Author Comments – Response to Referee 1

Referee comments are marked in black and author responses are marked in blue.

General comments:
This is a well-written paper that reports on 2 decades of CO_2 exchange measurements at an intensively managed grassland in Switzerland with the aim of disentangling the influence of management amidst variable environmental conditions and ongoing climate change. The paper builds up on Feigenwinter et al. (2023) who analyzed the first 16 years, here the focus is more on the analysis of the drivers using a machine learning approach. I think the manuscript is ready for publication following some minor changes, detailed below.

Dear Dr. Wohlfahrt,
Thank you for your positive comments! We appreciate the opportunity to improve the manuscript based on your constructive feedback. We have addressed your comments and suggestions in the responses below.

There are however two terminology issues that I struggle with and ask the authors to consider:

- The authors analyze what they refer to as regrowth periods in between management events, especially harvesting. What I struggle with is the terminology "GPP/RECO regrowth rates" which the authors use to refer to the GPP/RECO during the regrowth periods. The terminology to me however suggests GPP/RECO "to regrow", i.e. rebound, during these periods, which may not be the case. In fact, the negative SHAP values for days since last management and GPP suggest a negative relationship. I think the authors could simply say something like GPP/RECO during regrowth periods, which may be a little awkward at times, but less ambiguous.

Thank you for pointing out this ambiguity. We will change the term to "GPP or Reco during regrowth periods" throughout the text. For each regrowth period, cumulative GPP and Reco were first calculated and then averaged based on the length of the regrowth period.

Moreover, taken together with the comments from Referee 2, to put more emphasis on "regrowth periods" instead of just "regrowth", we will also modify the title of the manuscript as "Drivers of long-term grassland CO_2 fluxes: effects of management and meteorological conditions during regrowth periods".

- The authors suggest, e.g. in the abstract but also elsewhere, that the fact that there was no trend in CO_2 exchange over the two decades despite ongoing climate change shows that the farmers are using a climate-smart management. This statement to me implies that the management is deemed climate-smart as it prevented a decrease in the CO_2 sink strength. This ignores the possibility that an alternative (truly climate-smart?) management could have profited from ongoing climate change and increased the sink strength. Neither option (a decrease or increase in sink strength was prevented by the actual management) can be answered with the present data that are conditional on the actual management. This would need a manipulative experiment (with alternative management like in Ammann et al. 2007) or the use of some model which represents management and the resulting consequences on CO_2 fluxes (which would be an intriguing follow-up). I thus suggest to down-tune the climate-smart aspect and rather leave it with saying that the adaptive management that the farmer practiced in response to interannual and intra-seasonal variability in weather conditions apparently was able to keep CO_2 exchange stable in the face of ongoing climate change during the two decades of observations.

We appreciate this input. 'Climate-smart' agriculture (CSA) includes a set of practices and technologies that improve productivity, while enhancing resilience and reducing GHG emissions during on-going climate change (FAO, 2019; World Bank, 2024). The FAO defines CSA as "an approach that helps guide actions to transform agri-food systems towards green and climate resilient practices". Similarly, the World Bank defines CSA as "an integrated approach to managing landscapes—cropland, livestock, forests and fisheries—that address the interlinked challenges of food security and climate change.". Science communities have been using this term as well since long (e.g., Lipper et al., 2014; Walter et al., 2017). We will include this context in the introduction.

With more frequent extreme events in recent years that were observed in our time series, we would expect a decreasing trend in GPP during regrowth periods and ultimately a decrease in CO_2 sink strength. In contrast, the non-significant trend detected in our GPP data shows that the existing management practices were able to maintain productivity, thus suggesting resilience to extreme events which is considered 'climate-smart'. Meanwhile, we also agree that more "climate-smart" management practices aiming to improve resilience and sustainability or even increase productivity of agroecosystems under ongoing climate change – albeit in the absence of extreme events, have to be tested with experiments or certain models, for example to see the effect of the timing and intensity of certain management practices on productivity and GHG emissions. We indeed have ongoing work in the group using the process-based model MONICA (Nendel et al., 2011) on this exact topic (Kamali et al., submitted). With all these considerations in mind, we will put our argumentation in context and explain this aspect better throughout the manuscript.

Detailed comments:

1. l. 8: the temporal development of management practices and meteorological conditions is uncertain? Aren't the interactive effects of these on grassland CO_2 fluxes uncertain?

We argue that both the temporal development of the drivers themselves and their impact/effects are uncertain. We will rephase this sentence into "… CO_2 fluxes of managed grasslands are substantially influenced by land management practices and meteorological conditions, but the temporal development of drivers and their effects are still uncertain".

2. l. 9-10: this sentence could be removed in the abstract without loss of information

We wanted to introduce the terms of NEE, GPP, and Reco in the very beginning, but we also introduced these terms again in the introduction. We will delete this sentence as suggested and introduce the abbreviations when they are first mentioned in the abstract.

3. l. 42: GPP and RECO are the essential part of C cycling of any ecosystem

Agreed. We will change the sentence into "As an essential part of ecosystem C cycles…".

4. l. 71: in my view Wohlfahrt et al. (2008, 10.1029/2007JD009286) were one of the first grassland papers to look into the interactive effects of management and environmental drivers and in fact also analyzed data in periods stratified by management (harvesting) events

Thank you for the comment. We were aware of this study and cited it later in the discussion. Here we focused on “long-term studies”, but we will mention this 6-year study in the introduction as well.

5. l. 130: what about the self-heating correction of the Li-7500 – I guess at least during the early phase of the time series the used models required this correction? In addition, the early Li-7500 models had some intrinsic lag of the digital signals that could be increased on the software side to result in a lag that is some multiple of the sampling rate in order to be removed – what lag value was set – 0.3 s?

Regarding self-heating: No self-heating correction was applied to open-path LI-7500 fluxes. There are several reasons for this decision:

(1) We found that the current standard self-heating correction (Burba et al., 2008) produced unsatisfactory and unreliable results at multiple Swiss FluxNet sites. Comparative analysis using parallel (en-)closed path measurements (LI-7200 vs. LI-7500) at these sites revealed significant, conflicting biases depending on the dataset (e.g., strong underestimation or overestimation of NEE, as detailed in Figures R1-1 and R1-2, respectively). Our observations, demonstrating that the standard correction can lead to fluxes substantially deviating from the "true" flux, are consistent with similar findings by Wohlfahrt et al. (2008, their Fig. 3), who utilized an earlier correction version (Burba et al., 2006). Furthermore, we note that the Burba et al. (2008) correction was derived from a limited dataset, validated specifically for vertically mounted IRGAs, and does not account for the non-vertical (15° tilted) installation geometry of the LI-7500 at our site.

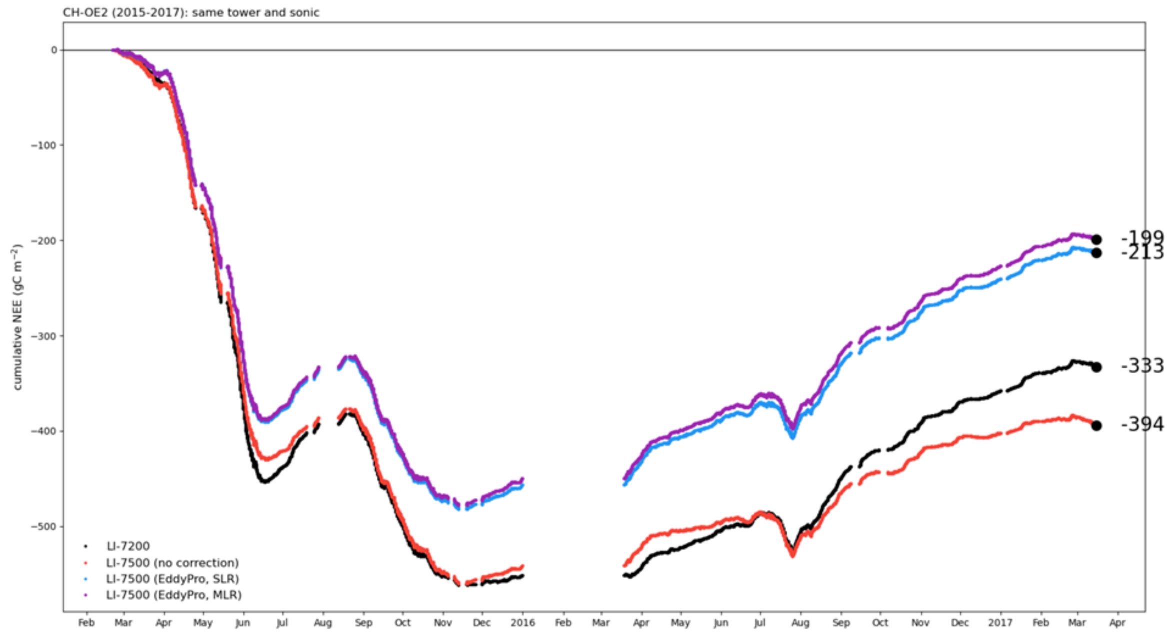

Figure R1-1. Cumulative NEE fluxes from Feb 2015 until Apr 2017 at the cropland site CH-OE2. Shown is a comparison of self-heating correction approaches: open-path LI-7500 fluxes (only WPL corrected, red) with enclosed-path LI-7200 fluxes (black, assumed to show the “true” flux). Also shown are cumulative fluxes after applying the Burba et al. (2008) correction as implemented in EddyPro using the single linear regression method (SLR, blue) and the multiple regression method (MLR, purple).

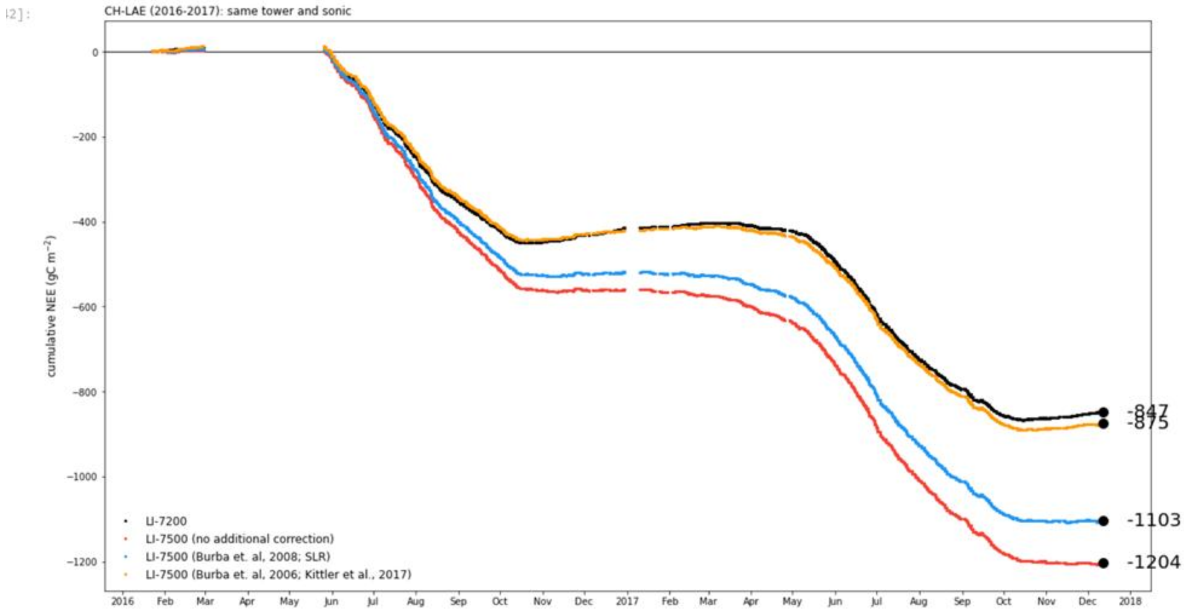

Figure R1-2. Cumulative NEE between Jan 2016 and Dec 2017 at the forest site CH-LAE. “True” flux from LI-7200 (black), no self-heating correction for LI-7500 fluxes (red), after correction in EddyPro Burba 2008 (blue) and after correction Kittler 2017 (orange).

(2) The absence of concurrent validation data from a co-located (en-)closed path IRGA, such as the LI-7200, introduces a significant methodological uncertainty when applying the self-heating correction. Without these parallel measurements, we cannot independently validate the corrected fluxes, creating an unverified "black box" scenario. This black box application of any available correction poses a substantial risk to data quality, a concern echoed by Deventer et al. (2021). They highlighted that utilizing current self-heating corrections without parallel reference flux measurements "[...] yields uncertainties that are larger than random flux errors - substantially degrading confidence in ecosystem carbon [...] budgets", underscoring the necessity of empirical validation.

(3) For forest sites in the Swiss FluxNet, we apply the correction described in Burba et al. (2006), with the modification that we also apply a scaling term ξ to account for the tilted angle of the LI-7500 (similar to Kittler et al., 2017; see orange line in Figure R1-2). The scaling term is site-specific and must therefore be determined empirically from parallel measurements. We have tried to generalize ξ, based on data from other non-forest sites (grassland, cropland), and found that ξ can be complex with variations over the course of one day and differences between daytime and nighttime data. We concluded that the correction is not possible without parallel measurements.

(4) We are cautiously optimistic that the self-heating effect at this site is small. In July 2025, we started parallel measurements at CH-CHA. We found a mean difference of approx. 3% between the LI-7500 and LI-7200 fluxes, with the open-path showing slightly more uptake (Figure R1-3). The main difference was found during a time period characterized by high temperatures >= 32°C at the end of July 2025. However, during the preceding weeks in July, NEE from the two IRGAs were virtually identical. We are aware that the correction was originally meant for colder climate conditions, in particular with air temperatures < -10°, but we currently have no winter LI-7200 data from CH-CHA. In a comparison of parallel measurements during winter for a high-altitude alpine grassland (CH-AWS, about 2000 m a.s..l.) with a comparable setup, we found that the self-heating effect was small, similar to Haslwanter et al. (2009). Parallel measurements at CH-CHA will continue, and we will investigate more data once available.

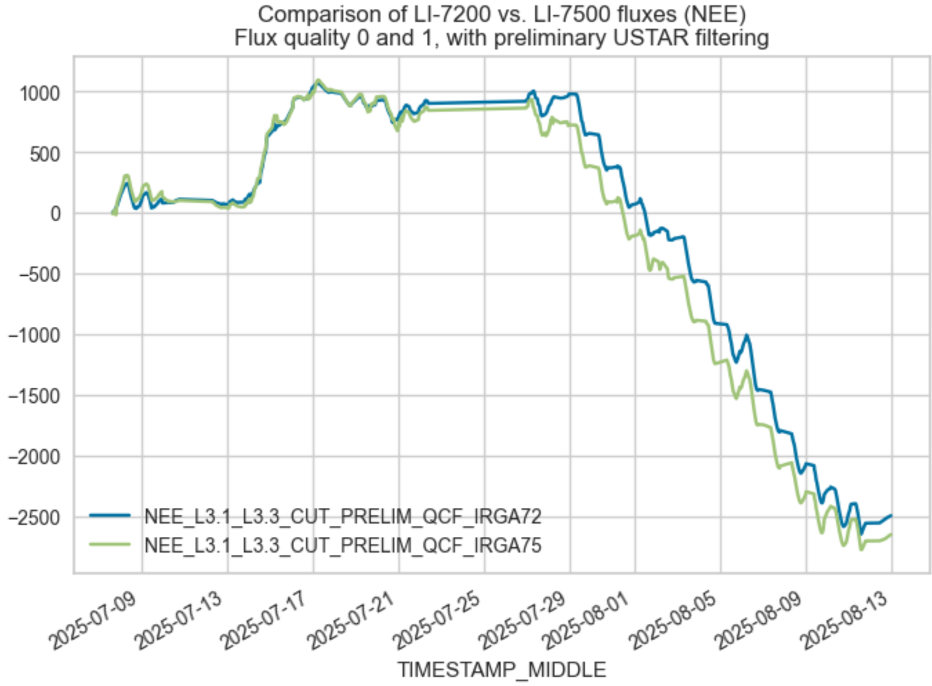

Figure R1-3. Cumulative, directly-measured (not gap-filled) NEE fluxes measured at the grassland CH-CHA in 2025. Fluxes were measured with an open-path LI-7500 (IRGA75, green) and (en-)closed path LI-7500 (IRGA72, blue).

We will add more details in the Methods on this aspect.

Regarding intrinsic lag: All raw data coming from the sonic and IRGA were directly logged using the custom made, real-time logging software *sonicread* (concept described in Eugster and Plüss, 2010), circumventing the LICOR software to store data. Found time lags for the LI-7500 CO_2 and H_2O signals were between 0.20 s and 0.35s throughout all years. We detected the time lags on a yearly basis and collected results from a detailed analysis (results available online: https://holukas.github.io/dataset_ch-cha_flux_product/L0.html#openlag-runs-to-determine-final-lag-ranges).

6. l. 135: which approach for flux partitioning was used – day or nighttime?

The nighttime partitioning method was used. We mentioned this in the next paragraph (line 143 in the original manuscript). We will add this info earlier in a revised version of the manuscript.

7. Fig. 1e: given the length of the time series I feel a bit overwhelmed with the day-to-day variability and thus I suggest showing CO_2 fluxes on a monthly timescale, possibly as a stacked bar chart that might nicely visualize the interplay between GPP and RECO on NEE

Thank you for this comment. We presented daily fluxes to show the basis of our analysis. Since this site is being intensively managed, common aggregation methods (e.g., monthly mean/sum or weekly mean/sum) do not represent this complex situation and information about management will – in the best case – be lost, or – in the worst case – bias the results during any longer aggregation. Therefore, we prefer to keep Figure1e as is. In Figure 3, we actually already show GPP and Reco aggregated for on the regrowth periods.

8. Fig. 1: would it possible to add an additional panel that shows the cutting events, grazing periods and re-sowing events?

Thank you for the suggestion. The original Figure A2 was meant to present all management information in detail. Given the width of the figures and the frequency of the management events within each year, putting all these events as an additional, sixth panel would make the figure very crowded. However, we received further comments from colleagues supporting the wish to not "hide" this management info in the appendix, since such info is typically very rare in such detail. In a revised version of the manuscript, we will thus move Figure A2 to the main text as a panel in Figure 3 (see below, comment 10).

9. Table 1: is huge but conveys limited information and might thus go into the supplement?

Agreed. We will move this table to the appendix as Table A2.

10. Fig. 3: I suggest adding Fig. A2 as a third panel here; overall the information content of this figure is limited - GPP/RECO is smaller during the off-season period with short days and larger during the warm period with long days

Thank you for this comment. We will combine the original Figure A2 with the GPP and Reco panels as a new Figure 3 as shown below (also answering to comment 8 above).

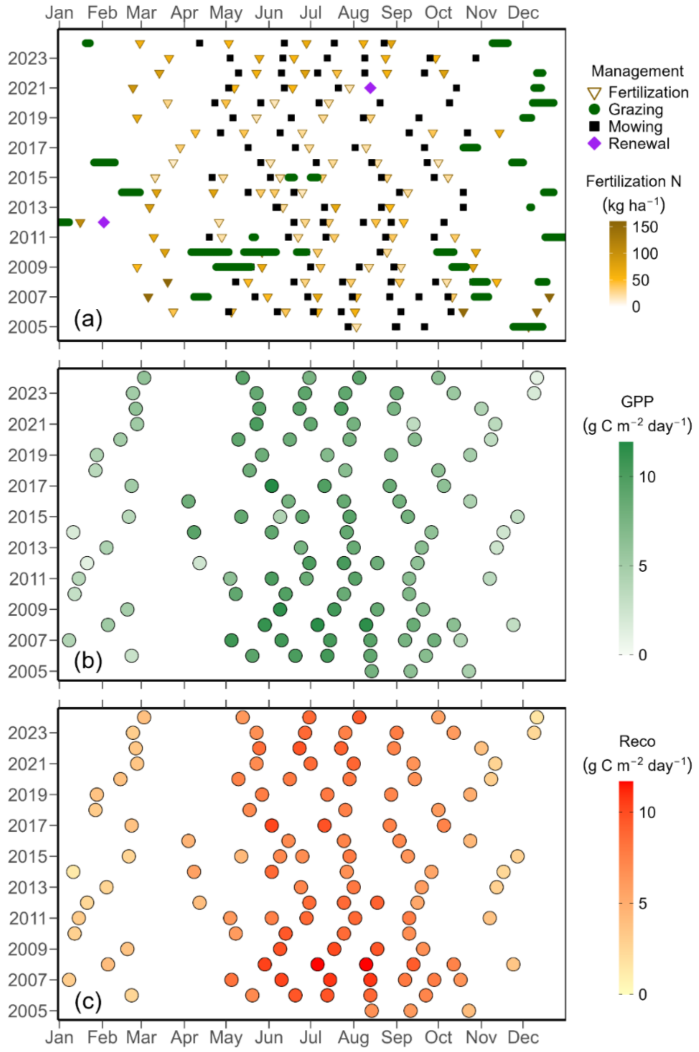

Figure R1-4. New Figure 3 for the revised manuscript

11. l. 270: DaysSinceUse shows negative SHAP values for GPP – correct? Does that mean that GPP declines the more time has passed since the start of the regrowth period? If so, might be worthing spelling this out

Thank you for the question. Indeed, DaySinceUse shows negative SHAP values for GPP in Figure 4 (based on SHAP analysis 1). Since the bars presented in Figure 4 are based on average SHAP values from each regrowth period, they represent the average effect of this variable on GPP, always compared to the grand mean or mean prediction of all GPP for all 115 regrowth periods. On the daily scale (Figure R1-5 below), SHAP values for DaySinceUse are normally very negative directly after moving/grazing (DaySinceUse < around 10 days) and then increase. This correctly reflects the effect of mowing/grazing: the more days since use, the higher GPP since the grassland could regrow, i.e., the more days since use, the larger the SHAP value for this driver, compared to the mean prediction (as explained in the figure caption). To avoid such confusion, we will add the partial dependence plot of DaySinceUse and its SHAP value in the appendix as part of new Figure A3. We will also add a sentence in Section 3.1 at current line 271: "When averaged over the entire regrowth period, SHAP values of management events (i.e., mowing and grazing, represented by DaysSinceUse) on GPP were often negative (Fig. 4a). However, at daily scale (Fig. A3c), SHAP values for DaySinceUse were first negative and then steadily increased before staying stable after around 20 days, indicating that GPP increased the more time had passed since the last management event.".

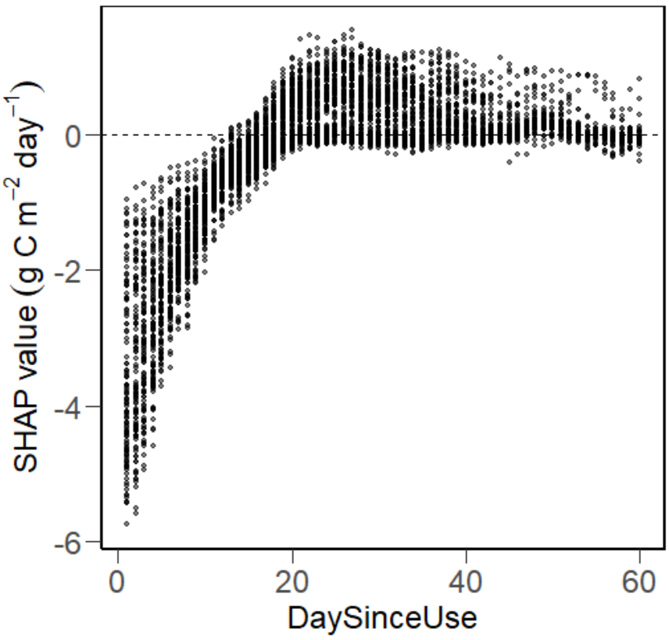

Figure R1-5. SHAP dependence plot for DaySinceUse of GPP (zoomed in to the first 60 days after management)

12. l. 311: these significant differences are not visible from Fig. 6b-c

Thanks for pointing this out. This significant difference is more obvious in Figure 2. with higher VPD and lower SWC on a monthly scale. We will change the sentence into "Focusing on years with more extreme summer months (i.e., July and August of 2018, July of 2019, July of 2022, and June of 2023; Fig. 2), we found normal daily PPFD (Fig. 6a), but significantly higher-than-normal daily temperature and VPD, accompanied by lower-than-normal soil water content (Fig. 6bc). Mean monthly air temperature in July 2018, 2019, 2022 was 1.2, 1.2, and 1.1 °C above the 20-year monthly average (19.6 °C) respectively, while 1.8 °C higher in August 2018 compared to 20-year monthly average (18.6 °C). All extreme summer months had SWC more than 10% lower than the 20-year monthly averages.”.

13. l. 372-377: these data should be first introduced in the Results section

Thank you for the suggestion. We mentioned these cumulative NEE numbers already in Section 3.1 (lines 230-233 in the original manuscript). We will add the numbers for renewal years to current line 232 as “… (Fig. A1). In 2012 and 2021 two grassland renewal events (i.e., ploughing and reseeding of the grassland) took place, with very different effects on annual NEE: while the event in 2012 led to a strong net CO_2 loss (cumulative NEE of 139 g C m^{-2} yr^{-1}; Fig. A1), the event in 2021 resulted only in a weaker-than-normal net CO_2 uptake (cumulative NEE of -163 g C m^{-2} yr^{-1}; Fig. A1). All three flux components…”. We will reformulate the discussion at current line 372 as “… such events. The observed differences in annual NEE during the two renewal events at the Chamau grassland (139 vs. -163 g C m^{-2} yr^{-1} for 2012 and 2021, respectively; Fig. A1) might be explained by differences in seasons (February 2012 versus August 2021) and soil disturbance intensities (ploughed at 20 cm in 2012 and 3-4 cm in 2021), which subsequently influenced the establishment and regrowth of the new sward. Other …”

14. l. 471: … in C cycle model simulations …

Thank you for the comment. We will change the sentence to “… creating large uncertainties in C cycle model simulations at all scales”.

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