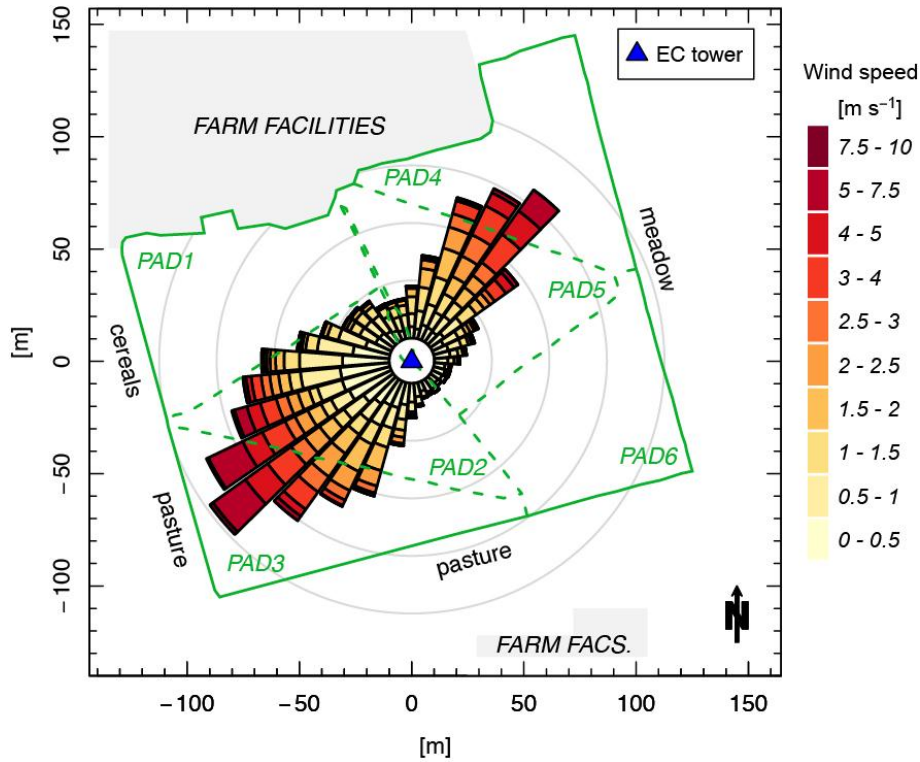
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Figure 1. Plan of the measurement site with the pasture (solid green line) and its division into six paddocks PAD1 to PAD6 (dashed green lines) used for rotational grazing. Around the EC tower in the center, the wind direction distribution for the year 2013 is indicated with a resolution of 10°. The grey circles indicate sector contributions of 2, 4, 6, and 8% (from inside outwards). Each sector is divided into color shades indicating the occurrence of wind speed classes (see legend).

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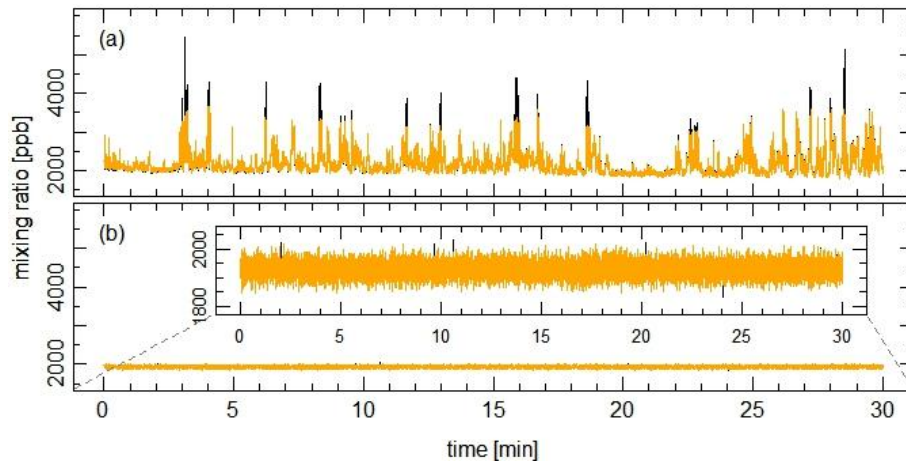
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1027 Figure 2. 10 Hz time series of CH_4 mixing ratio for two exemplary 30 min intervals on 15 June
1028 2013 between 12:30 and 14:30 local time (a) with and (b) without cows in the FP. In black
1029 untreated data, in orange data after de-spiking. The two cases correspond to the cross-
1030 covariance functions in Fig. 3a and b.
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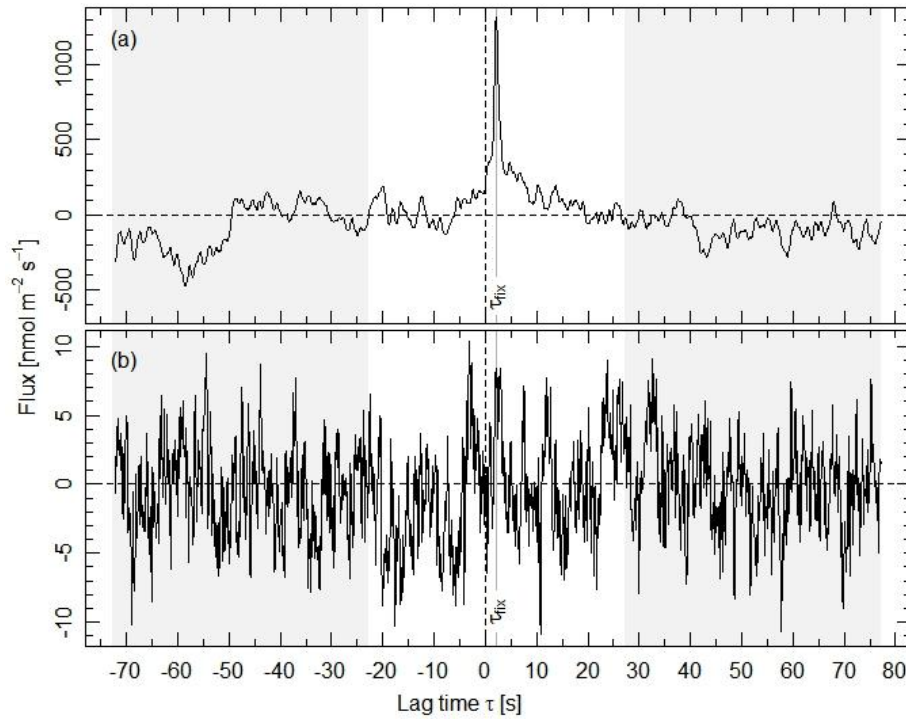
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Figure 3. Cross-covariance function of CH$_4$ fluxes for two 30 min intervals of 15 June 2013 (a)
with and (b) without cows in the footprint. The panels correspond to the intervals in Fig. 2. τ_{fix}
indicates the expected fixed lag time for the EC system. The grey areas on both sides indicate
the ranges used for estimating the flux uncertainty and detection limit.

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1040   Figure 4. removed

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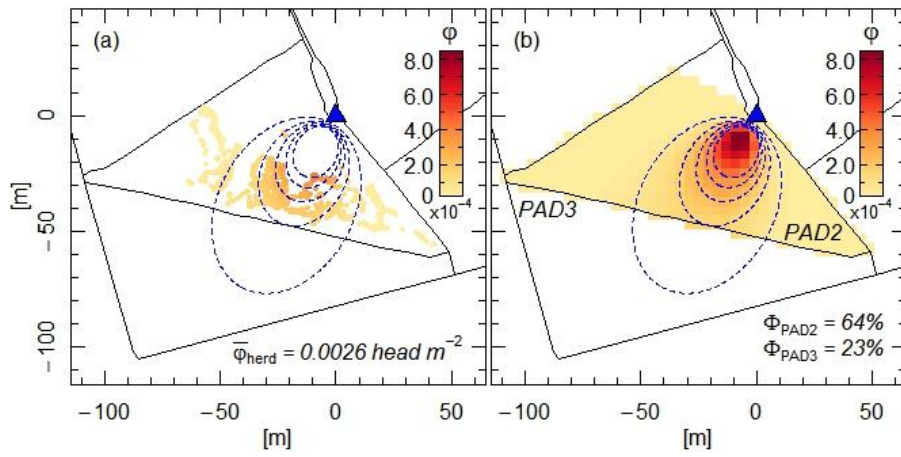
Figure 4. Determination of footprint weights for a cow herd in PAD2 during a 30 min interval with two different approaches: (a) 'GPS method' (Eq. 3) based on the actual cow positions. The color indicates the weight of each GPS point to the measured flux; (b) 'PAD method' (Eq. 5) calculating the area integrated footprint weight of the entire paddock area (here: $\Phi_{PAD2} = 64\%$). The color of each pixel (4 x 4 m grid) indicates the footprint weight. The blue triangle indicates the position of the EC tower and the blue dashed lines are isolines of the footprint weight function.

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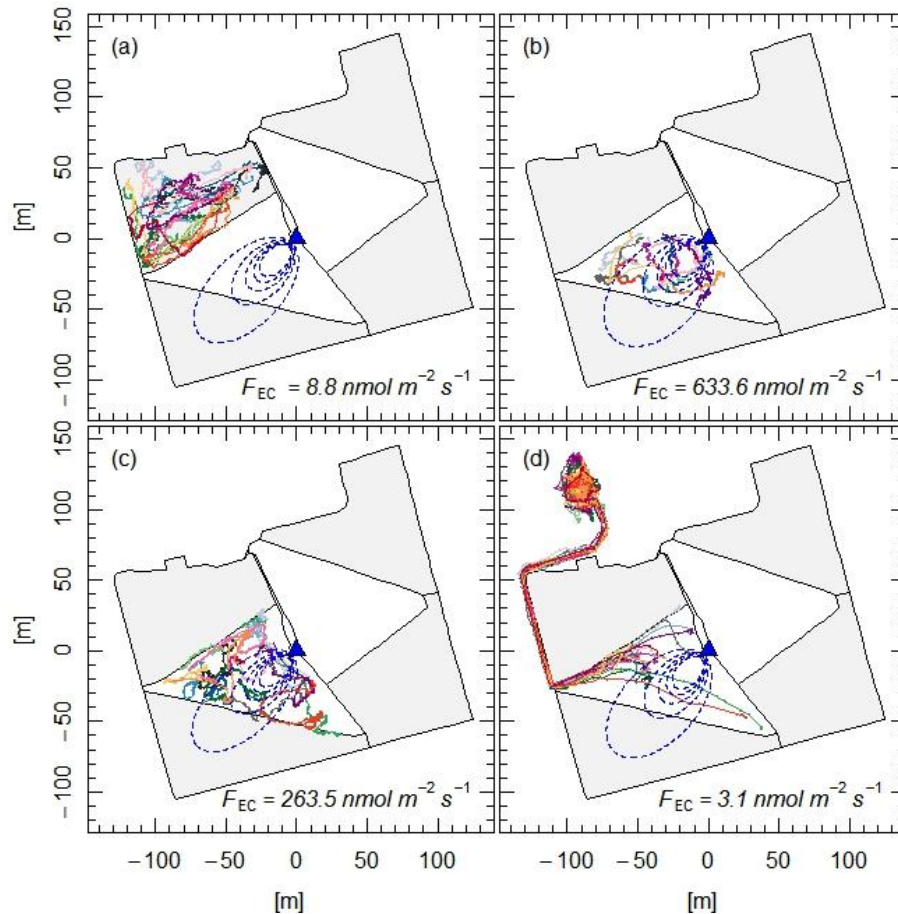
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1053 Figure 5. Four examples of 30 min intervals with similar wind and footprint conditions (blue
1054 isolines) but different cow distribution and observed fluxes (F_{EC}). For each cow, the GPS
1055 registered position (5 s resolution over 30 min) is marked with a line of individual color.
1056 Paddocks representing *near cows* situations are white and *far cows* are gray. (a) no cows in the
1057 footprint, i.e. soil fluxes are measured, (b)-(d) the higher the number and residence time of cows
1058 in the footprint the larger the observed flux.

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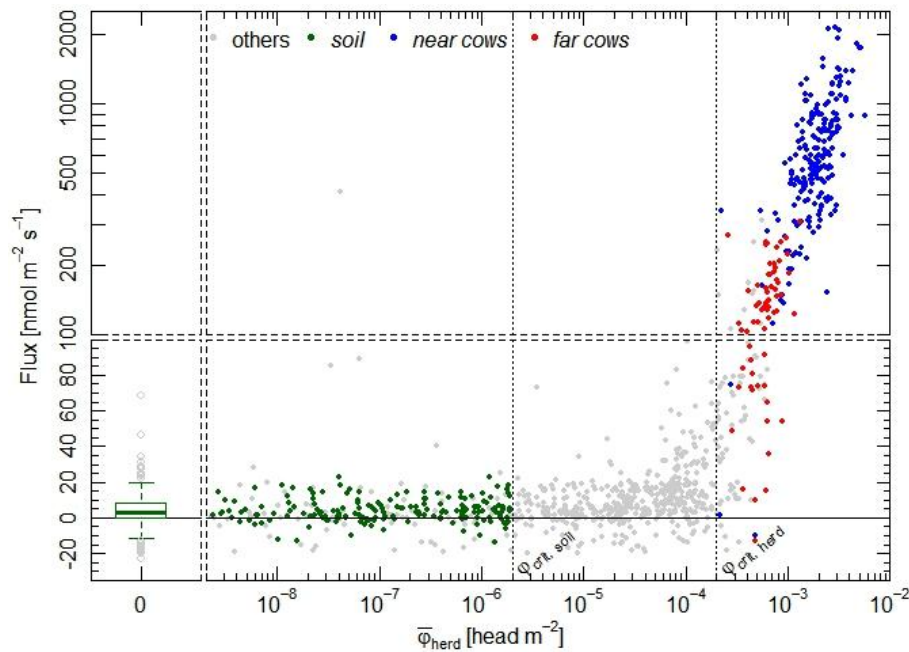
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1062 Figure 6. Observed CH_4 fluxes plotted against the mean herd footprint weight ($\bar{\varphi}_{herd}$). Cases

1063 selected for the calculation of the soil flux (green) and cow emission (blue/red) are marked in

1064 dark colors. The remaining points (gray) represent discarded outliers and cases with

1065 intermediate $\bar{\varphi}_{herd}$ values (i.e., with low but not negligible cow influence).

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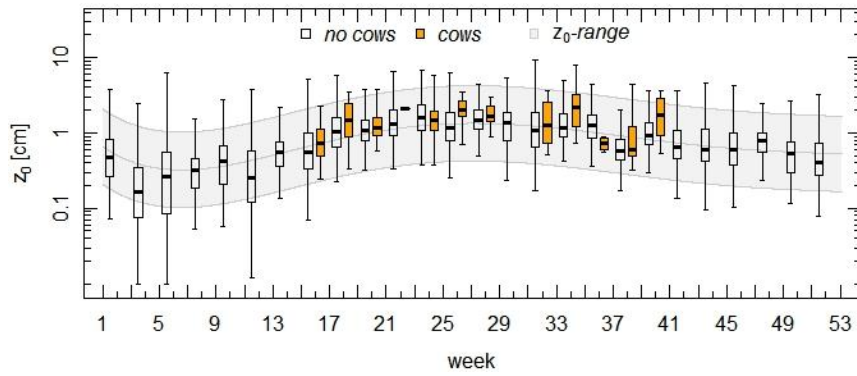
Figure 7. Bi-weekly distributions (boxplots) of calculated roughness length (z_0) for wind speeds > 1.5 m s^{-1} separated for cases with no cows in the FP (white boxes) and cases with cows present in the FP (orange). Whiskers for the cow cases cover the full data range, outliers for no cows cases are not shown. The gray area indicates the z_0-range where the 30 min z_0 value was accepted for FP evaluation. The middle curve in the grey range represents the 6th order polynomial fit to the values without cows.
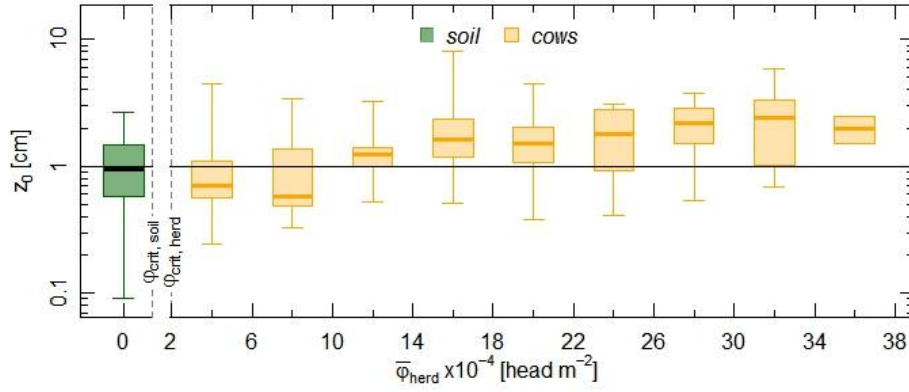
1082 Figure 8. Effect of cows on roughness length (z_0). Boxplots of 30 min z_0 values determined by

1083 Eq. (2) for $\bar{u} > 1.5$ m s^{-1} as a function of average footprint weight of the cow herd ($\bar{\varphi}_{herd}$) based

1084 on GPS data. Whiskers cover the full data range. Orange for situation with cows, green for

1085 situation with no cows in the footprint.

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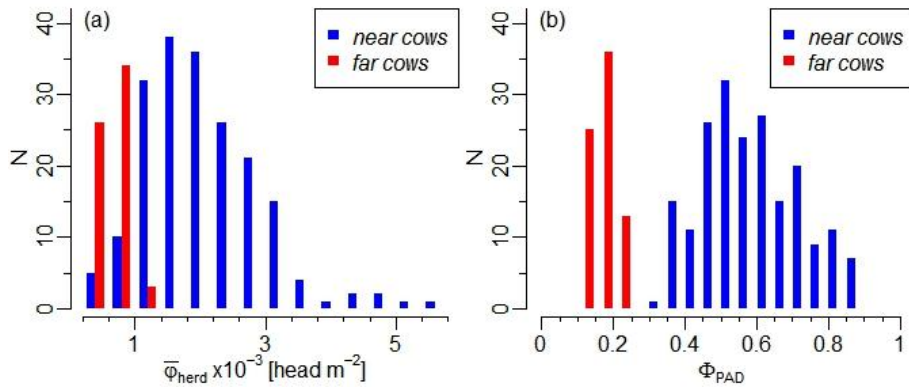
Figure 9. Histogram of footprint contributions (a) of cow positions used in the GPS method and (b) of occupied paddock area used in the PAD method. Cases are separated for distance of the cow herd from the EC tower in *near cows* and *far cows*.
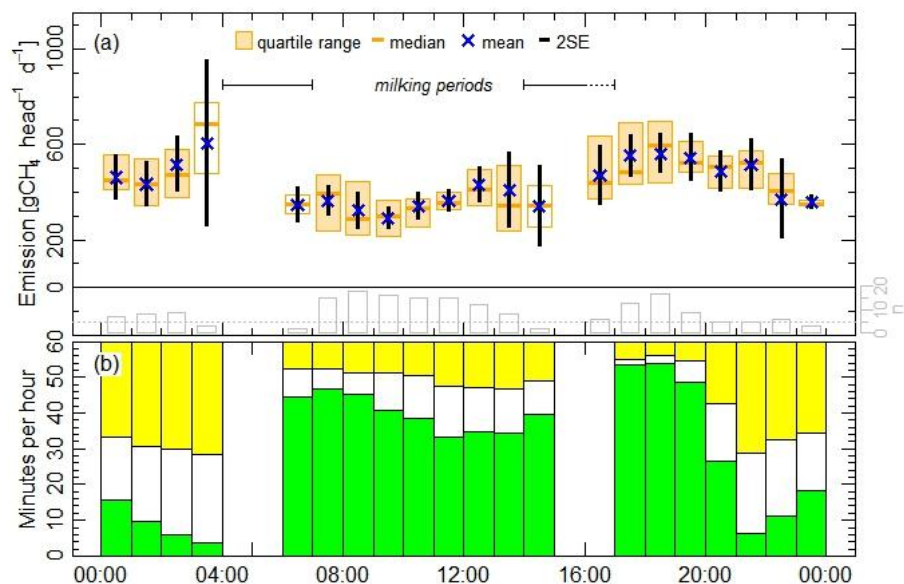
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1093 Figure 10. (a) Average diel variation of CH₄ cow emissions for the *near cows* case. White
1094 quartile range boxes indicate hours where less than five values are available. The uncertainty is
1095 given as 2·SE (black lines). White bars (bottom) show the number of values for each hour (right
1096 axis). The two gaps indicate the time when the cows were in the barn for milking. The dashed
1097 line in the second milking period indicates that the cows sometimes stayed longer in the barn.
1098 (b) Average time cows spent per hour for grazing (green), ruminating (yellow), and idling
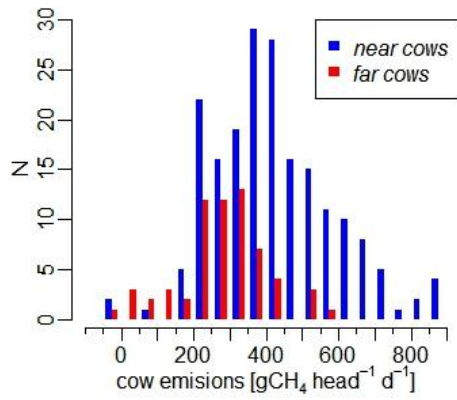1099 (white) activity, mean diel cycle for the entire grazing season.
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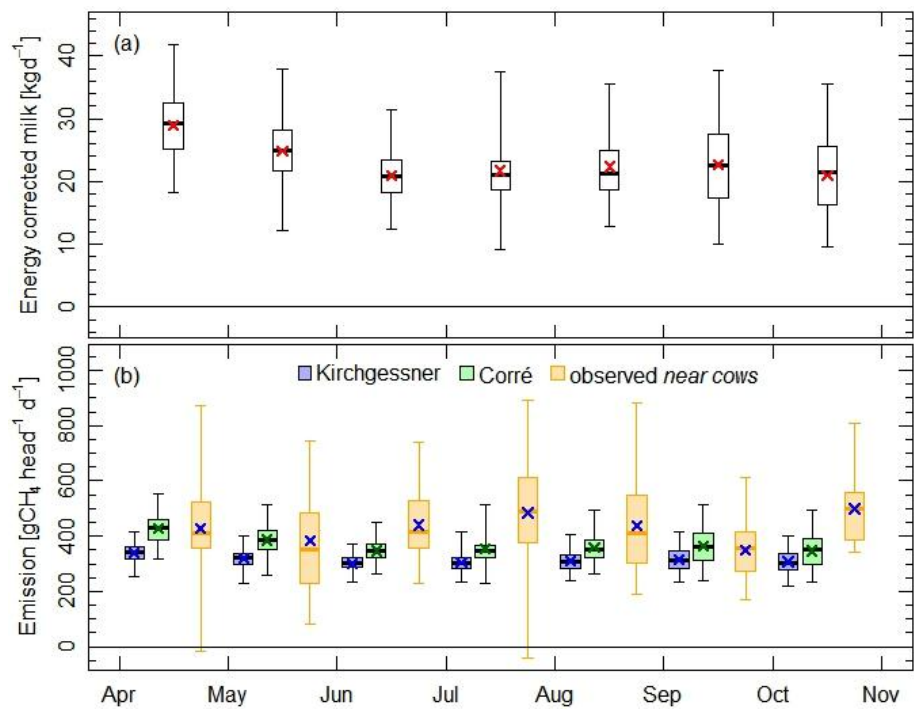
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1103 Figure 11. Monthly aggregated distribution of (a) energy-corrected daily milk yield (ECM) of
1104 the individual cows in the herd, and (b) cow methane emission as observed in this study (*near*
1105 *cows* cases) and modeled as a function of *ECM* and cow body weight (*m*) according to $10 +$
1106 $4.9 \cdot ECM + 1.5 \cdot m^{0.75}$ (Kirchgessner et al., 1995) and $(50 + 0.01 \cdot ECM \cdot 365)/365 \cdot 100$
1107 (Corré, 2002). Crosses indicate mean values, boxes represent interquartile ranges, and whiskers
1108 cover the full data range.

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Figure 12. Histogram of cow emissions for *near cows* and *far cows* for the GPS method (according to Eqs. 3 and 4).
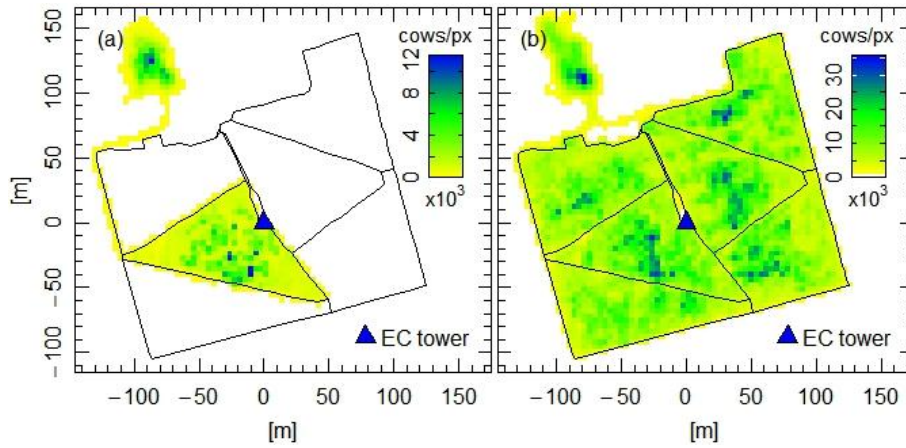
Figure 13. Cow density distribution (a) for one grazing cycle (i.e., two consecutive days) and (b) for the entire study field integrated over the full grazing season in 2013. The color of each pixel (4 m x 4 m) represents the number of data points collected at 5 s time resolution with the GPS trackers of all cows. Note the different color scales.