bg-2018-435

Author responses to comments

We thank the two referees and the editor for their very careful review of the manuscript. Their detailed and valuable comments helped to significantly improve the manuscript. For the majority of the language related comments we directly adopted the referee suggestions. Below, the scientific comments are listed that required a specific response.
The referee comments are printed in *italic*, and the author responses are printed in blue. The editor comments are printed in *green* and have been attached to the respective referee comment they are referring to.

Referee #1

General comments

1. However, one main point that needs to be addressed is the final conclusion; I strongly disagree that you can conclude that an optimised diet (with additional maize silage) in system M leads to a 25% reduction effect for N2O emissions based on the smaller area needed for grazing. The authors need to take the N2O emissions related to the maize production used in the diet into account; otherwise this comparison is not valid.

EDITOR: I agree that one can easily think of the evaluation of the upstream processes or the full production chain. Therefore, it must be made very clear what the (limited) scope of this manuscript is, but in the discussion, it the restricted scope should be mentioned again and briefly discussed what else would be needed to evaluate the whole chain. This is necessary for the readers not to draw wrong conclusions. The conclusions should also refer very clearly to the limited scope of the study to avoid any misinterpretation.

It needs to be noted, that we only considered the N_2O emissions related to the cow excreta on pasture in this study (as indicated by the paper title). This is in line with the IPCC concept for emission factors and inventory calculations that generally relate the N_2O emissions to specific N inputs (see Introduction). As suggested by the editor, we additionally clarified the scope of the study in the different parts of the manuscript. Yet we agree that the use of the term “integral system emission” (in units of kg N_2O-N) in the original manuscript version was misleading. In order to prevent confusion, we thus changed the units of this type of results (used for comparison of the two grazing systems) to emissions per cow and grazing hour (N_2O-N cow^{-1} h^{-1}), which have an equivalent meaning. Moreover, the direct comparison of the grazing related emissions of the two systems has been revised and is discussed in more details.
With the comparison of system M and G we mainly wanted to test whether an N-reduced feeding leads to reduced N excretion and N_2O emissions on the pasture. In the conclusions, we have added the consideration, that an N-optimized feeding strategy does not necessarily require supplement maize silage feed but may also be achieved by an improved energy to protein ratio of the pasture grass. Moreover, it needs to be noted that the comparison of different agricultural production systems with full accounting of the production chain (life cycle assessment) is a complex concept (usually not directly related to field measurements) using many different assumptions and data sources, and is well beyond the declared scope of this study.

2. Generally the authors need to be more careful with figure and table captions. The structure of some tables needs to be improved and the authors need to be more careful with units, especially when presenting cumulative fluxes (table 5). There are many abbreviations that were not explained (e.g. ECM, FAD, Q, A, V) or not very clearly (FD, FU, FU,temp, Fbg), which makes equations difficult to understand (section 3.2.2 and 3.2.3). Improving figures and tables and explaining abbreviations will help to make the manuscript easier to read.

We agree with the referee and improved the manuscript in the mentioned respects as far as possible (see responses to detailed comments below).

Detailed comments

P1, line 26/27: This conclusion is not correct, as the N2O produced during the production of Maize fed to the animal is not included in the calculations!

See answer to general comment 1 (above).

Introduction:

P1, line 30: Please add a reference for the GWP of N2O.

A reference was added (IPCC, 2014).

P2, line 6: Please insert "from excreta" after "N loading. . . was shown previously" and insert N after exceptionally high.."

"From excreta" would not be correct here as the referenced study showed the effect of different N loading rates of inorganic fertilizer nitrogen on N_2O emissions.

The "N" was inserted as suggested.

P2, line 16: Please give a suggestion of how emissions could be reduced if individual contributions are better understood.

We added the following sentence: "A better understanding of the individual contributions would also be very helpful to reduce the emissions, as e.g. dietary changes typically affect the excreted urine N which is mainly responsible for the high N_2O emission associated to excreta (Dijkstra et al., 2013)."

Material and Methods:

P3, line 15: use average values for clay, silt and sand from table 1

We omitted the redundant values in the text and only kept the reference to the values in Table 1.

P3, line 17: The range of 10-50 and 7-40 % of Lolium and Trifolium is quite large; could you give an average ± stdev and the method of how it was assessed?

We added the following information: "The vegetation consisted of a grass-clover mixture typical for Swiss pastures (78 ± 12 % grasses and 15 ± 10 % legumes; main species: *Lolium perenne* and *Trifolium repens*, 10 sampling times between May and September)."

P3, line 25: You write that the optimized protein content reduced the N input to the pasture. Did you measure this? Otherwise, just write that it was expected to reduce the N input to the pasture.

Following the referee's suggestion we rephrased to: "This was supposed to reduce the excreta N input to the pasture." The excreta N input to the pasture could not be measured directly but it was inferred from the data based animal N budget (Sect. 2.3).

P4, line 18: Please add the name of the model and give a reference

EDITOR: In your response you imply that a satisfactory description of the model may not exist. Am I right? The argument that the model has been used in other published work does not substitute the apparent lack of the model description. Using a model in science requires the description of the theory and how it is implemented in the model code. Furthermore you need to refer to how the model was tested and whether or not it was supported by the tests. If you are not able to refer to a published description, you need to describe the model yourself or use another model. Consider including the model description in the appendix .- basic equations, drivers, parameters, outputs, consideration of uncertainty, tests.

The online response to this comment was unfortunately not adequate. The term 'budget model' used in the original version was obviously misleading and not really appropriate for the applied cow nitrogen budget. We rephrased Section 2.3 to clarify the used approach. In short, the N budget of a dairy cow simply balances the N input by feeds with the N-accumulation in the cow body (weight gain) and the N losses by milk yield and excreta output. Thus the excreted N amount can be inferred from the other 3 terms. This calculation and the corresponding uncertainty has already been presented in the previous paper by Voglmeier et al. (2018) for the same experiment.

P4, line 20: Move this sentence up to the end of the sentence (line18-20)

After rephrasing the previous sentence, we would like to keep the sentence position unchanged.

P5, line 10: change (Fig.2) to (Fig.2b)

Has been changed (but to Fig. 2a ➔ soil moisture).

P5, line 20-21: I am not quite sure if I understand this modification. Did you add a vent to the box? Then better to call it vent than inlet as the inlet is connected to the QCL. Please be more specific: I assume the 4 cm is the diameter and the 1m is the length of the vent tube and the 10 cm is the length of the foam material within the tube? What is the foam made of?

We agree with the reviewer that the box modification was not properly described. As assumed by the referee, a vent tube (to ambient air) was added, instead of a fully closed loop originally used in the Fast-Box. We described the vent tube more specifically in the revised version.

P5, line 22: As you don't show or discuss any soil respiration measurements, I suggest to delete this information.

EDITOR: Both referees point to this. You can avoid this criticism by including a subordinate clause mentioning the purpose. BTW avoid the tautology "CO2 soil respiration"

We kept this information in the text, because the CO_2 signal (due to ecosystem respiration) was used as a proxy to check if the chamber was properly sealed (as mentioned in Sect. 2.4.3). We changed the sentence to: "The chamber was also equipped with a GMP343 CO2 probe (Vaisala, FL) to measure the soil respiration, which was used for quality control purposes (Sect. 2.4.3)."

P5, line 24: Insert "the" after "The inflow off. . ." I assume by "the inlet" you mean " the vent"? As the FB chamber is a closed dynamic system (acc. to Hensen et al.2006).

Was changed accordingly (see also response above).

P5 line 26: please add explanations to all abbreviations used in equation 1 (V, A, Fcham)

Definitions of symbols were added accordingly.

P6 line 12: please give the make of the thermocouple
Was added in the revised version (k type).

P7 line 24: 500; add unit
Was added (“500 data points”).

P8 line 12: change (see Fig 2) to (see Fig. 2c). Please show the harvest event in the Figure (see comments to Figures)
Was changed to "(see Fig. 2c-d)". We added the harvest event in the Fig. 2c and the fertiliser applications in Fig. 2d (see also responses to Figure comments below).

P8 line 33: Can you give a time period for the soil temperature classes?
The time period spanned over the GOP. We included this information.

P11 line 8/9: This last sentence is not clear. Please clarify which fluxes you are talking about (individual emission source; paddock or system M/G?)
We omitted this sentence as it was no more necessary in the revised version.

Results:
P11 line 12: “they varied significantly”; significantly different from what? Background fluxes?
We rephrased to "...showed considerable variation...".

P11 line 13: mention the harvest, were they increased after the harvest?
There was a short increase in N_2O emissions directly after the harvest event. We included this information in the text.

P12 line 15-19: In Figure 8 FU,temp and FD,temp are fluxes averaged over 3 days, while in the text you are describing average daily values (?), which is confusion. I suggest to show average daily values in Figure 8, or use different abbreviations (e.g. FU,temp3d vs FU,temp1d), or only discuss 3d averages in the text. Its not clear what the “absolute highest FUtemp“ is (5117 ug N2O-N m-2h-1), if the highest average value is 660 ug N2O-Nm-2h-1.
We agree with the referee that the paragraph was a bit confusing. We rephrased it in a more concise way and only describe the 3-day averages displayed in Fig. 8.

P12 line 20: you mention that Dung related emissions “showed a relation to excreta age”, please mention what kind of relation. Please change “dung patch emissions” to “dung patch fluxes”
The relation can be seen in Fig. 8. We added a reference to this Figure. Additionally we changed “dung patch emissions” to “dung patch fluxes”.

P12 line 25: Were the background fluxes not also sign. smaller compared to dung patch emissions? Looks like it in figure 8.
The background fluxes are also sign. smaller than dung patch emissions. We will rephrase the sentence to “…Background fluxes were on average considerably smaller than excreta fluxes”.

P12 line 32: How do you justify to set negative values to zero?

EDITOR: Consider using a better suited function that doesn't force predicted data into the negative domain.

The formulation in the text was probably misleading. We wanted to approximate the measured 3-day averages for the dung patch fluxes (all positive, see Fig. 8) with an empirical function as simple as possible (few fitting coefficients, simple regression statistics) and with conservative assumptions concerning the extrapolation beyond the observed age period. We thus rephrased the text in the following way:

"Because the evolution of dung emissions $F_{D,age}$ after the observed 20-day age period is unclear and a meaningful functional extrapolation was not possible, we decided to use a simple 2nd order polynomial for parameterization purposes. It allowed to reproduce the initial increase with age and a rapid decrease to zero beyond the measured age range. The fitted polynomial function is only applicable up to $\Delta t_{EOG} \approx 25$ d, where it crosses the zero line.

P13 line 6: As "FD,temp" is not influenced by environmental conditions it equals FD (?)This should be stated here.

We include this information as suggested.

P13 line 7-14: Please define the three sectors. I suggest to insert (<0.27, 27-33, >0.33) after ". . .by three different VWC sectors." It would help to show this in a graph.

EDITOR: Consider adding a graph to an appendix

We follow the referee's suggestion and insert (<0.27, 27-33, >0.33) after "… VEC sectors". However, we do not want to add a new graph as the paper already has quite a high number of graphs and the additional information provided by a graph would be comparatively low.

P13 line 13: do you mean "similar values" or comparable to what? Can you add a stdev?

Indeed, we mean "similar" values. The values including the stdev are 12 ± 3 µg N_2O-N m^{-2} h^{-1}. We included this changes in the text.

P14, line 17: It's not clear where the grazing period ends, therefore please add this information into the table (see comments table 10b).

We assume, that the referee refers to Fig. 10b. We include the information about the grazing phases on the different paddocks in the figure.

P14 line 25-27: these two sentences are not very clear. What do you mean by variations? The magnitude of fluxes varied less? I suggest to replace "rather limited" with "less pronounced"

We omitted one sentence and rephrased the the text as follows:

"The up-scaled FB fluxes compared well in magnitude with the measured EC fluxes and showed a similar temporal behaviour. While generally a response to variations in environmental driving parameter could be observed, it was less pronounced for the up-scaled FB fluxes in comparison to the EC fluxes."

P15 line 2: But in Figure 11 it looks like fluxes were slightly higher for up-scaled FB fluxes.

We agree with the referee on this mistake. We replaced "slightly lower" by "slightly higher".

Discussion:

P15, line 20/21: I don't understand this sentence

We agree with the reviewer, that the sentence was confusing and thus rephrased it as follows: "We assume that the EC fluxes are on average representative for the whole pasture system, although the contribution of the central paddocks X.11, X.12 and X.21, X.22 to the EC footprint is generally higher than the contribution of the other more distant paddocks (Fig. 4)."

P15, line 25: Include "(data not shown)" at the end of "other characteristics" as you didn't show any productivity (yield). Delete "Also" at the beginning of the next sentence.

Was changed accordingly.

P15, line 28-p16 line 4: This paragraph is difficult to understand. I strongly disagree that you can conclude that an optimised diet in system M leads to a 25% reduction effect for N2O emissions based on the smaller area needed for grazing. You need to take the N2O emissions related to the maize production into account, otherwise this comparison is not valid.

See answer to general comment 1 above.

P16, line 23: 1.03 kg N2O-Nha-1y-1, please explain in more detail how this value was calculated. This value should have been shown in the results section 3.3.2.

The value was calculated by using Eq. 5 (as stated) similar to the cumulative background emission in Fig. 12b (green area) but for the entire year using measured soil moisture. We specified this in the text. This full year extrapolation value was only calculated for comparison with (annual) literature values. Therefore, it does not fit into the results section, as the paper results are focused on the grazing-only period GOP.

P16, line 26/27: This last sentence is out of context

We rephrased the sentence to clarify the connection to the preceding text:
"On pastures, background emissions may additionally result from trampling of the cows that can further stimulate the N2O production via denitrification due to soil compaction (Bhandral et al., 2007)."

Tables:

Table 1: As soil depth is not really a parameter I suggest to re-arrange the table; one column for each soil depth, with missing values in each column as the different parameters have not been measured in all soil layers

Since the information on the deeper layer are not really relevant for the present topic, we decided to reduce the table and only show the soil characteristics for the near-surface layer. The information on differences in the exact layer depth were moved to the footnote.

Table 2: What does ECM stand for? Please explain abbreviation (maybe in footnote).

ECM is the 'energy corrected milk'. We added this explanation in the table caption.

Have the animals been weighted before and after the experiment? Was the weight increase considered in the calculations of the excretion (heavier animals will excrete more)?

The animals have been weighted on a daily basis and the possible weight gain is considered in the calculations of the excretions. We rephrased Sect. 2.3 and included this information. More details are given in the referenced article by Voglmeier et al. (2018) for the same experiment.

Table 3: Please add information of flux measurement method (FB)
Has been added accordingly.

Table 4: Please describe what the different equations are: Parameterisations of 3 day average fluxes from EB measurements, split into background, dung and urine fluxes.
A proper description of the five different equations would be quite complex and a (unnecessary) repetition of the information given in the text. This table is just used for listing the numeric values of the equation coefficients (not the equations themselves). However we added the following information relevant for the numeric values of the coefficient in the table caption: "The equation coefficients were fitted using FB chamber measurements and yield fluxes in units of µg N_2O-N m^{-2} h^{-1}. The input quantities are the soil temperature T_s (in units of °C), time since end of grazing Δt_{EOG} (in units of days) and volumetric water content VWC (as dimensionless fraction)."

Table 5: I assume that you are showing cumulative fluxes. You need to mention this together with the time scale (per GOP?). I suggest to simplify the table by only having two parts; add a dotted line above the N input and to move the FB urine and FB dung fluxes above the EFs. Please add N input from dung. What does FAD stand for?
We added the information about cumulative fluxes and the time scale (GOP). Furthermore, we rearranged the table based on the referee's suggestions. We also added the N input from dung. FAD was a term used in a development version of the manuscript and was deleted.

Table 5: What is "EC integral system emission EC," ? Reading in the text (P15, line 28-31) I have the impression these fluxes are up-scaled FB fluxes to the whole system. If they are EC emissions, please describe more carefully in the text. The unit is confusing as it is an emission (concentration per area per time). Reading in the discussion I understand what you mean, but in the table it's not clear. Maybe you can explain in a foot note. "EF total" is calculated from EC, while "EF urine" and "EF dung" are calculated from up-scaled FB measurements (or not?) This needs to be stated clearly.
The mentioned value/units represented integral emissions for the entire pasture area and the investigated grazing period. In order to prevent confusion and misunderstandings, we changed the units of this type of results (also in the abstract and in the main text) and express them in units of N_2O -N cow^{-1} h^{-1}, which has an equivalent meaning.
In addition we reorganized the table in a more logical way (see previous comment) and included a footnote with information on the listed quantities.

Figures:
Figure 1: P29 line4 Insert "(triangles)" after "the two EC towers. . ."
Has been added accordingly.

Figure 2 b): Move the legend, or change the scale so the bars for the high precipitation events in June and July are not cut off.
Has been changed accordingly.

Figure 2d): Add arrows for fertiliser application dates and for harvest date

We added the dates in Fig. 2c and 2d.

Figure 3: Change the area showing a) to being transparent
Has been changed accordingly.

Figure 5: Please explain the reason for dotted frame. It's confusing that the lines connecting #dung and # urine patches to "Paddock flux dung patches" and "paddock flux urine patches" cross the arrows leading to "paddock flux background" and "paddock flux urine patches", it looks like they are feeding into them as well. Try to show clearer (maybe with a curved line over the crossing line).
The dotted frame indicated a further processing step. We realized that this is actually not needed and changed it to a standard frame. We agree with the reviewer, that the line crossings are a bit confusing and thus updated the graph (less crossings, use of curved line).

Figure 6: Add arrows for exact fertilisation and harvest events. Add the date of the skipped value. It would be good to include the information of grazing periods in the graph to explain the increased fluxes.
We added vertical lines in the graph indicating fertilization and harvest events, and we added the date of the skipped value in the caption. Furthermore, we added the information that for the analysis of grazing related emission, the non-shaded periods of Fig.6 were used. Detailed information of the rotational grazing regime is already displayed in Fig. 3c.

Figure 7: I suggest to change the unit to ug N2O-N m-2h-1, it makes it easier to read the values in the graph and to compare to values you describe in the text (for Figure8, where ug N2O-N m-1h-1 are used). In the legend insert "from different sources" after "the comparison of fluxes.." and add the information that the fluxes were measured with FB technique.
We agree with the referee and changed the units accordingly. We also added the information on the flux measurement technique in the caption.

Figure 8: Same comments about units as for Fig. 7. Please add in legend that fluxes were measured with FB. Are there any standard errors for the background fluxes, or were they too small to be seen? I suggest to change to x-axis description to "age of excreta [d]". Give information about the fitted curves (refer to equation 3+4).
We changed the units and the x-axis description to "age of excreta [d]" and we added a reference to Eq. 3, 4.
There are standard errors for the background fluxes, but these are smaller than the symbols for the averages. We added this information in the legend.

Figure 9: Same comments about units and mentioning that FB method was used as for Fig. 7.
We changed the units as requested.

Figure 10: It would help to add the grazing period in either Fig 10 b) or c)
We added the grazing periods in Fig. 10b.

Referee #2

General comments

The authors used gap filling approaches to fill gaps in their eddy covariance N2O flux dataset but there was not much discussion about the gap filling results. My suggestion is that this discussion should be expanded.
We used only one approach (LUT) for the gap filling of our EC fluxes, as mentioned in Section 2.5.3. This approach was chosen based on the cited evaluation by Mishurov and Kiely (2011) who discussed different gap filling approaches in more detail. It was not the objective of this study to assess the performance of gap filling approaches. However, we used the variability between LUT and three other approaches for estimating the uncertainty of the gap filling procedure.

In addition, it would be important to include more details in the methodology on the EC and chamber measurements and scaling approaches (see specific comments). Some sentences in the text are difficult to understand, so the writing requires further work. I also noticed some grammar mistakes in the text. I recommend the authors to perform a thorough review of the manuscript to correct these mistakes before resubmitting the manuscript.
We think, the methodology on the EC and chamber measurements (including scaling approaches) is already described very extensively with about 6.5 pages (excluding figures). Nevertheless, we included most of the specific comments on methodology issues (see answers to specific comments below). Regarding the language related issues, we performed a thorough review of the text and corrected a larger number of language mistakes.

Specific comments

Page 1
L12 – replacing "season 2016" by "season of 2016". In addition, I suggest including the number of dairy cows for each herd.
Was changed accordingly. We also included the number of dairy cows (12 for each herd).

L15 – "Excreta patches and background surfaces on the pasture were identified manually". I suggest to be more specific here by saying that urine patches were identified based on the soil electric conductivity.
We rephrased the sentence to "After different grazing rotations, background and urine patches were identified based on soil electric conductivity measurements while fresh dung patches were identified visually."

L20 – "(960 ± 219 g N2O-N, or 25 %)" This number is a little confusing. What does the 25% represent and shouldn't the emission units be expressed in per area?
We agree with the reviewer that the number was confusing. Therefore we removed this quantitative statement from the abstract. In order to prevent confusion and misunderstandings, we changed the units of this type of results in the main text and expressed them in units of N_2O -N cow^{-1} h^{-1}, which has an equivalent meaning. Correspondingly we revised the phrasing related to the comparison of the two systems.

L29 – replace "In the atmosphere, nitrous oxide" by "Nitrous oxide". In addition, include the appropriate citation for this sentence.
Was changed accordingly. Additionally, we added a reference to the IPCC (2014) report.

L30 – replace "it has a strong potential" by "N2O has a strong potential". I noticed that the replacement of nous by pronouns in some sentences throughout the text can compromise the clarity

of those sentences. I suggest the authors to be as direct as they can in their sentences for the sake of clarity.
Was changed accordingly. Furthermore, we tried to locate those replacements of nouns and changed them to the proper nouns.

Page 2
L1 – "especially by cows". Are you referring specifically here to dairy cows? If so, please specify.
No, we refer to cows in general.

L3 to L5 – "Directly applied on a pasture soil. . ." this sentence is awkward and needs to be reworded.
We reworded the sentence to:
"The available reactive N is used by microbial nitrification and denitrification processes where significant amounts of N2O can be produced."

L17 – replace "(e.g. EF of 0-14% of applied urine N, n=40; Selbie et al., 2015) and many of those studies measured the" by "(e.g. EF of 0-14% of applied urine N, n=40; Selbie et al., 2015). Many of those studies measured the". In addition, give some examples of the "many of those studies".
We rephrased the sentence to:
"However, the range and thus the uncertainty of specific urine EFs is rather large (0-14%, n=40) as shown by Selbie et al. (2015) based on a survey of literature reports. Many of those studies measured…".

L20 – "these emissions" which emissions?
We rephrased the sentence to make it clear that we meant the emissions associated to animal excreta. "The efficient use of fed N is essential to reduce the emissions associated to animal excreta."

L20 - "(e.g. Arriaga et al., 2010)" provide more examples of studies and more the citation to the end of the sentence.
We provided more examples of studies and we put the citations to the end of the sentence.
"…N excreted by the animals (e.g. Yan et al., 2006; Arriaga et al., 2010; Dijkstra et al., 2013)."

L24 – "real practice conditions". Do you mean real management conditions?
We rephrased the sentence as follows: "…but corresponding emission experiments under real grazing conditions for a full season, to our knowledge, have not been reported hitherto."

L23-24 – "experiments. . . are very rare". Cite some of the existing ones.
Actually, to our knowledge, no comparable experiment exists. We rephrased the sentence as shown in the previous comment.

L26 –"and to attribute them to certain emission drivers" this statement needs to be reworded for clarity.
We rephrased the sentence to "…to attribute the measured fluxes to potential emission drivers…".

L30 – "by integration over a larger domain". Integration of what? Do you mean fluxes? Larger domain than chambers?
We rephrased the sentence to "…integrating over multiple emission sources over a larger spatial domain."

Page 3
L8 to 9 – "We aimed at a better understanding of the quantity of the overall pasture emissions, the different emission sources and the reduction of corresponding uncertainties". This sentence is awkward and needs to be reworded.

We omitted this sentence, as it is redundant.

L12 to 13 – provide the experimental period.
We provided this information (grazing period 2016).

L14 – "annual average rain amount". Is snow also included in the total amount? If so, replace the word "rain" by "precipitation".
Snow is also included, thus we changed "rain amount" to "precipitation".

L15 to 16 – "(about 20 % clay, 35 % silt and 45 % sand" there is no need to show this since this soil texture data are shown in Table 1.
Was changed accordingly.

L16 – "Soil measurements were performed. . .". Can you be more specific?
This sentence is referring to the preceding sentence (with reference to Table 1). We rephrased the sentence to: "Soil profile samples for analysis of texture and other soil characteristics were taken at four locations on the pasture in 2013 and 2016."

L19 to 20 – "the fertilization rate was in the order of 120 kg N ha-1 per year between 2007 and 2015". Can you please specify the fertilization timing?
EDITOR: Please reconsider you answer. Are the background emissions during the campaign not depending on the timing of previous fertilizations? Sometimes a small amendment of information can make the article relevant for other work, e.g. reviews, which will increase its scientific value.
We indeed have discussed in Section 4.2, that the background emissions may (partly) be attributed to fertiliser application in previous years. Therefore we added the information about the average annual fertiliser application rate of the previous years. However we cannot see the benefit of just adding fertiliser timings for the previous years (e.g. for modellers or synthesis/review studies) without additional detailed information about the management and the weather conditions. But that would be out of proportion to the scope of this study. We are planning to publish a multiple-year comprehensive dataset including metadata of the study site on a flux data repository.

L23 – "12 cows per system.". Please reference figure 1.
We included a reference to Fig. 1a.

L24 – "with additional maize silage". Was this silage offered to the cows in a different area? Did the silage supplementation influenced the time in which the cows spend in the grazing system?
The silage was fed in the barn when the cows had to go there for milking twice a day (this information was added in the revised manuscript). In order to avoid an influence of the supplement feeding on the grazing time, the barn and grazing times were always fully synchronous for both herds/systems.

L30 – "X indicating both systems". I suggest using M or G instead of X to avoid confusion.
We would like to keep the "X" because it simplifies the text considerably when referring to both systems equally.

Page 4
L15 – "For the comparison with the field-scale EC". Which comparison? Be more specific.
We agree with the reviewer that the sentence is not specific enough. We rephrased the sentence to "The comparison between the field-scale EC method and the small scale chamber measurements also required estimates of the number of dung and urine patches on the pasture."

Page 5

L1 to 2– "Conductivity values exceeding a threshold of 0.15 mS cm-1 were marked as possible urine patches for further chamber measurements." It is important to explain how this electric conductivity threshold was established.

We added more information in the text. The threshold of 0.15 mS cm^{-1} was chosen based on pre-experimental tests with artificially applied urine patches on the pasture and areas not affected by grazing for a few month (background). The value of 0.15 mS cm^{-1} was determined as the maximum of the observed background conductivity, and it was still far below the observed conductivity of fresh urine patches (see also Fig. 3).

L10 – "taken mainly during dry soil conditions" Can you provide the soil water content associated with "dry soil conditions"?

There is no fixed water content threshold for dry soil condition. Nevertheless, as can be seen in Fig. 2 and Fig. 9, we refer to volumetric soil moisture contents below roughly 0.4, thus clearly lower compared to the ones before July. We added this information in the revised manuscript.

L18 – "a 40 m 1/4" PA tube allowing". Use metric units do express the dimensions of the tubing. Does 1/4" refer to the internal diameter of the tube? Please specify. What does "PA" stand for?

We added some information as follows: "The sample air was drawn continuously from the FB headspace through a 40 m 1/4" polyamide (PA) tube to the analyser …". We would like to keep the tube diameter in inches, as this is the official commercial labelling of this product.

L19 – "The sample flow rate Q was typically around 8 l min-1". Did you use a mass flow controller to keep the flow rate constant?

No, we did not use a flow controller. The flow rate was controlled by the controlled pressure (30 Torr) in the QCL analyser cell and a flow restrictor needle valve at the QCL inlet. The inlet tube represented an additional flow resistance. Since the effect of the valve and the tube were constant over time, the flow also remained quite stable.

L21 – "foam material to avoid uncontrolled air exchange". Was the chamber covered with some insulating material? What was the typical temperature differences within and outside the chamber during these measurements?

No, the chamber was not covered with insulating material. Nevertheless, as the measurements with a fast-box are very quick (typically within 2 minutes), the temperature differences between inside and outside the chamber stayed typically below 0.5 °C. When starting a new measurement, the chamber volume was always flushed (by opening/tilting the box by 90° until the chamber volume was completely mixed with the ambient air).

L21 to 22 – "The chamber was also equipped with a GMP343 (Vaisala, FL) CO2 probe to measure the soil respiration." Do you show this CO2 data? If not, I suggest excluding this sentence.

EDITOR: Both referees point to this. You can avoid this criticism by including a subordinate clause mentioning the purpose. BTW avoid the tautology "CO2 soil respiration"

We kept this information, as the CO_2 concentration increase (related to the soil respiration) was used as a proxy to check if the chamber was properly sealed (as mentioned in Sect. 2.4.3). We added this information in the text.

L22 to 23 – "The increase in concentration after placing the chamber on the soil was recorded every three seconds for a time period of about 90 seconds." For your chamber flux calculations, did you take into account the time necessary to purge this long tube right after the sampling line was connected to the analyzer?

Yes, this time was of course taken into account. We added this information in the sentence.

Page 6

L2 – "(slow chamber volume exchange and short measurement time)". Can you provide an average value for the chamber volume exchange?
The average volume exchange time is a direct function of the given chamber dimensions and flow rate. It was about 40 min. We added this information in the text.

L13 to 14 – "a thermocouple for air temperature measurement within the chamber, a GS3 probe (see Sect. 2.4.1) and a ML3 Thetaprobe (Delta-T Devices Ltd, UK) for soil moisture and temperature observations (c. 0-5 cm and 0-10cm depth, respectively)." This sentence is a little confusing and needs to be reworded.
We reworded the sentence as follows: "a thermocouple (type K) for air temperature measurement within the chamber, a GS3 probe (see Sect. 2.4.1) for soil moisture, soil temperature and soil conductivity measurements (c. 0-5 cm depth) and a ML3 Thetaprobe (Delta-T Devices Ltd, UK) for soil moisture and soil temperature observations (c. 0-10 cm depth).".

Page 7
L4 – "were fenced to avoid unwanted animal contact". Can you provide the area of the fenced area around the tower?
The fence was in a distance of about 2 m around the tower in the main wind direction sectors. Only in the direction where the analysers were located in an air-conditioned trailer/container, a larger area was fenced (see white area around EC tower positions in Fig. 1a). We added the information with the fenced radius around the EC tower.

L9 – Does this sonic anemometer infers the air temperature based on the sonic temperature or it has its own temperature sensor?
It should be quite clear that a 'sonic anemometer-thermometer' infers the wind vector and the temperature from speed-of-sound (sonic) measurements.
EDITOR: Does this mean that you have recalculated the air temperature from the sonic temperature? This is prone to errors, because some sonic anemometers have obvious problems to give accurate temperature readings. Did you check your sonic anemometer for such errors?
We agree with the editor that such temperature measurements can have accuracy problems. We compared the sonic temperature to the weather station temperature and roughly checked the quality of the sensible heat flux by checking the energy budget closure and found no obvious problems. In the present study, we use the sonic temperature measurement only very marginally (and indirectly: e.g. in the spectral correction) and therefore a detailed assessment of its quality in the manuscript would not be adequate.

L11 – Please provide the pore size of the filters
The Midisart 2000 has a filter pore size of 0.2 µm and the AcroPak has a filter pore size of 0.2 µm. We included this information in the text.

L16- "The sample frequency of the EC system was generally 10 Hz". Does this mean that there was variation in the sample frequency? Why is that?
We agree with the reviewer about the confusing phrasing. The EC system was always operated at 10 Hz. We omitted "generally".

L18-19 – This sentence is awkward and needs to be reworded.
We reworded the sentence to "Additionally the program visualized the measurements of the N_2O concentrations and fluxes, calculated with a preliminary online flux calculation. The program also allowed to check the EC system by remote access."

L22 – "The approach is based on. . ." What approach are you referring to?

We refer to the customized program mentioned in the previous sentence. We rephrased the sentence accordingly.

L24 – 500 data points?
Yes, we meant 500 data points (added in the text).

L28 – "several seconds". Provide the typical time lag value and its standard deviation.
The typical time lag was about 6 seconds for system M and about 7 seconds for system G. We added this information in the manuscript. But it is not possible to give a meaningful standard deviation of the 'dynamic' lags determined by the peak position in the cross-covariance function. In many cases, the signal-to-noise ratio of the fluxes was small due to low emissions or non-stationarity. In these cases the 'dynamic' lags were often not meaningful and very large. Due to this reason we applied a lag window filter (as described in Sect. 2.5.2) and used an average default lag otherwise. Thus the selected good quality lags were by definition within a window of ±0.61 s.

L31 – "a time window of 0.61 seconds". How was the number determined
The number was determined empirically based on the variability of the determined dynamic lag times.

Page 8
L1 – "In order to minimize the effect of non-stationarities in the time series, the 30 min flux was finally calculated as average over six 5 min subinterval flux values.". I wonder what would be the effect of this averaging approach on the low frequency spectral losses of their EC system. Furthermore, if you are already screening the data for non-stationarity (page 8 L24) why to estimate fluxes for these short time intervals?
The low frequency losses were in the range of 1-5 %, based on theoretical calculations (Kaimal cospectra and transfer function for block averaging) as well as on the comparison of 30 min fluxes and 5 min subinterval fluxes. The theoretical approach was used to correct the fluxes for this low-frequency damping effect. This information was added in the manuscript.
We now recognized that we erroneously mentioned the application of a stationarity criteria in the EC method description. We actually did not apply a stationarity filter for the fluxes. As mentioned by the referee, this would not make much sense (and it did not have a significant effect) in combination with the minimizing of non-stationarity effects by using average 5-min subinterval fluxes. We removed the respective statement from the manuscript.
EDITOR: In your answer you mention that the use of 5 minutes measurement intervals lowered the effects of non-stationarity. Did you test this? And if yes, which of the 5 minutes intervals did you choose to represent the 30 minute average? If you used them all and averaged them, can you explain why that still reduces the effect from non-stationarity at the 30 minute time scale? Wouldn't you rather need to test whether the 5 minute interval was stationary and then give high-pass corrected flux values from all 5 minute covariances? A small self-critical discussion of this procedure is advised.
As stated in the text, we averaged all six 5-min subinterval fluxes to 30 min (without discarding any subinterval). The reduction of non-stationarity effects by this procedure is a fundamental assumption in the common flux stationarity test (Foken et al., 2012). In the spectral space, the use of shorter averaging intervals cuts off the lowest frequencies of the normal 30-min flux spectra, which largely contain the non-stationarity effects (red noise). As mentioned above, this also leads to a very moderate damping of the turbulent cospectrum, which was corrected for. It should be noted that the 5-min flux averaging time, as used here for a measurement height of 2 m, has about the same low-frequency damping effect as a normal 30-min flux averaging for a measurement height of 12 m (e.g. above a forest).
We indeed observed a significant reduction of the non-systematic (red noise type) variations in the aggregated 30 min averaged fluxes by this procedure, so that an additional stationarity filtering had only little effect and was therefore not used. We added this finding in Sect. 2.5.3.

L7 – “half-hourly damping factors”. Do you mean dampening factor?
L9 – “damping factors” see comment above
L10 – “damping effect” see previous comment
EDITOR: It looks as if damping was the more accurate term.
We think, both terms can be used, but the term “damping” is more commonly used in the EC literature. Therefore we kept it.

L19 – replace “which often result” by “, which often resulted”
We prefer to use “which often result” to indicate, that this not only happened in the past but is an ongoing issue with EC measurements.

L28 – “It was driven”. What is “it” referring to?
The sentence was rephrased to “The occurrence of data gaps showed a diurnal pattern with stronger data loss during the night, which was driven by the wind pattern with typically stronger wind speeds during daytime and calm nights.”

Page 9
L15 – “and it has to be checked”. What is “it” referring to?
We are referring to the spatial dimension of the footprint. This has been changed in the revised version.

L22 – “80’ 000 trajectories were released backwards in time” replaced by “80,000 fluid particles were released backwards in time”. Also, what is the time scale of this simulations? 30-min periods?
Yes, the footprint simulation time scale was 30 min. We added this information in the text and replaced trajectories by fluid particles.

L24 – “systematic uncertainty”. Do you mean “accuracy”?
We mean “systematic uncertainty” as described in the referenced articles at the end of the sentence.

Page 10
L1 – I think section 2.6 is out of place. It should come after section 2.7.
We think, it is actually not out of place as Sect. 2.7 builds on data retrieved from Sect. 2.6 (soil moisture / soil temperature measurements). Thus, we kept the structure of the sections.

L2 – what is the datalogger model used in this study?
The automated weather station was equipped with a Campbell Scientific CR10X data logger. We added this information in the manuscript.

L6 – In this section, it would be important to provide the spatial resolution of the grid used for upscaling the chamber fluxes. More details are also necessary on how the authors went from the output of Eq. 2 to the scaled fluxes. Did you generate digital maps of source emissions and then overlapped these maps with a footprint map? What was the software used to do these calculations?
EDITOR: You forgot to mention the software.
We are not completely sure, whether we understand the question of the referee. We did not use a grid to upscale the chamber fluxes to the EC system. Equation 2 was evaluated for each paddock (integrating the particle touchdowns within the respective paddock area) for each 30 min interval. This resulted in a footprint contribution for each paddock which was multiplied by the paddock scale emissions for urine, dung and background as described in Fig. 5 and Section 2.7.
We improved the description of the upscaling procedure in Sections 2.5.4 and 2.7 in this respect.
We used the statistical software R (R Core Team, 2016) for these calculations (and generally for all major calculations). We added this information in the text.

Page 11
L10 – "Occasional negative individual flux values". What is the detection limit of this EC system? I think this would be an important variable to know to interpret these fluxes.
The negative fluxes exclusively resulted in cases, when no peak in the cross-covariance function could be identified (and thus the value at the default lag was used). Thus is can be concluded that the negative fluxes were generally not statistically significant, i.e. below the detection limit (which was time dependent e.g. due to the varying influence of non-stationarity effects). We rephrased the text and added this information in the manuscript.

Page 12
L3 - "Fluxes of background and dung patches were significantly smaller". Did you perform a statistical test to support this statement?
Yes, we performed the Student's t-test which resulted in p-values < 1e-12. But we also think that the results plotted in Fig. 7 are very clear in this respect. We rephrased the sentence to indicate, that we actually meant the absolute value of the fluxes (and not only smaller in a statistically calculated way).

Page 14
L25 – "the variations were less pronounced". Which variations were less pronounces.
We rephrased the sentence to "…the variability of the up-scaled FB fluxes were less pronounced.".

Page 15
L 19 – "The good agreement between the two independent approaches" provide a statistical index to support this statement.
We expanded the sentence to: "The good agreement with a relative difference below 1.5 % for yearly sums (which is far below the uncertainty range, see Table 5) between the two independent approaches…".

L28 to 29 – This sentence is a little confusing and needs to be reworded.
We rephrased the sentence as follows: "For assessing the effect of the N reduced diet on excreta related N2O emissions, the emissions per cow and grazing hour have to be compared".

L21 – "significant system difference". Over which period of time and shouldn't this difference be expressed per area?
We agree with the reviewer and replaced this value by the emissions per cow and grazing hour of system M and G (see comment to Page 1, line 20 above).

Page 16
L3 to 4 – "e.g. N2O emissions related to the maize production. . .". Could you include values in the literature typical emission factors for corn silage production? These data would allow a fair comparison between the two grazing systems.
EDITOR: I agree that one can easily think of the evaluation of the upstream processes or the full production chain. Therefore, it must be made very clear what the (limited) scope of this manuscript is, but in the discussion, it the restricted scope should be mentioned again and briefly discussed what else would be needed to evaluate the whole chain. This is necessary for the readers not to draw wrong conclusions. The conclusions should also refer very clearly to the limited scope of the study to avoid any misinterpretation.
It needs to be noted here, that we only considered the N_2O emissions related to the cow excreta on pasture in this study (as indicated by the title). We revised and clarified the text in this respect in various parts of the manuscript (see also response to General Comment 1 of Referee#1).
We rephrased the sentence to make clear that a full accounting of the production chain on N2O emissions would require much more complex calculations (not just the inclusion of the maize production:

"Any further N2O emissions e.g. related to fertiliser application on the pastures or for the supplement maize production were not taken into account here. A comparison of entire production systems would require many additional assumptions outside the specific scope of this study. It also has to be considered that the N optimisation of the diet is not necessarily linked to the supplemental feed of arable crops like maize, but may as well be achieved with different feed strategies (e.g. grass varieties with a high content of water soluble carbohydrates; Misselbrook et al., 2013)."

L9 – "They are based on". Specify who are "they".
We meant the EFs. We rephrased that in the revised version of the manuscript.

Page 17
L23 – "emission optimum". What does the word "optimum" mean here? Low N2O emissions?
EDITOR: Your answer does not allow to judge whether you will adopt writing what you mean or what Butterbach Bahl et al. (2013) wrote, i.e. contrary to what you mean. Please be accurate in your responses.
No, we meant emission maximum. The term "optimum" is often used in this context (e.g. Butterbach-Bahl et al., 2013). We changed the term "optimum" to "maximum".

Page 28
Table 5 – "EC integral system emission EC". Do you mean: Integral EC flux system emission?
The entry represents integral emissions for the entire pasture area and the investigated grazing period. In order to prevent confusion and misunderstandings, we changed the units of this type of results (also in the abstract and in the main text) and expressed them in units of N_2O-N cow^{-1} h^{-1}, which has an equivalent meaning.

Grazing related nitrous oxide emissions: from patch scale to field scale

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Abstract.

Grazed pastures are strong sources of the greenhouse gas nitrous oxide (N_2O). The quantification of the N_2O emissions is challenging due to the strong spatial and temporal variabilities of the emission sources and so N_2O emission estimates are very uncertain. This study presents N_2O emission measurements from two grazing systems in western Switzerland over the grazing season of 2016. The 12 dairy cows of each herd were kept in an intensive rotational grazing management. The diet for the two herds of cows consisted of different protein to energy ratios (system G: grass only diet, system M: grass with additional maize silage) resulting in different nitrogen (N) excretion rates. The N in the excretion was estimated by calculating the animal nitrogen budget taking into account the measurements of feed intake, milk yield and body weight of the cow herds. Directly after the rotational grazing phases, background and urine patches were identified based on soil electric conductivity measurements while fresh dung patches were identified visually. The magnitude and temporal pattern of these different emission sources were measured with a fast-box (FB) chamber and the field scale fluxes were quantified using two eddy covariance (EC) systems. The FB measurements were finally up-scaled to field level and compared to the EC measurements for quality control by using EC footprint estimates of a backward Lagrangian stochastic dispersion model. The comparison between the two grazing systems was done during emission periods that were not influenced by fertilizer applications. This allowed the calculation of the excreta related N_2O emissions per cow and grazing hour and resulted in considerable higher emissions for system G compared to system M. Relating the found emissions to the excreta N resulted in excreta related emission factors (EF) of 0.74 ± 0.26 % for system M and 0.83 ± 0.29 % for system G. These EF values were thus significantly smaller compared to the default EF of 2 % provided by the IPCC guidelines for cattle excreta deposited on pasture. The measurements showed that urine patch emission dominated the field scale fluxes (57 %), followed by significant background emissions (38 %) and only a small contribution of dung patch emission (5 %). The resulting source specific EFs exhibited a clear difference between urine (1.12 ± 0.43 %) and dung (0.16 ± 0.06 %) supporting a disaggregation of the grazing related EFs by excreta type in emission inventories. The study also highlights the advantage of an N optimised diet which resulted in reduced N_2O emissions from animal excreta.

1 INTRODUCTION

Nitrous oxide (N_2O) is a strong greenhouse gas (GHG) with a 265 times stronger warming potential compared to CO_2 on a mass basis (IPCC, 2014). Typically an inert gas in the troposphere, N_2O has a strong potential to destroy the ozone layer in the stratosphere (Portmann et al., 2012). The largest share of N_2O emissions are attributed to nitrogen (N) fertilization in the agricultural sector, but also livestock grazing, especially by cows, can lead to significant direct and indirect N_2O emissions due to excreta from the animals (Luo et al., 2017; Reay et al., 2012). The nitrogen deposited by animal excreta often exceeds the N applied by fertilizer (Aarons et al., 2017). The available reactive N is used by microbial nitrification and denitrification processes where significant amounts of N_2O can be produced (Selbie et al., 2015). A non-linear response of N_2O emissions to N loading has been shown previously (Cardenas et al., 2010), and urine patches of cattle have exceptionally high N loading rates (up to 2000 kg N ha^{-1}) making them especially prone to high N_2O losses (Selbie et al., 2015).

For inventories and live cycle assessments, the magnitude of the N_2O emissions is usually calculated by applying emission factors (EF) related to the magnitude of N inputs to the agricultural fields (EF = emitted N_2O-N / N input). According to the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006) for national emission reporting, a separation is made between (i) emissions related to excreta N deposited by the grazing animals and (ii) emissions related to fertiliser applications and other N inputs. While for fertiliser induced N_2O emissions, a default value of 1% is proposed by IPCC (2006), the default EF related to excreta of grazing cattle (denoted as $EF_{3PRP,CPP}$) is 2%. Most countries including Switzerland presently use this default values. However, the default $EF_{3PRP,CPP}$ value often overestimates observed pasture emissions (Bell et al., 2015; Chadwick et al., 2018) and does not take into account country specific conditions (climate, soil, management). Therefore, some countries have developed a country-specific EF (e.g. New Zealand, Saggar et al., 2015) which is still lacking for Switzerland. Additionally, it has been shown that separate EFs for urine and dung might be beneficial in describing the emissions and understanding the contributions of the different emission sources on a pasture (Bell et al., 2015). A better understanding of the individual contributions would also be very helpful to reduce the emissions, as e.g. dietary changes typically affect the excreted urine N which is mainly responsible for the high N_2O emission associated with excreta (Dijkstra et al., 2013). However, the range and thus the uncertainty of specific urine EFs is rather large (0-14%, n=40) as shown by Selbie et al. (2015) based on a survey of literature reports. Many of those studies measured the emissions on artificially applied urine or under laboratory conditions making these results questionable with regard to the applicability within greenhouse gas inventories.

The efficient use of fed N is essential to reduce the emissions associated to animal excreta. Studies have shown that an optimised feeding strategy can lead to less N excreted by the animals (e.g. Arriaga et al., 2010; Dijkstra et al., 2013; Yan et al., 2006). For this purpose, forage with a low N content (e.g. maize) can be used as a supplement to N rich grass and this subsequently leads to less N in the excreta, mainly in form of less urine N. A lower amount of N input to the pasture is supposed to produce less N_2O emissions, but corresponding emission experiments under real grazing conditions for a full season, to our knowledge, have not been reported hitherto.

Historically, most studies used static chambers to quantify N_2O emissions (Flechard et al., 2007). Chamber measurements are ideal to quantify emissions on a small spatial scale and to attribute the measured fluxes to certain emission drivers, but for excreta emissions these measurements were often performed on manually applied urine and dung patches (Bell et al., 2015; Cai and Akiyama, 2016). Additionally, due to the strong heterogeneity of the emissions from a pasture (Cowan et al., 2015; Flechard et al., 2007) chamber techniques are not ideal to compute field scale emissions for grazing systems. The eddy covariance (EC) method overcomes this problem by integrating over multiple emission sources over a larger spatial domain. The EC technique was already applied successfully to quantify N_2O emissions from pastures and grasslands (Jones et al., 2011). Some studies also tried to compare different systems (e.g. intensive – extensive, different crops, land / lake) with one EC tower (e.g. Biermann et al., 2014; Fuchs et al., 2018) by partitioning the fluxes based on wind direction and systems geometry, but typically one tower for each system is preferable. In order to understand and quantify the emissions of a pasture, the combined approach of EC measurements and chambers is regarded as the best solution (Cowan et al., 2015). The EC systems can be used to quantify the field scale emissions while the chamber approach can be used to estimate the contributions from single emission sources (urine patches, dung patches and other "background" areas).

In our experiment, we measured N_2O emissions from two neighbouring pastures simultaneously with the EC method over a full grazing season. The two pastures differed in the energy to protein balance of the cows' diet. The small scale fluxes were quantified with a fast-box chamber and up-scaled to match the EC flux footprints for comparison. Further on, we computed the contribution of the different emission sources to the overall pasture emissions. The results were compared to default values provided by IPCC and other literature values. The main goal of the study was to quantify the excreta related emission and the corresponding EF for real grazing systems, and to analyse the specific contributions of dung and urine patches.

2 MATERIAL AND METHODS

2.1 Experimental site

The experiment was conducted at the research farm Agroscope Posieux in the Pre-Alps of Switzerland in the canton of Fribourg (46°46´04´´N, 7°06´28´´E) during the grazing season of 2016 and already has been described in detail by Voglmeier et al. (2018). The farm is located at an elevation of 642 m with an annual average temperature of 8.7 °C and a mean annual precipitation sum of 1075 mm (MeteoSwiss, 2018). The soil consisted mainly of a stagnic Anthrosol with a loamy texture (see Table 1). Soil profile samples for analysis of texture and other soil characteristics were taken at four locations on the pasture in 2013 and 2016. The vegetation consisted of a grass-clover mixture typical for Swiss pastures (78 ± 12 % grasses and 15 ± 10 % legumes; main species: *Lolium perenne* and *Trifolium repens*, 10 sampling times between May and September). After the last renovation treatment in 2007 the field had been used as an intensive pasture for cattle grazing with occasional grass cuts for maintaining a homogenous sward. Beside the N input through excreta from the grazing animals, additional N had been applied through fertiliser at a rate of about 120 kg N ha^{-1} per year between 2007 and 2015.

2.2 Experimental design

The experiment took place at a 5.5 ha pasture, which was divided into two separate systems differing in feeding strategy of the 12 cows per system (Fig. 1a). The northern system (system M) represented a N optimized feeding option where the diet of the cows consisted of grass with additional maize silage (roughly 20 % of the dry matter intake (DMI), fed in barn during milking periods) resulting in a demand optimized protein content in the diet (Arriaga et al., 2010; Yan et al., 2006). This was supposed to reduce the excreta N input to the pasture. The southern system (system G) represented a full grazing regime with no additional forage which resulted in a considerable protein surplus (see Table 2). Both systems were managed as a rotational grazing system with 11 paddocks (Fig. 1a) resulting in a typical rotation period of about 20 days. The size of the paddocks was adjusted for the different feeding strategies and resulted in typical sizes of 1700 m^2 for system M and 2200 m^2 for system G. The rotation of both systems was managed synchronously with a new rotation starting on the westerly paddocks (X.11 to X.16 with X indicating both systems) followed by the easterly ones (X.21 to X.25).

Grazing on the paddocks started with intermittent grazing phases in March and ended in early November with the main grazing season being between end of April and early October. During this time period eight full rotations took place. The cows typically spent 18 to 20 hours per day on the pasture and were brought to the barn twice a day (around 05:00 and 17:00 LT) for milking. However, in July and August the cows spent a longer time in the barn during daytime (up to six hours, see Fig. 2c) mainly due to high air temperatures and to a minor degree due to additional experiments of other research groups. Heavy rain events in June led to very wet soil conditions, which prevented grazing between the 8th of June and 4th of July and necessitated a grass cut on the 22nd and 27th of June (Fig. 2c).

2.3 N input to the pasture

During the grazing season, N input to the pasture mainly occurred in the form of excreta of the grazing animals and to a lesser extent as mineral fertilizer (Fig. 2d). The mineral fertilizer was ammonium nitrate (28 kg ha^{-1}) applied at the end of June and urea (42 kg ha^{-1}) with a split application between mid of August (western paddocks X.11–X.16) and early September (eastern paddocks X.21–X.25) due to concurrent grazing. In the present study we focus on the N input by grazing excreta and their effect on N_2O emissions. The comparison between the field-scale EC method and the small scale chamber measurements also required estimates of the number of dung and urine patches on the pasture. These numbers were calculated as described in Sect. 2.7 based on the excreted N amounts. N excretion cannot easily be measured in the field, but it can be calculated based on the energy demand of the cows and measured N in feeds and products (e.g. milk, body weight gain). We followed the approach described by Felber et al. (2016) to calculate the energy and N flows of the dairy cows in the experiment and to calculate daily values of excreted N per cow. Input parameters to the budget calculation were daily measurements of milk yield, milk N content and body weight gain as well as seasonal measurements of protein content of the grass (eight times between end of April and end of September) and of the maize silage (three times between beginning of May and beginning of

September). The breakdown of the excreted N in urine N and dung N was based on work by Bracher et al. (2011). For further details see Voglmeier et al. (2018), where the corresponding uncertainty of the total N and urine / dung N was estimated to be 15 % (2σ) for the same experiment. Seasonal statistics of the input variables are given in Table 2.

2.4 Small scale flux measurements

2.4.1 Excreta detection

The localisation of fresh dung and urine patches was essential in this study to measure N_2O emissions attributable to specific excreta sources. Intensive observation areas of 10 x 10 m or 15 x 15 m close to both EC towers in the paddocks X.11 and X.21, respectively, (see Fig. 1a) were selected. Within these areas fresh dung and urine patches were mapped typically 1-3 days after grazing of the respective paddock. Dung pats were mapped visually and labelled for subsequent chamber measurements. For urine patches a direct visual identification was not possible. Bates et al. (2015) demonstrated the ability of surface-soil electrical conductivity measurements to detect urine patches. Using this approach we mounted a soil probe (GS3, Meter Group, US; for soil moisture, temperature and electrical conductivity measurements) on a hand-held stick and mapped the intensive observation area on a 25 cm grid (Fig. 3). Based on pre-experimental tests, areas with conductivity values below a threshold of 0.15 mS cm^{-1} (dark blue areas in Fig. 3a) were considered as 'background' without recent influence of excreta. Spots with a conductivity above the threshold were marked as possible urine patches for the chamber measurements. Time series of electrical conductivity measurements (Fig. 3b) on manually applied urine patches in 2017 illustrate the long term effect and demonstrates the possibility to distinguish between background areas and urine patches more than 10 days after the application of urine.

2.4.2 Fast-box measurements

Small scale emissions from urine and dung patches as well as background pasture areas were measured with a fast-box (FB) chamber (Hensen et al., 2006). The measurements took place on the paddocks X.11 and X.21 (Fig. 1a) between beginning of July and mid of October and were therefore taken mainly during dry soil conditions (Fig. 2a, periods with VWC < 0.4). Measurements usually started after the excretion detection (Sect. 2.4.1) and about 1-2 days after the end of grazing (EOG). The age of the excreta patches is important for the interpretation of the measured fluxes. However, the exact determination of the excreta age was not possible. Thus, the time since EOG was used as excreta age for each FB measurement. The potential age variability of a single excreta patch resulted from the sojourn time of the cows on the paddock which typically was in the range of 1–1.5 days.

The manually-operated opaque 0.8 m x 0.8 m x 0.5 m box was connected to a fast response quantum cascade laser analyser (QCL, Aerodyne Research Inc.) that was also used for the EC system on the respective field (see below Sect. 2.5.1). The sample air was drawn continuously from the FB headspace through a 40 m 1/4" polyamide (PA) tube to the analyser, allowing measurements within a radius of about 35 m on the paddocks X.11 and X.21 (see Fig. 1). The sample flow rate Q was typically around 8 l min^{-1}. The box was modified by using a defined vent to ambient air through a tube of 4 cm diameter and 1 m length. The inlet of the vent tube was packed with a foam material over a length of 10 cm to avoid uncontrolled air exchange due to wind induced pressure fluctuations. The chamber was also equipped with a GMP343 CO_2 probe (Vaisala, FI) to measure the soil respiration, which was used for quality control purposes (Sect. 2.4.3). The increase in N_2O concentration after placing the chamber on the soil with a flux F_{Cham} was recorded every three seconds for a time period of about 90 seconds (taking into account the time delay due to tube sampling). The inflow of the background concentration C_{bg} into the chamber volume V (with area A) through the vent lead to lower measured concentration values C. This can be described by the following differential equation for the chamber headspace concentration $C(t)$:

$$V\frac{\delta C}{\delta t} = A \cdot F_{\mathrm{Cham}} - Q\left(C - C_{\mathrm{bg}}\right) \tag{1a}$$

This is a combination of the two equations for static chambers (right-hand term = 0) and for the dynamic chamber (left-hand term = 0). Solving of the equation yields the explicit time function:

$$C(t) = \frac{A \cdot F_{\mathrm{Cham}}}{Q}\left(1 - e^{-\frac{Q}{V}\cdot t}\right) + C_{\mathrm{bg}} \tag{1b}$$

For small values of the exponent Q/V*t (slow chamber volume exchange of about 40 min and short measurement time) as characteristic for the present fast-box measurements, the entire bracket term can be linearized with a series expansion to (Q/V*t). Inserting the resulting function for C(t) into Eq. 1a yields:

$$V\frac{\delta C}{\delta t} = A \cdot F_{\mathrm{Cham}}\left(1 + \frac{Q}{V}t\right) \tag{1c}$$

With the FB dimensions and sampling flow rate as given above and a maximum accumulation time t ≤ 2 min, the deviation from the ideal linear increase of a fully closed static chamber was ≤ 5%. The flux was finally calculated by using the HMR package (Pedersen et al., 2010), which uses linear and non-linear regression to fit the measured concentration values. The uncertainty of an individual box measurement is estimated to be around 20 % (Hensen et al., 2006).

In order to relate the measured fluxes to environmental driving parameters the following sensors were placed inside on the chamber: a thermocouple (type K) for air temperature measurement within the chamber, a GS3 probe (see Sect. 2.4.1) for soil moisture, soil temperature and soil conductivity measurements (c. 0-5 cm depth) and a ML3 Thetaprobe (Delta-T Devices Ltd, UK) for soil moisture and soil temperature observations (c. 0-10 cm depth). All measured data values were stored on a data logger mounted on top of the box and transferred to a computer in the nearby shelter or trailer. A customized LabView (National Instruments, US) program allowed for online inspection of all measured data values including the gas concentrations.

2.4.3 Quality control and system comparison

FB fluxes were selected for post-processing after fulfilling certain quality criteria. In a first step, the R-squared value of any flux calculation had to exceed 0.9 (e.g. for N_2O flux either the R-squared value of N_2O, CH_4 or CO_2 had to exceed 0.9). For urine patches, the soil conductivity had to exceed 0.25 mS cm^{-1} at the beginning of the measurements (see also Fig. 3b) in order to exclude possible old urine patches (of previous management rotations). Presumable old patches were therefore rejected for further processing. Background fluxes were removed from further processing if the flux value exceeded 40 µg m^{-2} h^{-1} (=4 x median value) to ensure that undetected urine patches at the chamber surroundings did not influence the flux measurements. Finally, 360 and 293 flux measurements met the criteria on system M and G, respectively. These measurements were composed of 238 background fluxes, 242 urine patch fluxes and 173 dung fluxes.

For a direct comparison of the FB measurements on the two pasture systems, the fluxes obtained on the same day were ordered based on their magnitude for each system and source class. Due to the synchronous grazing regime, the fluxes represented the same excreta age (e.g. on day 3 after EOG). However, synchronous FB measurements on both systems were not always performed. Resulting numbers of data pairs are 46, 54 and 40 for background, urine and dung fluxes, respectively.

2.5 Field scale flux measurements

2.5.1 Eddy covariance system

For field scale flux measurements EC towers were installed in the middle of the two pasture fields to account for the predominant wind directions north-east and south-west (Fig. 1) and were fenced with a radius of 2-3 m to avoid unwanted animal contact. The measurement height was 2 m which enabled a good footprint coverage (Fig. 4, Sect. 2.5.4) of both fields and allowed to measure fields-scale fluxes of both systems.

The two EC systems were identically equipped with an ultra-sonic anemometer-thermometer (further on named sonic, HS-50, Gill Instruments Ltd., UK) to quantify the turbulent mixing by measuring the three dimensional wind velocity (u,v,w) and air temperature. Dry air mixing ratios of N_2O were measured with closed-path quantum cascade laser spectrometers (QCL, QC-TILDAS, Aerodyne Research Inc.) that analysed air samples drawn through a 25 m PA tube (inner diameter 6 mm) by a vacuum pump (Bluffton Motor Works, flow rate ca. 13 l min^{-1}). One filter at the inlet (AcroPak, Pall Corporation, 0.2 µm) and one before the instrument (Midisart 2000, Sartorius Stedim Biotech GmbH, 0.2 µm) were used for each system to filter out particles. The distance of the inlets of the QCL from the centre of the sonic head were around 20 cm and the QCL instruments were placed in a temperature controlled environment (trailer at system M, shelter at system G) about 20 meters north (system M) or south (system G) of the EC towers.

The sample frequency of the EC system was 10 Hz. A customized LabView (National Instruments, US) program was used to combine the data strings of the individual instruments and store them as binary raw data for offline analyses. Additionally the program visualized the measurements and fluxes of the N_2O concentrations and fluxes, calculated with an online flux calculation. The program also allowed to check the EC system by remote access.

2.5.2 Flux calculation

A customized program written in the statistical software R (R Core Team, 2016) was used to calculate EC fluxes for 30 min intervals (similar to Felber, 2015a; Felber et al., 2015b). The program is based on Ammann et al. (2006, 2007). In a first step, 10 Hz data outside a plausible physical range were identified and replaced by a running mean filter with a window size of 500 data points. In a next step, wind vector components were rotated into the mean wind direction using the double coordinate rotation technique (Kaimal and Finnigan, 1994), and concentration values were subject to linear detrending within an averaging interval of 5 min.

The EC flux is defined as the covariance of the vertical wind speed and the trace gas mixing ratio. Due to the long inlet tube the time series of the trace gas signals are delayed in relation to the wind measurements by a quasi-constant lag time of about six seconds for system M and seven seconds for system G. Thus, the trace gas signals have to be shifted to obtain the correct covariance flux (Langford et al., 2015). In a pre-evaluation, the 'default lag' was determined as the most frequent position of the maximum absolute value of the cross-covariance function over periods of weeks to months (depending on instrument maintenance). Then it was checked for each half-hour period whether the individual 'dynamic' lag was within a time window of 0.61 seconds around the default lag. If this was the case, the dynamic lag was used, otherwise the default lag was used. In order to minimize the effect of non-stationarities in the time series, the 30 min flux was finally calculated as average over six 5-min subinterval flux values. This caused a minor low-frequent spectral loss (1-5%) that was quantified (and corrected for) using Kaimal-cospectra and the theoretical transfer function for block averaging.

The fluxes measured by EC systems are also subject to different high-frequency losses due to sensor separation and in case of N_2O air transport through the inlet tubes (Foken et al., 2012). These damping effects can lead to a significant underestimation of the flux and must be corrected. Based on Ammann et al. (2006) the half-hourly high frequency losses were quantified using the 'ogive' method where the damping factor was calculated by fitting the normalized cumulative co-spectrum of N_2O to the one of the sensible heat at a frequency of 0.065 Hz. In a post processing step, these half-hourly damping factors were filtered for favourable conditions e.g. low noise level of the ogive and the flux. The selected values were used to compute a wind speed and stability dependent damping function which was finally used to estimate the damping factor. Depending mainly on the wind speed, a damping effect of 10 – 30 % was found and corrected for.

EC fluxes were measured continuously over the grazing season. Since the present study is focussed on N_2O emissions from grazing, time periods with strong influence of N_2O emissions from fertilization and harvest events (see Fig. 2c-d) were excluded for computation of cumulative emissions and for comparisons between field scale and small scale measurements. These exclusion periods were limited to the 15 d following fertilization or harvest and led to a rejection of 47 days during the grazing season. The criterion is based on observed EC fluxes (Sect. 3.1) and is in accordance with Jones et al. (2011). The time periods used for calculation of the cumulative grazing emissions are further on defined as grazing-only periods (GOP) and accumulated to 198 days.

2.5.3 Quality control and gap filling

EC flux measurements are subject to different sources of measurement problems and quality issues which often result in data loss or data rejection. These sources can be instrument specific like power failures or malfunctioning, environmental driven like measurements under non ideal conditions (e.g. low turbulence) or a combination of both (Papale, 2012). Power outage, instrument maintenance (only on system M) and delayed installation (only on system G) led to data losses during the GOP of 12 and 17 % for systems M and G, respectively. Data rejection due to low friction velocity (u_*<0.07 m s^{-1}) and large vertical tilt angle (-2° to 6°) of the wind vector led to a further data loss of about 35 %. Because non-stationarity of the flux was already reduced by the short averaging/detrending interval of 5 min., a quality selection based on non-stationarity (Foken et al., 2012) had little effect and was therefore not used here. Additional rejection of wind sectors influenced by the farm facilities, trailer or shelter and to avoid cross-influences from the other pasture system (wind dir = 280° - 25° and wind dir = 97° - 195°) contributed to an overall data loss of 64 and 69 % for systems M and G. The resulting occurrence of data gaps showed a diurnal pattern with stronger data loss during the night, which was driven by the wind pattern with typically stronger wind speeds during daytime and calm nights.

The gaps in the flux time series needed to be filled in order to compute cumulative sums over a certain period of time. However, no well-established reference method for the gap filling of N_2O fluxes exists to date. We followed the evaluation of Mishurov and Kiely (2011) and used a lookup table method (LUT) with three parameters: one for the preceding cumulative rainfall of the last 12 hours with three classes (no rainfall, 0-2 mm, >2 mm), one for the percentiles of the soil temperature at 5 cm depth during the GOP with four classes (0-25th percentile, >25th percentile – median, >median – 75th percentile, >75th percentile), and one for the footprint-weighted (Sect. 2.5.4) averaged cow density (cows ha^{-1}) on the single paddocks over the preceding five days (0, 0 – 2, > 2 cows ha^{-1}). To check the sensitivity towards different gap filling methods three other techniques were compared to the LUT approach. [I] Running mean with a variable filter window size and at least 12 values; [II] Monthly mean diurnal variation (MDV, see Zhao and Huang, 2015) with a running half hourly window size of five in order to have more values during night-time, [III] seasonal MDV based on half-hourly values averaged over the whole grazing season. Due to the delayed installation of the EC tower on the southern field all values prior to the 14th of April on system G resulted from the gap filling routine. The uncertainty of gap filling for seasonal cumulative fluxes was estimated from the standard deviations of monthly cumulative fluxes retrieved with the different gap filling methods during GOP, which resulted in an uncertainty of 14 and 18 % for the system M and G, respectively (1 σ). It was assumed, that this uncertainty reflects the sum of all important individual uncertainties of the cumulative emissions (e.g. Sect. 3.3.1 and 4).

The experimental setup was expected to result in very similar systematic errors of the two EC systems, thus only the independent (or random) errors have to be considered for comparing the two neighbouring systems (Ammann et al., 2009). As the cumulative fluxes of both EC systems were by chance of similar magnitude (Sect. 3.1 and Sect. 3.3.1), the random uncertainty of the cumulative EC fluxes was determined from the differences between the cumulative, monthly EC fluxes of the two towers and resulted in a relative uncertainty of 5 % (1 σ).

2.5.4 Footprint modelling

EC measurements yield a spatially integrated flux over a certain area represented by the flux footprint (Schmid, 2002). In the present study, this fooprint typically extends over multiple grazing paddocks depending on wind direction and turbulence intensity. Therefore quantitative footprint information is needed for the comparison of the EC fluxes with the up-scaled FB measurements (Sect. 2.7), and the footprint has to be checked for the spatial dimension to be sure that the measured flux is mainly dominated by the area of the system and not contaminated by the neighbouring systems (either the other grazing system or fluxes originating from surrounding fields). In this study an open source version of a backward Lagrangian Stochastic dispersion footprint model (bLS) was used (Häni, 2017; Häni et al., 2018), based on Flesch et al. (2004). The flux to emission ratio is calculated following Eq. 2

$$\frac{F_{EC}}{E_j} = \frac{2}{N}\sum_{i=1}^{n_j}\frac{w_{ini}^i}{w_o^i} \tag{2}$$

where F_{EC} is the measured EC flux, E_j the surface emission of paddock (source area) j, N the total number of released particles, n_j the number of touchdowns within paddock j, w_{ini}^i the vertical release velocity and w_o^i the touchdown velocity of the particles.

In order to calculate the footprint for a 30 min period, N = 80’000 fluid particles were released backwards in time using the wind and turbulence parameters calculated from the sonic measurements of the EC systems. The systematic uncertainty of the bLS model was estimated to about 10 % (Flesch and Wilson, 2005; Wilson et al., 2013). The half-hourly footprint fractions of the individual paddocks were used to up-scale the small scale measurements to the EC flux footprint (Sect. 2.7) for inter-comparison of the two flux measurement methods.

In addition, the seasonally integrated footprint extension was analysed, taking into account the wind direction and u_* filtering as described in Sect. 2.5.3. The analysis showed a distinct separation of the footprint distributions for the two systems (Fig. 4) with only marginal contributions of the other system (<2.5 %). More than 80% of the footprint contributions was from the actual rotation area (without the optional areas indicated in grey colour in Fig. 1a).

2.6 Environmental parameters

In order to relate the measured fluxes to meteorological driving parameters an automated weather station (with data logger CR10X, Campell Scientific Ltd., UK) was installed at the northern field next to the Sonic. A WXT520 (Vaisala, Vantaa, FL) measured the wind speed, precipitation, temperature and barometric pressure, and global radiation was measured with a pyranometer (CNR1, Kipp&Zonen, Delft, NL).

Soil moisture and soil temperature were measured continuously with two repetitions on each pasture system close to the EC towers with ML3 Thetaprobe (Delta-T Devices Ltd, UK) devices at a depth of 5, 10, 20 and 40 cm.

2.7 Up-scaling of chamber measurements to eddy covariance footprint

Pasture N_2O emissions result from a combination of 'hotspot' emissions from urine and dung patches and of 'background' emissions from the other pasture areas. Even though the FB measurements (Sect. 2.4.2) allowed for quantification of single emissions sources, quantifying the contributions to the overall pasture emission is challenging due to the inherent heterogeneous nature of these emissions (e.g. spatial dimension, emission strength, temporal behaviour, number of excreta patches). The EC method, on the other hand, allowed to measure the combination of all pasture sources by integrating over multiple paddocks (see footprint, Fig. 4).

FB measurements were up-scaled to the EC footprint to allow a direct comparison between the two measurement approaches and to compute the contributions of the different emission sources to the overall pasture emission. The up-scaling procedure is illustrated in Fig. 5. The number of urine and dung patches on the paddocks was estimated by using the daily N excretion rate (Sect. 2.3), the daily grazing duration of the cows, a N loading of 22 g N per urination event (Misselbrook et al., 2016) and of 12.5 g N per dung pad (Cardenas et al., 2016). During the grazing season, about 12.5 dung patches d^{-1} cow^{-1} and a ratio of dung to urine patches of 1.3 for system M and 1.1 for system G was calculated. This compares well to values from literature (Orr et al., 2012; Oudshoorn et al., 2008; Villettaz Robichaud et al., 2011). Due to very similar field scale N_2O emission pattern (Sect. 3.1) and comparable soil measurements (Fig. 2), it was assumed that soil parameters were homogenous on the pasture and that the soil measurements on system M were representative for the whole field.

The FB derived N_2O emissions for the different sources were analysed for the potential driving parameters excreta age, soil temperature and soil moisture. For this purpose various regression models (using the statistical software R; R Core Team, 2016) were tested using different predefined function types (linear, exponential, polynomial functions, sigmoidal). Based on goodness of fit and statistical significance of regression coefficients, the most suitable relationships were chosen and applied to produce continuous emission time series for the paddock areas (Fig. 5):

(I) Background fluxes were parametrized as a function of soil moisture at a depth of 5 cm using the soil profile information provided in Sect. 2.4 by using a logistic regression.

(II) Urine patch emissions were parametrized as an exponential decay function of excreta age. To account for different environmental conditions, the deviations of the single emissions to this temporal emission pattern was again parametrized as a function of soil temperature and moisture at a depth of 5 cm (Sect. 2.6). Up-scaling fluxes to the paddocks sizes involved additional information on the computed number density of urine patches (as mentioned previously).

(III) Dung patch emissions were parametrized as a second order polynomial function of excreta age. Paddock emissions were calculated by applying this function to the computed number of dung patches (as previously mentioned) per paddock.

The up-scaled paddock emissions were finally compared to the EC fluxes by applying the computed footprint fractions of the paddocks (Sect. 2.5.4) in order to validate the FB measurements and to quantify the uncertainty of the up-scaling process.

The area related N_2O emissions for urine and dung were also converted to emissions per cow and grazing hour. For this purpose, the up-scaled paddock emissions were combined over all paddocks, accumulated for the GOP, multiplied by the pasture area of each system and divided by the number of cows and the grazing duration (Fig. 5). The resulting emissions associated to animal excreta were then related to the excreted N of the cows (Sect. 2.3) to obtain an excreta related EF that is comparable to the one provided by the IPCC guidelines ($EF_{3PRP,CPP}$; IPCC, 2006).

3 Results

3.1 EC fluxes

Observed EC fluxes on both pasture systems showed an almost identical temporal pattern (Fig. 6). The half-hourly fluxes on each system showed considerable variation during the grazing season with clear peaks after fertilization (grey shaded areas) and after grazing phases in the nearby paddocks (e.g. peaks in May, beginning of August). The overall highest emissions (28.7 and 21.6 g N_2O-N ha^{-1} h^{-1} for system M and G) were measured directly after the fertilizer application, which followed a harvest of hay at the end of June. This harvest event also led to an increase in the measured N_2O fluxes (0.5 – 3.0 g N_2O-N ha^{-1} h^{-1}) which lasted less than one day. The partial fertilizer application in mid of August resulted in higher fluxes compared to the following one in early September. The relatively high emissions during the first full grazing event beginning of May were characterized by high soil moisture contents (see also Fig. 2a) whereas the very wet soil conditions and the corresponding grazing break during June resulted in low fluxes in both systems. The small observed fluxes from mid of March until end of April resulted mainly from background fluxes and sporadic grazing (Fig. 2c). Occasional negative individual flux values between 0 and -1.5 g N_2O-N ha^{-1} h^{-1} were observed in both systems (7-8% of the cases). However, these fluxes exclusively occurred in cases, when no defined peak in the cross-covariance function could be identified (and thus the default lag was used, Sect. 2.5.2). Thus it can be concluded that the negative fluxes were generally below the detection limit.
During the GOP (excluding the grey shaded fertilizer influenced time periods in Fig. 6), the fluxes were still very similar for the two pasture systems M and G with a mean and standard deviation of 0.32 ± 0.36 vs 0.33 ± 0.37 g N_2O-N ha^{-1} h^{-1}, respectively. A mean diurnal cycle of the measured fluxes could be observed in both systems with highest values typically occurring in the afternoon and, on average, about 10 – 20 % lower values during the night.

3.2 Chamber fluxes

3.2.1 Comparison of pasture systems

FB chamber fluxes of background and dung patches were considerably smaller compared to the fluxes of urine patches (Table 3, Fig. 7). Freshly deposited urine patches under 3 days old could result in N_2O emissions larger than 100 times the values of background areas. The relative variability within the different source classes (urine, dung, background) were very high and resulted in standard deviations larger than the associated mean values. The excreta fluxes measured on system G tended to be somewhat higher in magnitude compared to system M, but no significant difference ($p>0.05$) was found. Also for the background fluxes no significant ($p>0.05$) difference between the two pasture systems was observed. Therefore all FB fluxes were combined for further processing without taking into account the different pasture systems.

3.2.2 Dependence on excreta age

The information on the temporal pattern of the excreta and background fluxes after grazing is important for the time integration of the individual sources and for the comparison with the EC measurements. In order to analyse and parameterize the temporal evolution of the emissions, the measured FB fluxes of each source class were averaged over 3-day periods and were related to the excreta age Δt_{EOG} (Fig. 8), defined as days after EOG (Sect. 2.4.2).

Background fluxes were on average considerably smaller than excreta fluxes and showed small persisting emissions without systematic dependence on time since grazing. In contrast, for urine patch fluxes a clear relation to Δt_{EOG} was found. Highest fluxes were usually observed within the first days after the urination event. Afterwards, they rapidly decreased with time although with a high variability that can partly be attributed to the influence of environmental conditions (see Sect. 3.2.3). The age dependent evolution of urine patch emissions ($F_{U,age}$) was parameterised with an exponential decay function fitted to the data points in Fig. 8:

$$\boldsymbol{F_{U,age}} = \boldsymbol{a_1} \cdot \mathbf{exp}^{\boldsymbol{b_1} \cdot \Delta \mathrm{t_{EOG}}} \qquad (3)$$

The coefficients of Eq.3 – Eq.8 are presented in Table 4 and apply to fluxes in units of µg N_2O-N m^{-2} h^{-1}.

Dung patch fluxes also showed a relation to excreta age (Fig. 8), however less pronounced compared to urine patches, and the highest emissions were typically observed between 4 – 11 days after dung deposition. However they were still smaller on average than the urine patch emissions during the entire observed age period. Because the evolution of dung emissions $F_{D,age}$ after the observed 20-day age period is unclear and a meaningful functional extrapolation was not possible, we decided to use a simple 2nd order polynomial for parameterisation purposes. This allowed to reproduce the initial increase with age and a rapid decrease to zero beyond the measured age range:

$$\boldsymbol{F_{D,age}} = \boldsymbol{a_2} + \boldsymbol{b_2} \cdot \Delta \boldsymbol{t_{EOG}} - \boldsymbol{c_2} \cdot \Delta \boldsymbol{t_{EOG}}^{\mathbf{2}} \qquad (4)$$

The fitted polynomial function is only applicable up to $\Delta t_{EOG} \approx 25$ d, where it crosses the zero line.

3.2.3 Dependence on environmental conditions

Measured chamber fluxes were analysed in relation to driving soil parameters (Sect. 2.6). For dung patch emissions, no relation to these parameters was found (thus $F_D = F_{D,age}$). For background fluxes no significant dependence on soil temperature ($p<0.05$), but a clear dependence on the volumetric water content (*VWC*) at a depth of 5 cm was found. The background fluxes had a large variability and could roughly be separated by three different *VWC* sectors (<0.27, 0.27-0.33, >0.33). In the sector below a *VWC* of 0.27, fluxes typically ranged between -3 µg N_2O-N m^{-2} h^{-1} and 15 µg N_2O-N m^{-2} h^{-1} whereas in the upper sector above a *VWC* of 0.33 the fluxes showed typical values between 0 µg N_2O-N m^{-2} h^{-1} and 30 µg N_2O-N m^{-2} h^{-1}. Nevertheless, the variability was especially pronounced in the VWC range between 0.27 and 0. 33 with fluxes ranging between 0 µg N_2O-N m^{-2} h^{-1} and 40 µg N_2O-N m^{-2} h^{-1}. Thus this VWC range also comprised of the overall highest background fluxes. However, averaging the fluxes by *VWC* intervals of 0.05 resulted in very similar values of about 12 ± 3 µg N_2O-N m^{-2} h^{-1} above a VWC of 0.3. Hence, the measured background fluxes could be parametrised with the following functional relationship:

$$\boldsymbol{F_{BG}} = \frac{\boldsymbol{a_3}}{\boldsymbol{1+exp^{(b_3-VWC)/c_3}}} \tag{5}$$

This logistic regression curve has a strong effect below VWC values of 0.30 but stays fairly constant at higher VWC contents and converges to a flux of 12.6 µg N_2O-N m^{-2} h^{-1}. Below a *VWC* of 0.2 the logistic regression converges to a background flux of 0 µg N_2O-N m^{-2} h^{-1}.

Measured urine patch emissions not only showed a clear response to the excreta age as shown in Sect. 3.2.2 but also to changes in T_S and *VWC*. On a specific Δt_{EOG}, $F_{U,age}$ could vary significantly and correlated typically with soil conditions. The highest flux (5117 µg N_2O-N m^{-2} h^{-1}, Δt_{EOG} = 6d) was measured at a T_S of 18 °C and a *VWC* of 0.42 while the lowest measured flux (34 µg N_2O-N m^{-2} h^{-1}) on a similar Δt_{EOG} was measured at a low T_S (1°C) and a lower *VWC* (0.3). Maximum positive measured FB flux deviations (Sect. 2.7) from Eq. 3 were generally observed for wet (VWC > 0.45) and warm (>17 °C) soil conditions while low T_S and *VWC* resulted in negative flux deviations. Thus, the final regression model for urine patch emissions (Eq. 6) consists of multiple equations (Eq. 3, 7, 8) which relate the measured fluxes to the temporal decay (Eq. 3) and a deviation $\Delta F_{U,env}$ to it, where $\Delta F_{U,env}$ was parametrized as a function of environmental driving parameters T_S and VWC_U (Eq. 7 and 8, Fig. 9).

$$\boldsymbol{F_U = F_{U,age} + \Delta F_{U,env}} \tag{6}$$

$$\Delta F_{U,env} = (a_4 + b_4 \cdot VWC_U + c_4 \cdot T_S) \cdot Corr_{U,env}(\Delta t_{EOG}) \tag{7}$$

$Corr_{U,env}$ corrects $\Delta F_{U,env}$ for different urine patch ages as the deviation can be larger for relatively new patches compared to older ones. This correction factor was found to be a linear relationship (p<0.01) between 1.35 for a Δt_{EOG} of 0 days (after the patch deposition) and 0.35 after 20 days. VWC_U (Eq. 8) accounts for different soil moisture conditions at the surface below an urine patch and nearby background areas and was parametrised as a function of background *VWC* and $\Delta t_{,EOG}$ (Eq. 8).

$$VWC_U = VWC + a_5 \cdot exp^{b_5 \cdot \Delta t_{EOG}} \tag{8}$$

3.3 Up-scaled chamber fluxes

3.3.1 Comparison between up-scaled chamber and EC fluxes

Generally the field scale fluxes represent the area integral of management related (excreta patches) and environmentally driven small scale fluxes. Therefore the relationships presented in Sect. 3.2.2 (dependency on excreta age) and Sect. 3.2.3 (environmental driving parameter) were applied to up-scale the FB measurements to the paddock size during the GOP.

As shown exemplary for an 18-day period in Fig. 10b, the magnitude of the management related up-scaled paddock fluxes depended mainly on the grazing duration on the single paddocks (similar slope for different paddocks M11–M14). The maximum of the emissions was typically calculated at the end of the grazing period on the respective paddocks. The lower limit of the fluxes was given by the estimated background fluxes, especially at the beginning of a new rotation and stayed therefore rather constant for *VWC* values above 0.3 (Eq. 5, Sect. 3.2.3). Variations in environmental conditions (mainly important for soil moisture) led to rapid changes in the emission level as long as significant urine patch emissions were present. These rapid variations occurred typically after stronger precipitation events (as shown in Fig. 10a for onsite meteorological and soil measurements).

Up-scaling the paddock fluxes to the EC footprint allowed a direct comparison with the EC fluxes on a half-hourly basis (Fig. 10c). The up-scaled FB fluxes compared well in magnitude with the measured EC fluxes and showed a similar temporal behaviour. While generally a response to variations in environmental driving parameter could be observed, it was less pronounced for the up-scaled FB fluxes in comparison to the EC fluxes.

Gapfilling of the EC fluxes (Sect. 2.5.3) allowed the calculation of the cumulative N_2O emissions during the GOP (solid lines in Fig. 11). These area related emissions were very similar between the two systems throughout the GOP with seasonal sums close to 1500 g N_2O-N ha^{-1}. Cumulating the N_2O emissions not only enabled a more quantitative comparisons between the systems, but also allowed a better comparison between the two measurement approaches (Fig. 11). The emissions of the up-scaled FB matched the EC emissions rather well with differences of the seasonal sums below 3 %. Distinct differences were mainly observed in May and June when FB derived emissions were significantly overestimated compared to EC. At the end of the grazing period slightly higher emissions were estimated from the up-scaling routine compared to the measured EC emissions. Monthly absolute differences between the cumulative EC and the up-scaled cumulative FB sums were normally distributed ($p<0.05$) with 1σ values of 26 % and 25 % for system M and G, respectively. Within this uncertainty range no difference between the two measurement approaches was observable.

3.3.2 Emission breakdown into contribution sources

The excellent match between the EC fluxes and the up-scaled chamber based fluxes showed that the used relationships with excreta age and environmental drivers (see Sect. 3.2) was reasonable and allowed the separation into single emission sources (Fig. 12). Except for the beginning of the grazing season when grazing rate was very low (see Fig. 2), the urine patch emissions dominated the field scale fluxes. In May, this effect was even more pronounced due to the wet soil conditions. Based on the up-scaling, the averaged urine patch emission of both systems were responsible for about 57 % of the pasture emissions. Background contributed to about 38 % and dung emissions to about 5 % to the overall field emissions. Both systems had very similar contributions, with only 1 % difference in the dung contribution as a result of a different N excretion ha^{-1} on the pasture by dung (Table 5). Background emissions were simulated to be constant for most of the GOP due to the weak sensitivity of Eq. 5 to VWC and the undetected sensitivity towards soil temperature.

4 Discussion

4.1 Area related and animal related emissions

The EC and up-scaled FB emission results presented in Sect. 3.3.1 are normalized by area and showed the emissions for the EC footprint (see also summary in Table 5). The good agreement with a relative difference below 1.5 % for yearly sums (which is far below the uncertainty range, see Table 5) between the two independent approaches supports their quality (including the up-scaling procedure) in this study. We assume that the EC fluxes are on average representative for the whole pasture system, although the contribution of the central paddocks X.11, X.12 and X.21, X.22 to the EC footprint is generally higher than the contribution of the other more distant paddocks (Fig. 4). We found no indication of significant differences between the paddocks concerning soil conditions, vegetation productivity or other characteristics (data not shown). An alternative up-scaling of the FB measurements to the entire pasture system (without taking the EC footprint into account) representing the average emission over all rotation paddocks (Table 5, FB up-scaled to pasture system emissions) differed less than 4 % from the EC footprint related emissions.

For assessing the effect of the N reduced diet on excreta related N_2O emissions, the emissions per cow and grazing hour were compared, taking into account the different pasture sizes for system M and G (acc. to Sect. 2.7). The corresponding results in Table 5 show about 25 % lower excreta related N_2O emissions per cow for the herd in system M than for the herd in system G during the GOP. The difference is not statistically significant probably due to the considerable uncertainties resulting from the FB up-scaling procedure. For comparing the two herds the parallel direct EC measurements are better suited as only random uncertainties have to be taken into account (Sect. 2.5.3), yet they also include the background emissions. The EC based N_2O emissions per cow were 0.20 ± 0.03 and 0.27 ± 0.05 g N_2O-N cow^{-1} h^{-1} for system M and system G, respectively, and resulted in a significant difference of 0.07 ± 0.02 g N_2O-N cow^{-1} h^{-1} between the two herds. This indicates the ability of an N adjusted forage to reduce the excreta N content and related emissions of N_2O. It has to be noted, that this evaluation does not comprise the full N_2O emission of the pasture fields or of the milk production system but only the emissions related to grazing excreta following the IPCC concept ($EF_{3PRP,CPP}$; IPCC, 2006). Any further N_2O emissions e.g. related to fertiliser application on the pastures or for the supplement maize production were not taken into account here. A comparison of entire production systems would require many additional assumptions outside the specific scope of this study. It also has to be considered that the N optimisation of the diet is not necessarily linked to the supplemental feed of arable crops like maize, but may as well be achieved with different feed strategies (e.g. grass varieties with a high content of water soluble carbohydrates; Misselbrook et al., 2013).

4.2 Excreta related emission factor

Area or cow related emissions as described in Sect. 4.1 enabled the comparison of the different measurement approaches and the discussion of the diet effects on N_2O emission. However, results presented in literature or used in national inventories typically relate emissions to the N inputs within a given time period using EFs. The annual excreta related EF (Table 5) in the present study was 0.74 ± 0.26 % for system M and 0.83 ± 0.29 % for system G. These EFs are based on the combined, up-scaled FB measurements of urine and dung patches (see Sect. 3.3.2) relative to the N excreted on the pastures during the GOP (Table 5). Their uncertainty is defined by the combined uncertainty of the up-scaling method (Sect. 3.3.1) and the N input estimation (7.5 %). The difference in the EFs between the systems is therefore not statistically significant.

The resulting EFs were significantly smaller compared to the proposed default $EF_{3PRP,CPP}$ of the IPCC guidelines for cattle excreta (2%; IPCC, 2006), which makes the use of the latter in the Swiss national inventory questionable. The up-scaled FB measurements also allowed to separately calculate the EFs for urine and dung. We found EFs of 1.12 ± 0.43 % and 0.16 ± 0.06 % for urine and dung, respectively (average of both systems due to small difference, see Table 5). These EFs are comparable to the results of newer studies (0.59 % and 0.26 % for urine and dung patches combined from cattle and sheep; Cai and Akiyama, 2016; 1.18 % and 0.31 % for cattle urine and dung; Krol et al., 2016). The large difference of the EFs for urine and dung also supports the suggestion of Krol et al. (2016) to disaggregate the EF by excreta type in emission inventories. The implementation of excreta specific EFs could allow for a more precise calculation of the grazing related N_2O emissions e.g. as dietary effects regarding the N intake predominantly affect the excreted urine N, which is the main source for the high N_2O emission associated to excreta (Dijkstra et al., 2013).

The background emissions measured by FB cannot be attributed to a specific N input in a quantitative way, but the annual sum of 1.03 kg N_2O-N ha^{-1} yr^{-1} from this study (extrapolated using Eq. 5 and VWC data for the whole year) compares well with background emissions reported by a meta study of Kim et al. (2013, median: 0.7 and mean 1.52 kg N_2O-N ha^{-1} yr^{-1}) for agricultural lands. In agricultural systems, background emissions are usually determined as emissions from (managed) plots receiving no fertilisation in the study year. Thus they still include N inputs from plant residues and atmospheric deposition. Background emissions are also often regarded as a late effect of fertilization events from previous years (Bouwman, 1996; Gu et al., 2009). On pastures, background emissions may additionally result from trampling of the cows that can further stimulate the N_2O production via denitrification due to soil compaction (Bhandral et al., 2007).

4.3 Up-scaling of FB fluxes

Urine patch emissions were parametrized with an exponential decay and maximum initial emissions of about 600 µg N_2O-N m^{-2} h^{-1} that is close to the maximum averaged emissions measured by Barneze et al. (2015) from manually applied urine in laboratory conditions and on a grassland. A strong emission response to urine application was generally reported in the literature, however, with a large range of different emission dynamics and magnitudes (e.g. two emission peaks due to nitrification and denitrification; emission peak after a few days with near exponential decay afterwards; significant emissions after weeks to month; Bell et al., 2015; Cardenas et al., 2016; Chadwick et al., 2018). Similar to our study, reported dung patch emissions by those studies were much lower compared to urine induced emissions.

We found that pasture emissions were dominated by excreta related emissions during the GOP (about 60 %). On a seasonal basis, the up-scaled aggregated fluxes compared well with the gap filled EC measurements, which also indicates the validity of the source attribution in the up-scaled emissions. Especially during time periods where both FB fluxes and EC fluxes were measured (July – October) the agreement between the systems was very good.

However, the parameterisations used for up-scaling resulted in a poor performance for certain soil conditions. The limited sensitivity towards changes in *VWC* of the background fluxes is probably due to the fact that FB measurements were mainly performed during dry soil conditions. We have no explanation why we did not find a significant sensitivity of the background fluxes towards changes in *Ts* as reported by other studies (Butterbach-Bahl et al., 2013; Schindlbacher, 2004). Typically, increasing soil temperature leads to increased soil respiration which subsequently can lead to a depletion of soil oxygen and further to higher denitrification rates. In contrast to background fluxes, the urine patch emissions showed a clear response to changes in *Ts* and *VWC*. This effect could be parametrised with a bi-linear regression (Eqs. 7 and 8). This regression led to high up-scaled emissions from urine patches especially during wet soil conditions and subsequently to an overestimation of the cumulative emissions in May and June compared to the EC systems. N_2O emissions often have an emission maximum during moderately wet soil conditions (VWC between 0.40 and 0.45) while completely anaerobic conditions at saturated VWC can lead to a complete denitrification with only marginal N_2O emissions (Butterbach-Bahl et al., 2013). Such conditions have been very rare during the FB measurements (see Fig. 9) and therefore may not be adequately represented in the derived parameterisation. A general trend towards lower emissions during very wet soil conditions was also observed by the EC systems (not shown). However, in order to avoid mixing results of the different measurement systems and thus reducing the explanatory power of the system inter-comparison we decided to base the environmental regression analysis (Sect. 3.2.3) only on measured data by the FB.

4.4 Advantages and problems of experimental setup

The presented field campaign was designed to estimate the N_2O emissions of two parallel grazing systems and to compare different feeding diets of the herds. Field scale emissions derived by the EC method resulted in a wide range of measured emissions which were mainly driven by environmental and management related parameters. Nevertheless, the setup with two towers allowed for a good comparison with a sufficient number of measured fluxes from both systems. Due to a delayed installation of the EC tower at system G all fluxes prior mid of April had to be gap filled which resulted in a higher associated uncertainty.

The excreta N input derived by the animal budget approach at a temporal resolution of 1 day was needed in order to quantify the EF of the two systems and to up-scale FB chamber measurements to the field scale. Nevertheless, direct measurements would have been preferable. However, as the N content in the excreta is highly variable (Betteridge et al., 2013) on a seasonal (e.g. due to variability in the N content of the fodder) and short term scale (e.g. different urine volume, different cows, difference between day and night) continuous measurements throughout the grazing period for a representative number of cows would have been needed. This is only possible with measurement equipment directly placed on the cow. Beside the still considerable uncertainty associated to these measurements, they are often limited regarding animal welfare and are not well established (Misselbrook et al., 2016). Thus, they were not used in this study.

The combined approach of EC and FB measurements allowed the quantification of the uncertainty of the up-scaling routine and the good match between the two measurement approaches also validates the resulting contributions of the different emission sources on the field scale. The uncertainty associated with the up-scaling mainly resulted from missing FB measurements during wet soil conditions (e.g. in spring), which prevented the use of a more complex parameterisation of environmental driver effects on background and urine emission. In summary, the experimental setup resulted in robust field scale emissions, allowed to compare the two pasture systems, and yielded source specific emission factors for dung and urine patches.

5 Concluding remarks

The temporal dynamics of background areas and excreta patches were observed by fast-box (FB) chamber measurements on the pasture. We found no significant temporal pattern of the background fluxes. Urine patch emissions were parametrised by an exponential decay with time whereas a less pronounced dependency on excreta age of dung emissions was observed. This relation was parametrised with a quadratic function and a maximum after about 10 days. On a field scale level, urine patch emissions dominated the pasture emissions during the grazing season. Nevertheless, background fluxes contributed significantly to the pasture emissions as well. The origin of these background fluxes is still uncertain and should be addressed in further studies.

The combined approach with EC and FB measurements proved to be appropriate to observe and quantify the magnitude of the pasture emissions and to calculate the contribution of the single emission sources. The different diet of the cows resulted in a excreta related N_2O emission difference of about 25 % between the two cow herds and revealed the large potential of an N optimised feeding strategy to reduce grazing related N_2O emissions. In this study, the N optimisation was achieved by feeding additional maize silage to the fodder in system M. However, a reduction in excreted N can potentially be realised by other means as well (e.g. grass varieties with a high content of water soluble carbohydrates). The excreta related EFs derived from the up-scaled FB measurements were 0.74 ± 0.26 % for system M and 0.83 ± 0.29 % for system G and were thus significantly lower compared to the current default EF of 2 % for cattle excreta provided by the guidelines of the IPCC. The findings also exhibited clear differences in the individual EFs for urine and dung (1.12 ± 0.43 % and 0.16 ± 0.06 %, respectively, averaged over system M and G) suggesting a corresponding disaggregation in emission inventories.

Data availability. Data obtained in this study will be online available at the time of publication from the data repository zenodo.org. (the DOI will be included in the final paper version).

Competing interests. The authors declare that they have no conflict of interest.

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Table 1: Near-surface soil parameters (5-10 cm depth) averaged over four locations on the pasture. The measurements are given as mean ± 1 standard deviation.

Parameter	Value
Pore volume (%)	57 ± 4
Bulk density (g cm^{-3})	1.09 ± 0.11
pH (-)	6.0 ± 0.3
Sand (%)	42.6 ± 2.5
Clay (%)	18.7 ± 1.7
Silt (%)	33.0 ± 1.3
Soil organic matter (%)	5.7 ± 0.3
Total N (%)[#]	0.38 ± 0.03
Total C (%)[#]	3.76 ± 0.20

[#]were measured at a depth of 0-10 cm

Table 2: Measured averages ± standard deviation of observed cow properties (ECM: energy corrected milk) and feed protein contents used by the dairy cow nitrogen budget approach for both pasture systems during the grazing season 2016.

Input parameter (units)	System M	System G
Number of cows	12	12
Milk yield, ECM (kg cow^{-1} day^{-1})	25.1 ± 2.9	24.2 ± 3.7
Animal weight (kg)	633 ± 14	633 ± 10
Grass crude protein (g kg-DM^{-1})	195 ± 23	196 ± 23
Maize crude protein (g kg-DM^{-1})	84 ± 8	n.a.

Table 3: Flux measurements using the FB technique (mean ± std) of background and excreta patches averaged over 20 days following a grazing phase.

Measurement location	System M	System G
Background (µg N_2O-N m^{-2} h^{-1})	8 ± 8	5 ± 8
Urine (µg N_2O-N m^{-2} h^{-1})	121 ± 130	162 ± 190
Dung (µg N_2O-N m^{-2} h^{-1})	16 ± 18	35 ± 60

Table 4: Coefficients (a-c), corresponding indices i and significance levels for the equations presented in Sect. 3.2. The equation coefficients were fitted using FB chamber measurements and yield fluxes in units of µg N_2O-N m^{-2} h^{-1}. The input quantities are the soil temperature T_S (in units of °C), time since end of grazing Δt_{EOG} (in units of days) and volumetric water content VWC (as dimensionless fraction).

Equation	I	a_i	b_i	c_i
Eq. 3	1	587 ***	-0.082 **	
Eq. 4	2	23 *	5.4 *	-0.25 *
Eq. 5	3	12.6 ***	0.267 ***	0.012 *
Eq. 7	4	-1490 ***	2900 ***	23.9 **
Eq. 8	5	0.098 ***	-0.086 **	

***Significant at level $p<0.001$; **Significant at level $p<0.01$; *Significant at level $p<0.05$

Table 5: Summary of cumulated grazing related emissions for both pasture systems during the GOP 2016. The table shows the emissions per area (first part), pasture area and excreta N input (second part) and the emissions per cow and grazing hour as well as the calculated EFs (third part). The uncertainties are given as 1σ.

Parameter	System M	System G
EC emission (kg N_2O-N ha^{-1})	1.49 ± 0.21	1.49 ± 0.27
FB emissions up-scaled to EC footprint (kg N_2O-N ha^{-1})	1.51 ± 0.39	1.50 ± 0.37
FB emissions up-scaled to pasture system (kg N_2O-N ha^{-1}) [a]	1.48 ± 0.38	1.48 ± 0.37
Pasture system area (ha)	1.88	2.51
Excreta N total (g N cow^{-1} h^{-1})	16.5 ± 1.2	19.6 ± 1.5
Urine N (g N cow^{-1} h^{-1})	10.2 ± 1.1	13.0 ± 1.3
Dung N (g N cow^{-1} h^{-1})	6.3 ± 0.7	6.5 ± 0.7
FB excreta emissions (g N_2O-N cow^{-1} h^{-1})	0.12 ± 0.04	0.16 ± 0.05
EF excreta total (%) [b]	0.74 ± 0.26	0.83 ± 0.29
EF urine (%) [b]	1.09 ± 0.43	1.15 ± 0.43
EF dung (%) [b]	0.16 ± 0.06	0.17 ± 0.06

[a] average emissions over all paddocks

[b] based on FB emissions up-scaled to pasture system

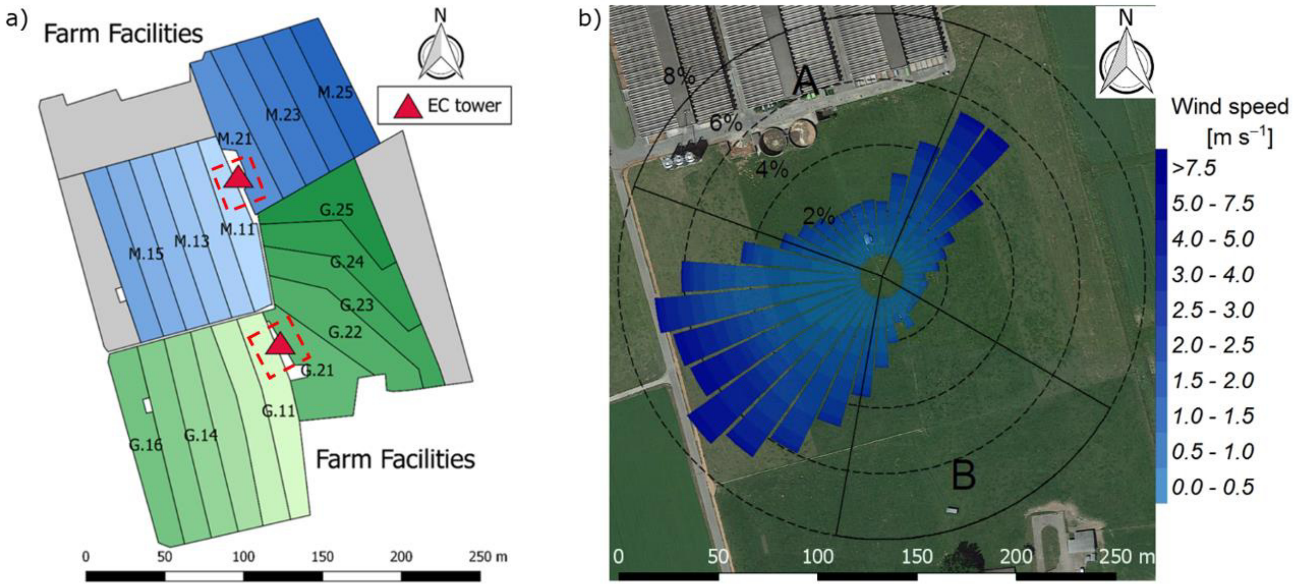

Figure 1: a): Measurement site with the pastures for the two herds (blue: grass diet with additional maize silage; green: full grazing regime; grey: optional pasture areas) and the division into the paddocks (M.11–M.25, G.11–G.25). Additionally the location of the two EC towers (triangles) and the area of the chamber measurements (red dashed rectangles) are shown. b) Wind distribution for the northern sonic anemometer with the corresponding sector contributions (black dotted circles) for the period May – October 2016. The areas A and B indicate wind sectors from which advection from nearby farm building can occur. The wind distribution was overlaid on a Google Earth image of the experimental area (Map data: Google, DigitalGlobe)

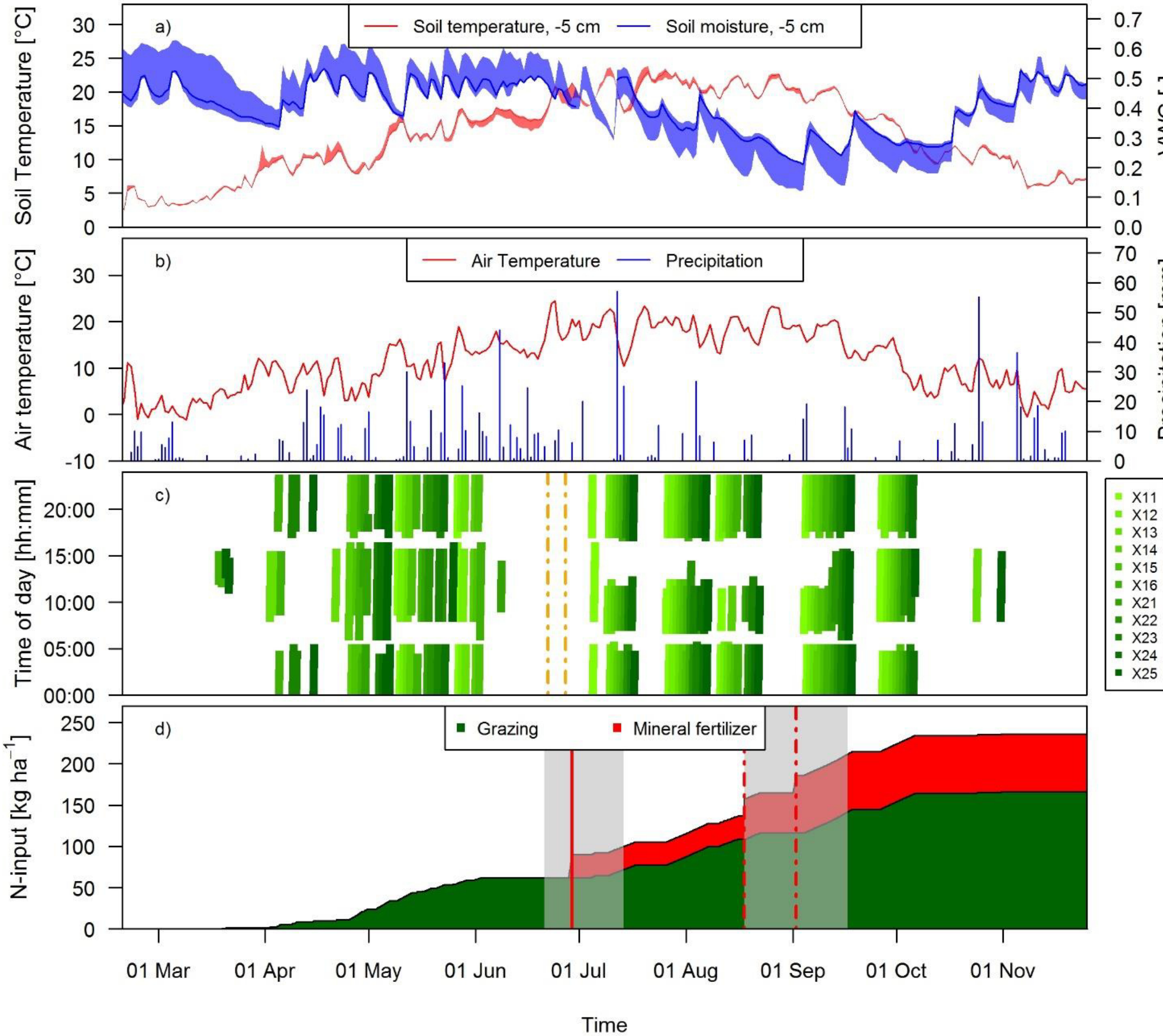

Figure 2: Time series of a) daily averaged soil temperature and moisture at a depth of 5 cm measured at system M (solid lines) and spread of the four measurement locations, b) daily air temperature at 2 m above ground and precipitation at the measurement site, c) grazing duration on the single paddocks of the pasture (X: both pasture systems M and G) for the study year 2016. The dashed vertical orange lines indicate the harvest event (split between X.11-X.16 and X.21-X.25) d) N input to system M during the main grazing season in 2016. Fertilizer was applied two times (vertical red lines). The second application (dashed lines) in August was split in two parts due to concurrent rotational grazing. The grey shaded areas indicate time periods influenced by fertilization or harvest events as explained in Sect. 2.5.2.

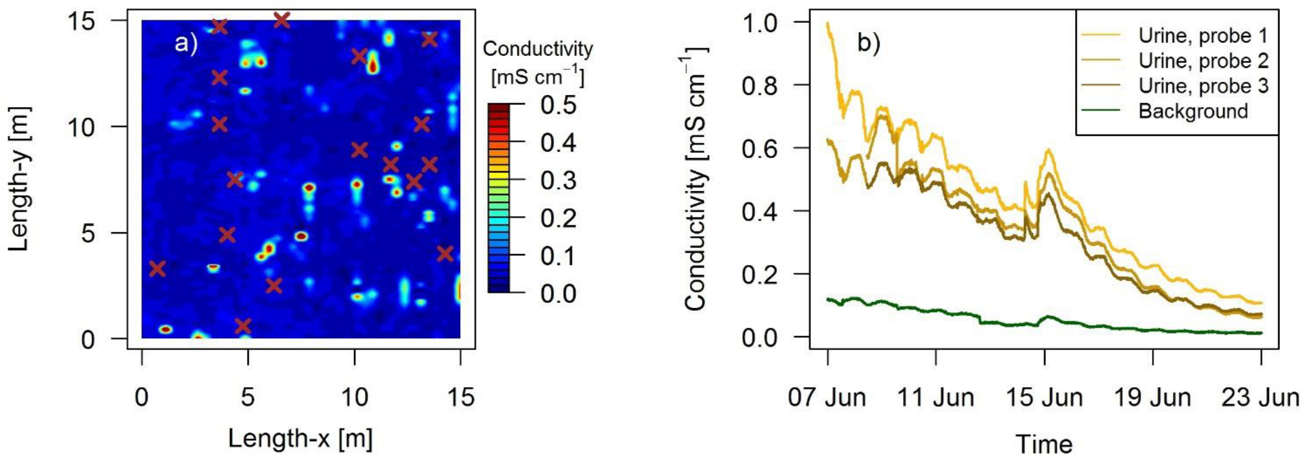

Figure 3: a) Measured conductivity within a quadratic 15 x 15 m intensive observation area on the 3rd of October, 2016 in system G. High values (>0.15 mS cm^{-1}) indicate urine patch locations and brown crosses indicate observed dung pats. b) Conductivity measured continuously during a field experiment in 2017 with four GS3 sensors.

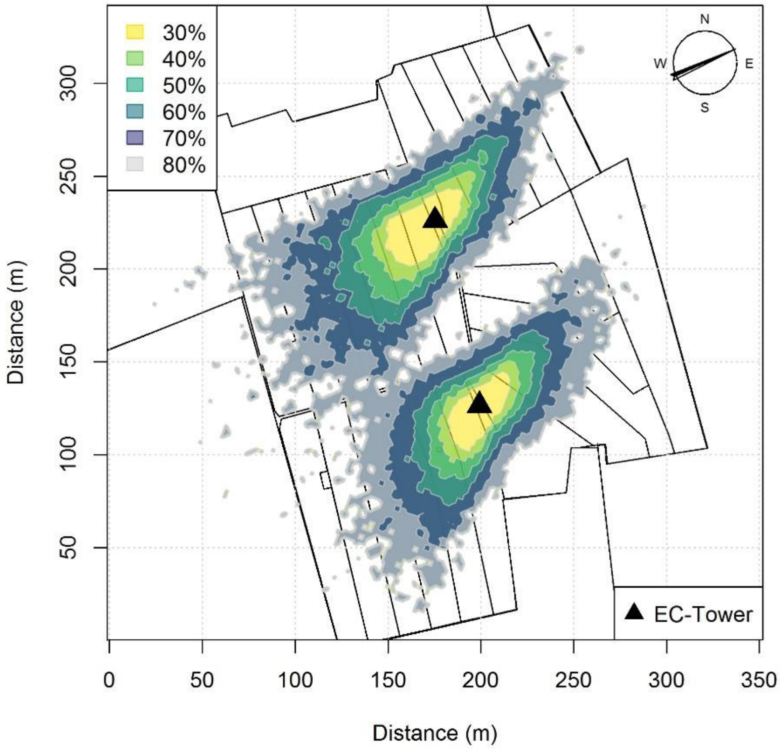

Figure 4: Footprint climatology for both EC towers averaged for the time period between 15th March 2016 and 15th November 2016. The legend values indicate the percentage of the total footprint weight.

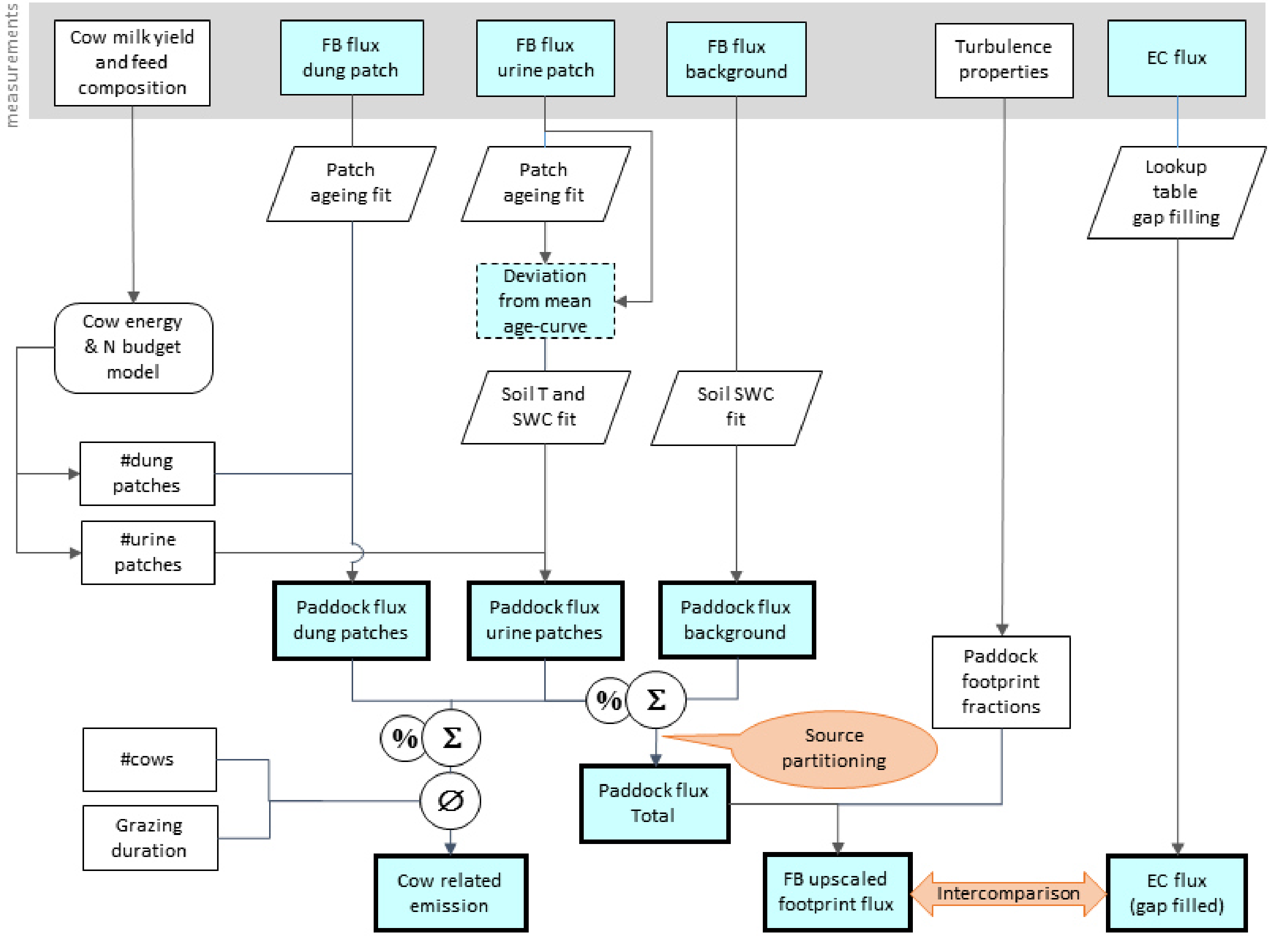

Figure 5: Flowchart of up-scaling procedure to compare small scale chamber fluxes with EC fluxes and to estimate the contribution of excreta emissions to the overall pasture emission. Rectangular shapes indicate data sets / time series data. Time series data with thin frames have gaps whereas bold frames indicate complete data sets. The light blue colour specifies N_2O flux data. Other shapes show operations (e.g. fit or gap-filling routines).

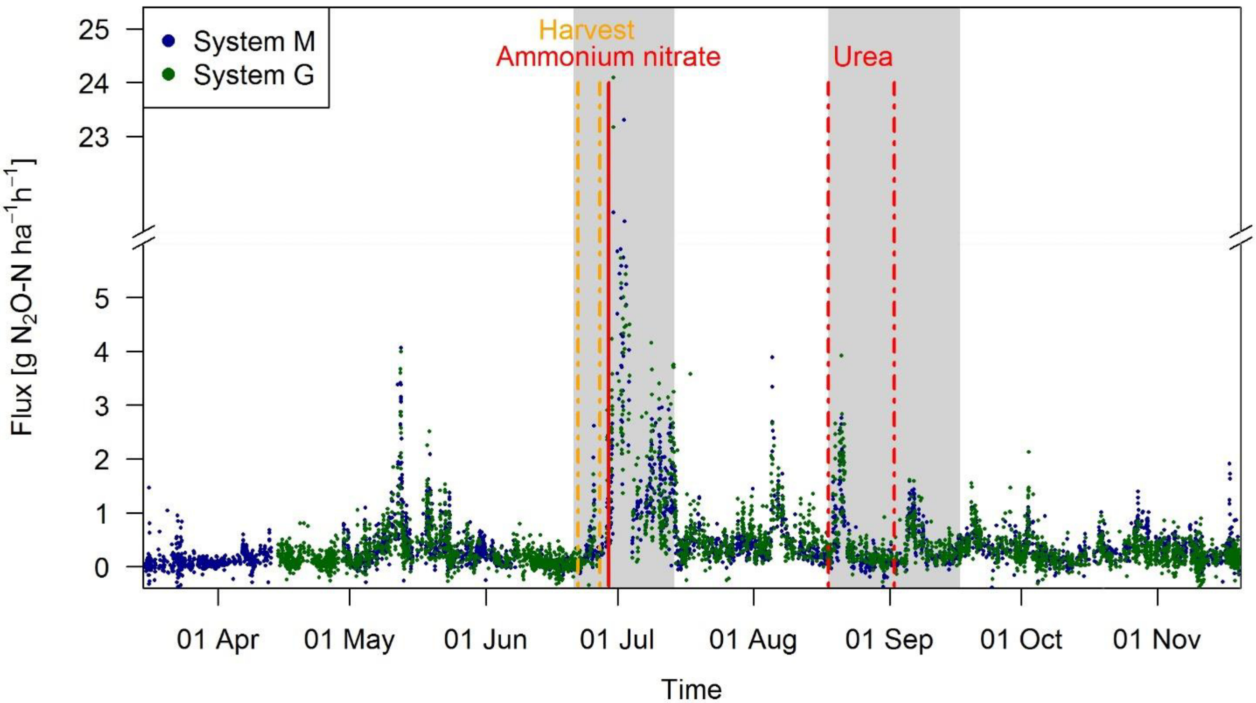

Figure 6: Time series of half-hourly EC flux measurements in both systems during the grazing season 2016. For the analysis of grazing related emissions, only the non-shaded periods (GOP) were used. The vertical lines show the timings of fertilization (red) and harvest (orange) events. Dashed lines indicate that harvest and urea application were split for western (X.11-X.16) and eastern (X.21-X.25) part. The shaded areas indicating time periods influenced by fertilization events or harvest were excluded for the evaluation of grazing excreta related emissions. One flux value (28.7 g N_2O-N ha^{-1} h^{-1} on system M, 30.06.2016) was skipped for better readability.

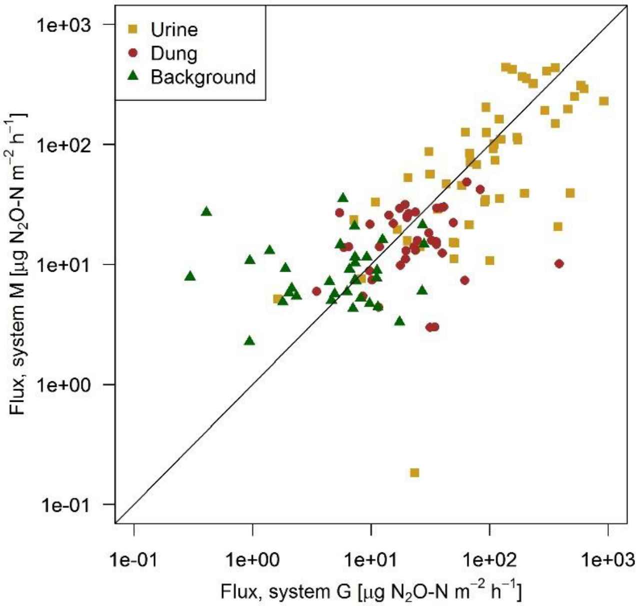

Figure 7: Scatterplot shows the comparison of near-simultaneous fluxes for different sources measured with the fast-box on the two pasture systems. The black line indicates the 1:1 line.

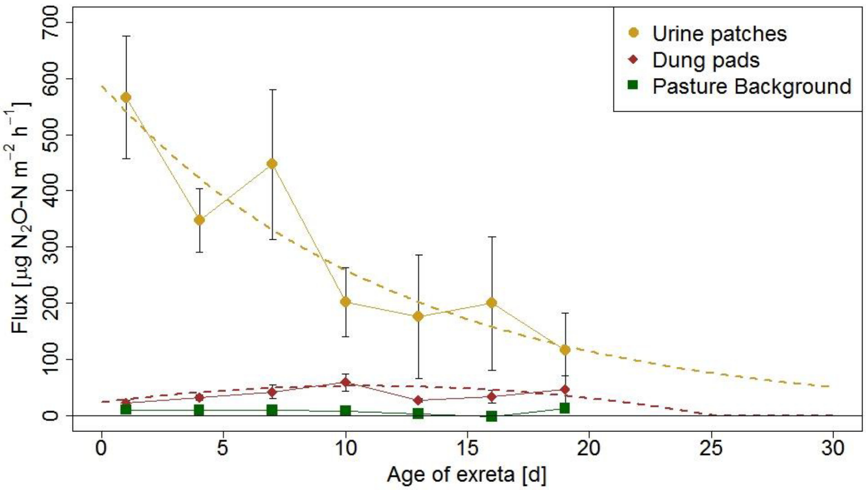

Figure 8: N_2O flux evolution with time for urine patches, dung pats and background areas. The fluxes were measured with the fast-box and averaged over 3-day periods and the error bars show the standard error of the measurements. The standard errors for the background fluxes are smaller than the symbols. The dotted lines show the fitted curves through the averaged values of urine and dung patch emissions (see also Eqs. 3 and 4).

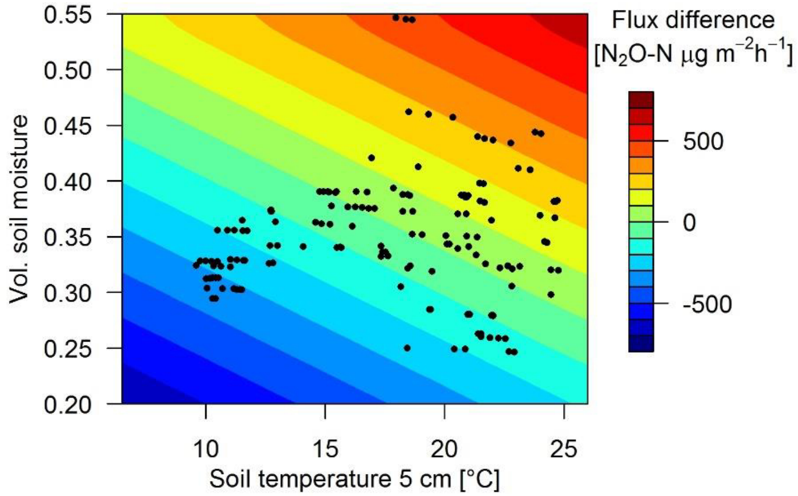

Figure 9: Surface plot shows the estimated N_2O flux deviation (Eq. 6, 7; $Corr_{U,env}$ = 0) from the exponential fit (Eq. 3) for urine patches depending on soil moisture VWC_U and temperature at a depth of 5 cm. The black dots indicate the conditions under which flux measurements with the FB were obtained.

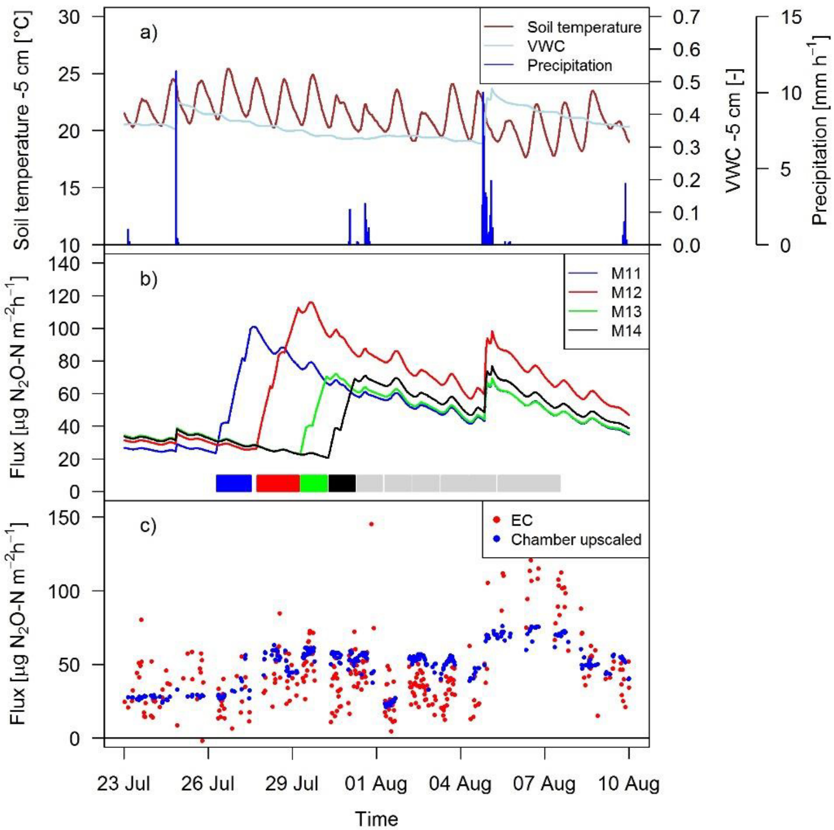

Figure 10: Time series of a) environmental parameters and b) up-scaled FB fluxes (Sect. 2.7) for different paddocks (M11-M14) in system M. The coloured rectangles at the bottom show the grazing phases on the four considered paddocks (grey colours indicating grazing on the remaining paddocks). c) N_2O fluxes by EC and up-scaled FB during a full rotation between 23th September and 10th August 2016 for system M.

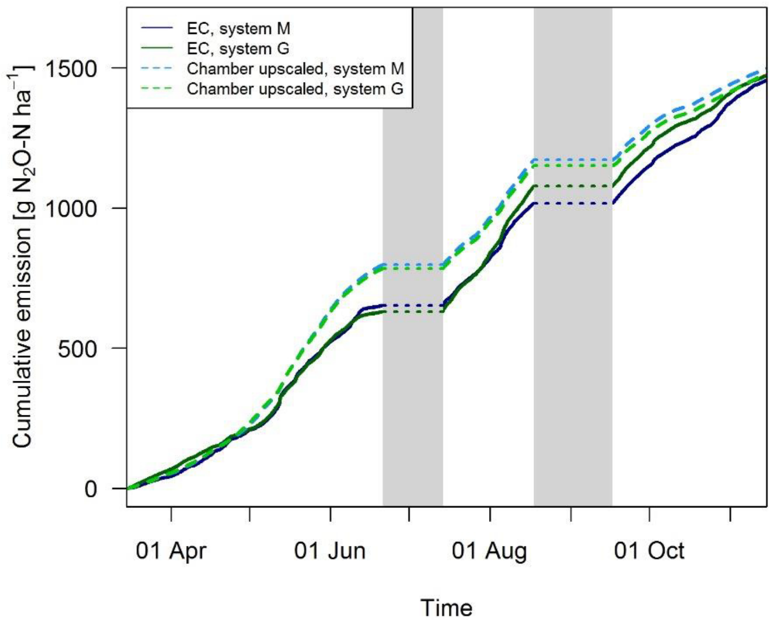

Figure 11: a) Cumulative emissions for both systems obtained with FB and EC technique during GOP 2016. The grey shaded bars indicate time periods which were excluded due to significant overlapping N_2O emissions from fertilization / harvest and grazing (Sect. 2.5, 3.1).

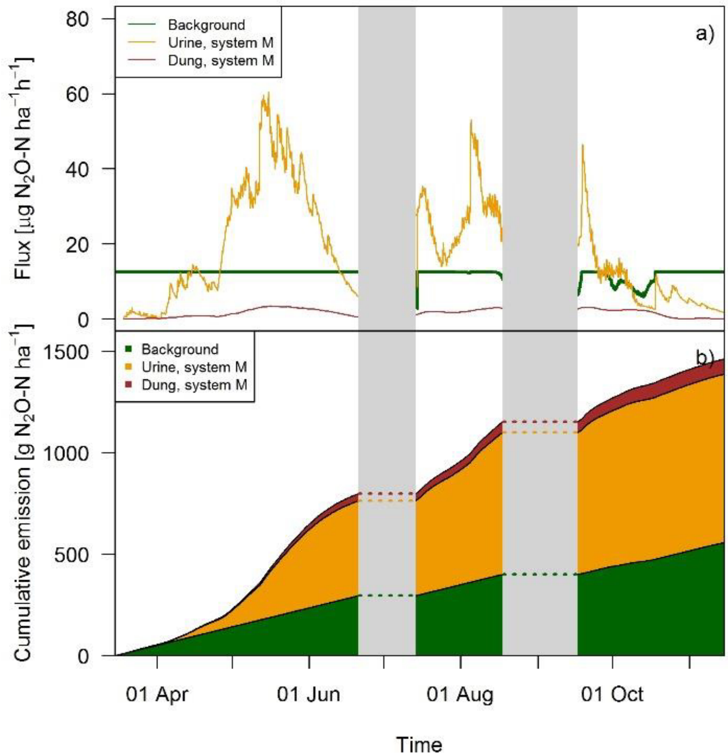

Figure 12: a) Time series of up-scaled FB fluxes averaged over all paddocks of system M for all three emission sources during the grazing season 2016, and b) retrieved cumulative emission contribution of the emission sources to the overall field emission.