Response to the reviewer comments

Dear Dr. Ivonne Trebs, and two reviewers,

Referee #2:
1 General comments

The manuscript of Pihlatie et al. on carbon monoxide (CO) flux measurements above an agricultural bioenergy crop (reed canary grass) represents an important study on the biosphere-atmosphere exchange of CO. While previous studies mainly focused on short term measurements of CO fluxes, the authors present the first eddy covariance measurements of CO fluxes over an entire growing season, making it a unique study. Like this, the authors can investigate the dependency of the CO flux on different environmental parameters such as irradiation, temperature, crop cover, fertilization status, etc. Interestingly, the authors find that the reed canary grass ecosystem acted as a net source of CO at the beginning and a net sink during of the rest of the growing season.

Also, they measured a strong diurnal cycle, as opposed to other previous studies over cropland, with mostly net emission during daytime and net uptake during night. In their study the authors correlate the net CO flux with environmental parameters to obtain an understanding on the controlling processes. As the nature of CO exchange is complex with many possible sinks and sources that have been observed in previous studies, this is challenging. As a consequence, the conclusions made on the underlying processes can often only remain assumptions, and therefore, the study provides only limited new insight into processes of CO exchange. As stated by the authors, further process related studies are necessary for future research.

The authors use state of the art measurement techniques for the quantification of CO fluxes and the fluxes were analyzed according to standard quality control procedures. Furthermore, the manuscript is clearly structured and well written. Due to the unique data set, I suggest the manuscript to be published in BG, after the more specific comments below have been addressed.

We want to sincerely thank the reviewer for constructive comments that help to improve the quality of the manuscript. We have carefully addressed all the comments and responded to them as follows. We acknowledge the concern of risks in process-based interpretations of the results. We hope the corrections will satisfy these concerns and underline the future research needs and gaps in knowledge in this field of research.

2 Specific comments

P. 3, L. 16-20: At which day was the crop cultivated? For completeness, I suggest to add this information to this short description of the growing season.
The crop cultivation date was added to the Materials and Methods section.

P. 4, L. 21-28: In this paragraph it is not clear that these are the same analyzers as used for the flux N2O intercomparison in Rannik et al. (2015). It would be good to state this in this manuscript or move the above sentence “The comparison of four laser-based. . .” to the end of the paragraph.
We modified this chapter so that it better states the same analyzers were used for the flux N2O intercomparison in Rannik et al. (2015). We also give more information of the data collection periods for the two analyzers used in this manuscript, and give reasoning why data from only

one of them is used in correlation analysis of this paper. Please, see also our response to the comment concerning the results section at P. 6, L. 22. In response to this comment, we show the intercomparison of the two analyzers with respect to FCO, and we give this information shortly in the corrected manuscript.

P. 6, L. 4-7: Here it would be interesting to know, what the magnitude of the CO flux loss was, regarding the given response times of the EC systems. In context of the effect of the inlet lines, it would also be beneficial to mention their inner diameters in this section. According to Rannik et al. (2015) the reason for the larger response time of the system was caused by laminar flow due to a larger tubing diameter.

For AR-CW-QCL the 5 and 95 percentile values of flux underestimation were 2.1 and 12.2% and for LGR-CW-QCL 5.7 and 21.4%, respectively. We added the information of the inlet lines (inner diameter and lag time from tube flow).

P. 6, L. 8-10: As stated here, more data had to be removed during daytime than during night-time. However, especially at night-time flux data has to be often rejected due to insufficiently developed turbulence. For this, a flux quality criterion using e.g. integral turbulence characteristics as suggested by Foken and Wichura (1996) is often applied. Also a test on stationarity, which was not applied for the N_2O fluxes in Rannik et al. (2015) for intercomparison reasons, might be important for CO.

We did not perform flux stationarity test. First, a range of tests was applied according to Vickers and Mahrt (1997), which ensure data screening for system malfunctioning as well as physical but unusual behavior, including the non-stationary conditions. Therefore we did not perform an additional test for stationarity according to Foken and Wichura (1996), and we relied on the tests performed. It is the choice of the researcher to choose the test, however, statistically different tests tend to identify the same occasions of measurements, whereas the result depends also on the threshold criteria applied. E.g. Rannik et al. (2003) analysed performance of different tests and concluded that flux tests based on relative errors such as the stationarity test by Foken and Wichura (1996) are not feasible when the fluxes are small and therefore the relative errors becomes large. Therefore, we chose to perform tests on single time series to ensure quality of measurements used in the analysis and not using the flux stationarity test because the CO fluxes are frequently small and respectively with large relative random errors.

Rannik, Ü., Aalto, P., Keronen, P., Vesala, T. and Kulmala, M., 2003. Interpretation of aerosol particle fluxes over a pine forest: Dry deposition and random errors. J. Geophys Res., 108 (D17), pp. AAC 3-1—3-11. DOI: 10.1029/2003JD003542.

P. 6, L. 22: The results chapter presents the measured CO flux and its correlation with various environmental parameters. In addition, I find it important to also present the CO mixing ratios as they can influence the CO flux significantly. Especially, the amount of CO uptake might be largely dependent on the available atmospheric CO. To rule out the effect of changing atmospheric CO levels on the CO flux when interpreting the results, CO mixing ratios should then also be included in the correlation analysis.

We had the atmospheric CO mixing ratio data [CO] in the original correlation analysis, however, as the correlations between daytime [CO] and FCO were very poor ($r<0.2$) and mostly not significant, we did not include [CO] in the table 2. Now we have added [CO] in the Table 2. To assess whether diurnal FCO depends on the diurnal trend in [CO], we performed additional correlation analysis using the half-hourly mean values of FCO and [CO] for each of the six measurement periods (Spring, Early Summer, Mid Summer, Late Summer, Autumn, Late

Autumn). This analysis showed strong significant negative correlation between FCO and [CO] during all other periods except in the spring, also seen in Figure 1 (below). This analysis indicates that CO uptake increases with increasing [CO], and that CO uptake may be limited by [CO] at this site.

It is noteworthy, however, that the variation in [CO] are very small and hence we doubt that this is the sole factor controlling CO uptake. At the same time, the same correlation analysis using the mean diurnal FCO and other measured variables (radiation, sensible heat flux, latent heat flux, soil heat flux, NEE, RESP, soil temperature) produce highly significant and strong correlations between FCO and the measured scalars. This shows that the diurnal FCO is strongly driven by these variables, and that the correlation between FCO and [CO] may result from the dependencies of FCO and its driving variables, not solely on substrate limitation of CO consumption.

At this point, we added the results from this correlation analysis to the text, and we included new discussion on the effect of variation in [CO] on FCO. We also consider adding a new table presenting the correlation analysis between the mean diurnal FCO and all other measured variables.

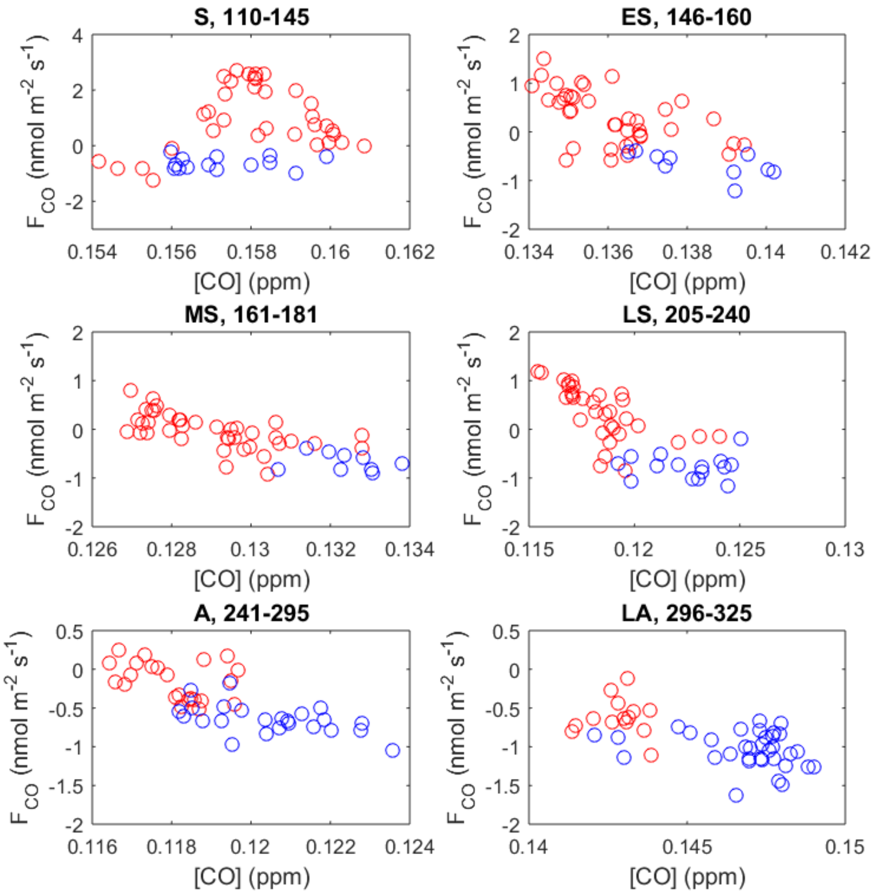

Figure 1. Dependency of FCO on the mixing ratio of CO [CO] during mean diurnal cycle from the six measurement periods from April to November 2011 at the reed canary grass crop. Values marked in red denote for daytime and values in blue denote for night-time data.

P. 6, L. 22: As it was mentioned in the method section, two different instruments for the CO flux measurements were used. However, in the result section the data from both analyzers is only shown as the cumulative flux in Figure 1f. If two independent analyzer are used, I would expect a paragraph or statement on the comparability of both measurements. This would give a better insight into the associated flux errors and would be also be valuable information for the CO flux community. Looking at the cumulative flux estimates, there seems to be a good agreement between days 205-270, while after that both fluxes seem to differ. Also, it should be stated in the manuscript that the presented fluxes (despite the green cumulative curve) are from the AR-CWQCL instrument while the LGR-CWQCL instrument was only operated from day 205.

We agree that it would benefit the scientific community to show the intercomparison data of these two gas analyzers. For the period when both AR-CWQCL and LGR-CWQCL were measuring FCO, we made plots showing the FCO measured by LGR-CWQCL against the FCO measured by AR-CWQCL (Figure 2). Also, we plotted the time series of half-hourly mean FCO and the daily mean FCO from both analyzers (Figure 3). This comparison shows considerable agreement between the analyzers with a slope of 0.96 and correlation coefficient of 0.95. The comparison shows that LGR-CWQCL shows slightly (4%) smaller fluxes compared to AR-CWQCL. The difference between the analyzers, however, is very small, giving us confidence in the use of either of the analyzer in further analysis. We have added a chapter in the results section describing the intercomparison of the two analyzers, however, we think it is unnecessary to show a figure from this comparison.

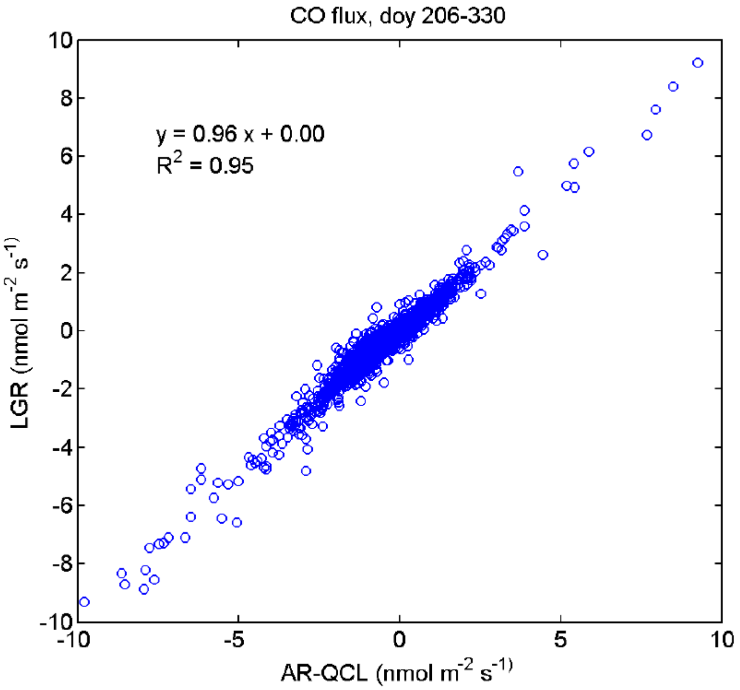

Figure 2. Comparison of FCO measured by LGR-CWQCL (LGR) against the FCO measured by AR-CWQCL (AR-QCL) over the period days 206-330 at the reed canary grass crop.

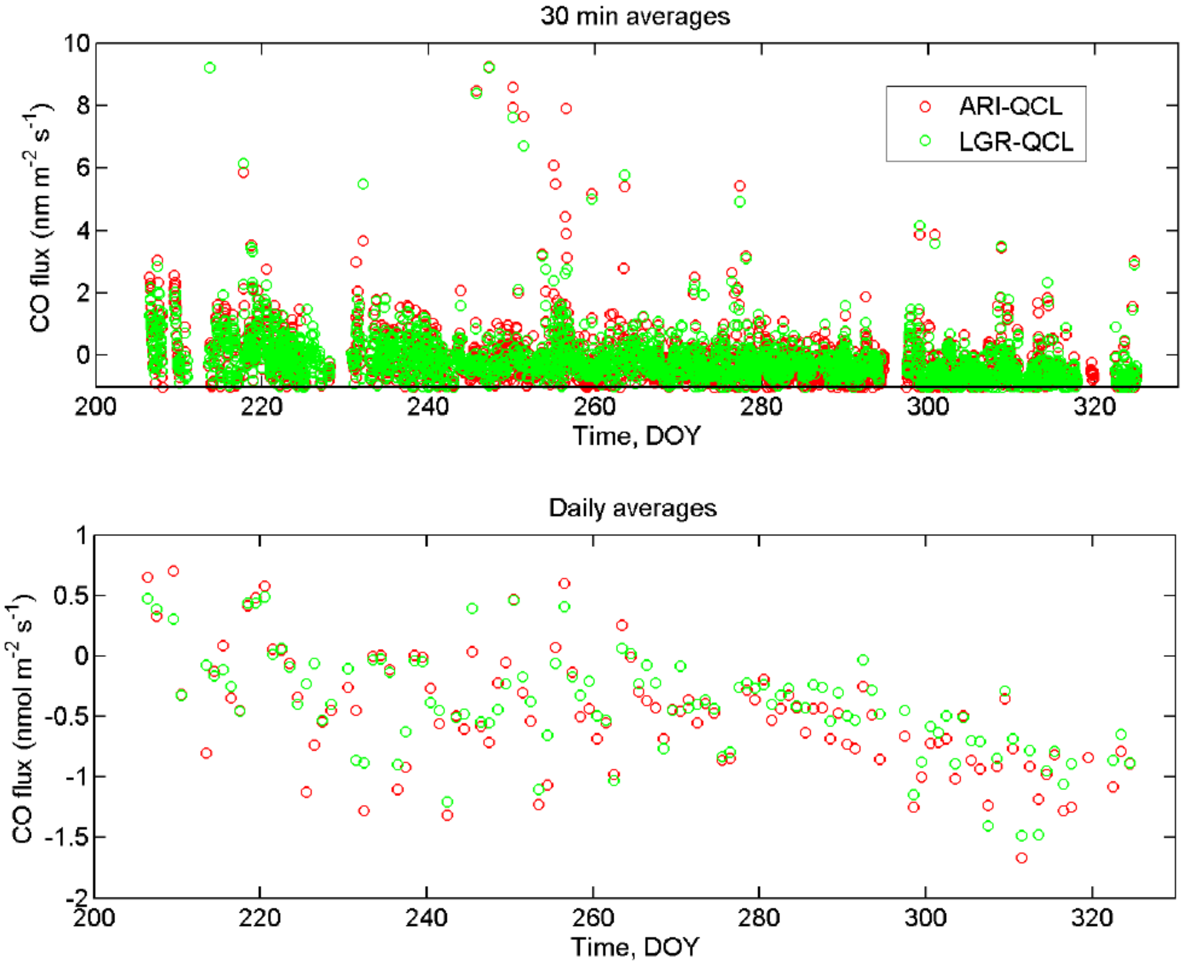

Figure 3. Half-hourly mean FCO and daily mean FCO measured by AR-CWQCL (ARI-QCL) and LGR-CWQCL (LGR-QCL) during the period of days 206-330.

P. 9, L. 11-13: To correct for this bias, a gap-filling method can be applied for the calculation of cumulative CO fluxes.

We used a simple statistical gap-filling method to test how this would affect the cumulative FCO over the whole measurement season (Figure 4). The gap-filling was performed by choosing randomly the unique missing values from within time-window +- 5 days, by differentiating days and nights (according to elevation of sun). This simple gap-filling was performed for days excluding those which had no single measurements available. Hence, the gap-filling method removes possible bias due to different fraction of missing during day- and night-time. However, it does not guarantee correct cumulative sum because days with no data were not gap-filled including the measurement break. We hesitated to gap-fill the periods when no data was available due to the relatively poor correlations between the measured variables and FCO, especially during summer period (days 181-205).

The gap-filling exercise in Figure 4 shows that the emission period in the spring and in late summer is strengthened due to the even contribution of daytime and night-time data, which in this case includes a higher number of positive FCO. Similarly, the gap-filling leads to strengthened CO uptake in the autumn indicating that a higher number of night-time data was missing from that period. Overall, the cumulative curve of the original data and the gap-filled FCO result in very similar CO uptake rate after the 7-months of measurements. At this point, we hesitate to include the gap-filled data in the manuscript as it does not change the interpretation of the results. Still, we are happy to include the data if the reviewers/Editor see this as an informative and important part of the manuscript.

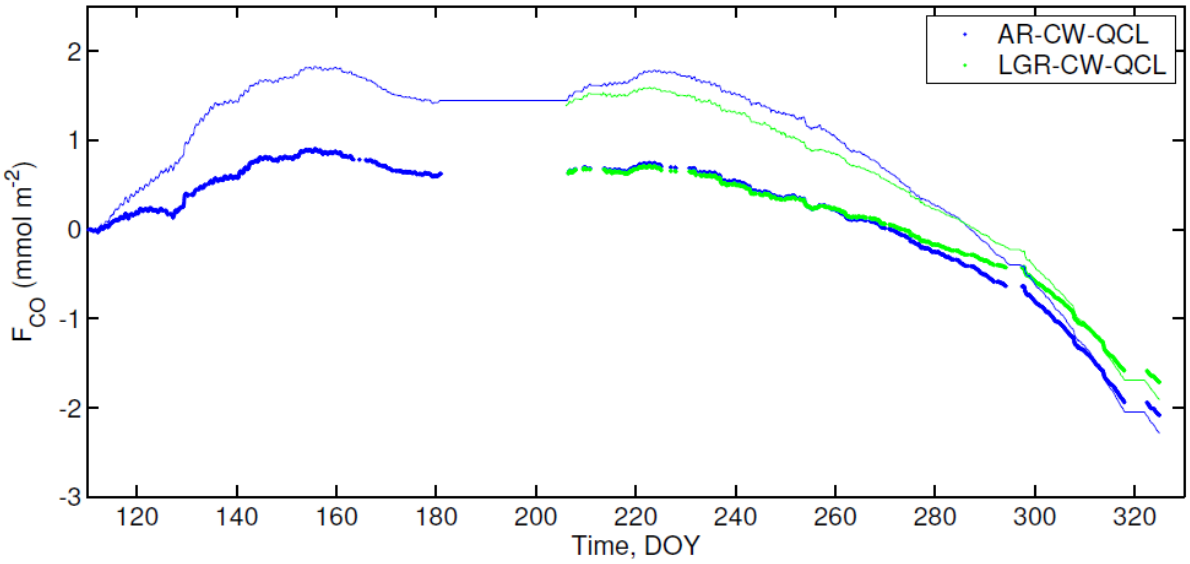

Figure 4. Cumulative FCO calculated from the measured data (bold lines) and gap-filled data (thin lines).

P. 7, L. 19-21: As stated, the concept of the gross FCO only holds if the CO uptake can be assumed to be constant over the entire diurnal cycle. However, especially turbulent transport and transport through the quasi-laminar boundary layer at the surface typically show distinct diurnal cycles with maxima during daytime. Hence, I would expect the CO uptake to increase during the day, unless the CO uptake is limited mainly by soil microbial consumption or transport in soil (then, the CO flux would also mainly be independent from above surface CO-concentrations, which would change during day). Is there more evidence that can support the assumption of a constant CO uptake? The authors note that there is evidence from previous studies that the temperature effect on microbial consumption can be assumed to be small. In my opinion it should also be shown that the CO uptake is mainly limited by soil microbial consumption or transport in soil for the assumption of a constant CO uptake to be valid. Otherwise, the diurnal variation in the aerodynamic and the quasi-laminar boundary layer resistances would have to be taken into account. In general, the use of a bi-directional exchange model would be useful to address the issue of flux partitioning and importance of soil uptake, although I understand that this is challenging given the lack of detailed process studies on CO exchange and might be the scope of future research.

We agree that the use of the assumption of constant CO uptake may have been wrong. This was pointed out also by the referee #1, who suggested to use reported temperature dependencies of CO uptake from e.g. Whalen and Reeburgh (2001). As suggested, we used a Q10 value of 1.8 (Whalen and Reeburgh, 2001) to calculate the daytime CO uptake from the night-time CO fluxes over the six distinct measurement period. This allowed us to recalculate the gross CO emissions during daytime. Assuming this temperature dependency, the CO uptake was up to 2 times higher during day than during night. As the net daytime FCO remained positive during the spring, early summer and late summer, we expect that also CO emissions must have increased during the day. In a new table (Table 2), we report the daytime and night-time soil temperatures, the temperature difference between day and night, which is used for calculating the temperature dependent CO uptake during daytime, and the consequent gross CO emissions.

Based on the correlation analysis between FCO and [CO] we also found that the CO uptake seem to increase with increasing [CO] (see comment above). This indicates that the microbial CO consumption may be substrate limited during daytime, when the [CO] is slightly lower than in the night. This furthermore, may decrease the CO uptake during daytime, possibly and partly eliminating the increase in CO consumption due to increased daytime temperatures. It is not possible to differentiate between the microbial CO consumption and the physical substrate limitation, however, we acknowledge these mechanisms, and we added discussion of them to the text.

P. 8, L. 8-16: What was the applied definition for daytime and night-time periods? This is valuable information, as the correlation values are often largely dependent on the variation of the used parameters, which are typically larger during daytime. In this context, it might be also valuable to mention if the flux error had an impact on the weak correlations found during night-time.
Since random uncertainty of flux estimates is inherent property of the eddy covariance method, the correlations can be affected by these errors. Day- and night-time fluxes differed significantly in magnitude only during the first sub-period of the campaign, doy 110-145, see Fig. 2, therefore we can expect that night-time correlation values were affected by the random flux errors more than the day-time values only during the first period. We added the definition of daytime and night-time periods in the text by stating that we used sun elevation angle (h<0 for night-time, h>0 for daytime) to separate between daytime and night-time data.

P. 9, L. 11-13: To correct for this bias, a gap-filling method can be applied for the calculation of cumulative CO fluxes.
As explained above, we tested a use of gap-filling for missing data to estimate the effect of uneven data removal during daytime and night-time. This gap-filling indicates that the real FCO are more positive during the spring and summer compared to the actual quality screened data, which removes more data during daytime than during night-time. The cumulative gap-filled FCO curve (above) shows that both the emission period in the spring and the uptake period in the late summer and autumn may be more pronounced than that of the data without gap-filling. The resulting net cumulative FCO over the whole measurement period, however, seems to be very similar with or without gap-filling (see above).

P. 9, L. 14-15: As FCO describes the net CO flux, one should differentiate here more explicitly between the emission component and uptake component of the flux. Otherwise the reader may assume you are referring to the net emission/uptake.

3 Technical comments

P. 3, L. 4: Write “reed canary grass” instead of “read canary grass”. Correct also on P. 13, L. 9 and 19, L. 1.
Corrected.

P. 3, L. 13: Omit space after “27◦” or introduce after all units (◦, ‘, “). Use same degree sign as used in L. 15.
Corrected.

P. 3, L. 17: Use superscript for “-1” in “ha-1”.
Corrected.

P. 4, L. 10: Shouldn’t it be “L=+-100 m” for the definition of the near-neutral range?
We used L = -100 m as the simulation case for neutral stratification. Since the absolute value of this L is much larger than the measurement height, the neutral stability assumption for this case is well justified.

P. 4, L. 16: Insert space before “Considering”.
Corrected.

P. 4, L. 26: Write “LGR-CWQCL” instead of “LGRCW-QCL” as in the rest of the manuscript.
Corrected. And in fact, we chose to use the abbreviation LGR-CW-QCL as in Rannik et al. (2015).

P. 6, L. 1: Do you intentionally differentiate between “co-variances” (here and L. 5) and “covariance”?
We did not intend to use “co-variances” but rather “covariance”. This is now corrected.

P. 6, L. 10: Write “daytime” instead of “day-time” as in the rest of the manuscript. Correct also on P. 7, L. 15 and on P. 9, L. 24.
Corrected.

P. 6, L. 27: I suggest using “over the 9-month measurement period” instead of “in the end of the 9-month measurement period” as the used expression could be misleading otherwise.
Corrected.

P. 7, L. 17: Use superscript in units.
Corrected.

Figures 2-5: Instead of using the day of year numbers, I suggest to use the introduced classification of S, ES, MS . . . in the subplot titles (or use both, DOY + the classification). This makes it easier to compare with Figure 1 and descriptions in the text.
We modified the figures 2-5, and a new figure 6 to include the classification of S, ES, MS… + DOY (e.g. S, 110-145), similar to that presented in Table 1.

4 References

Foken, T. and Wichura, B.: Tools for quality assessment of surface-based flux measurements, Agric. For. Meteorol., 78(1-2), 83–105, doi:10.1016/0168-1923(95)02248-1, 1996.

Rannik, Haapanala, S., Shurpali, N. J., Mammarella, I., Lind, S., Hyvönen, N., Peltola, O., Zahniser, M., Martikainen, P. J. and Vesala, T.: Intercomparison of fast response commercial gas analysers for nitrous oxide flux measurements under field conditions, Biogeosciences, 12(2), 415–432, doi:10.5194/bg-12-415-2015, 2015.