

Uncertainty in Land Carbon Fluxes Simulated by CMIP6 Models from Treatments of Crop Distributions and Photosynthetic Pathways.

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We are grateful to the referees for their comments and suggestions, which we have used to improve the manuscript. Below we describe the modifications we have made to the manuscript in response to the comments.

Responses to Referees

Referee 1 Major Comments and Responses

Comment 1

For models lacking explicit C₃/C₄ crop fractions, authors used $\text{cropFrac} \times \text{c3PftFrac}$ or $\text{cropFrac} \times \text{c4PftFrac}$ to obtain the values. This can propagate large biases into estimates of C₃/C₄ crop area. For example, in a grid with 90% C₃ tree and 10% C₄ crop, you'll get C₃ crop = 0.09 and C₄ crop = 0.01, which is totally wrong. Although the authors already acknowledged this issue, this process was problematic and largely influenced the reliability of the findings.

Response to Comment 1

This is a good point. To evaluate biases in the estimated values of C₃ and C₄ crops obtained from $\text{cropFrac} \times \text{c3PftFrac}$ and $\text{cropFrac} \times \text{c4PftFrac}$ in the models where this was applied (CESM2, CESM2-WACCM, CNRM-ESM2-1 and CNRM-CM6.1) we conducted a reliability analysis. We determined the similarity between the calculated distribution of C₃ and C₄ crops and LUH2 distribution using kernel density estimates (KDE) (Silverman 1986, Chen 2017) and spatial probability distributions (Chiang et al., 2021). We also visually compared the spatial distribution of these values to the LUH2, UKESM1 and MPI-ESM-1-2-HAM - two models that provided their C₃ and C₄ crop fractions to check if they are consistent. Our results show that the values obtained from the calculation are not inconsistent with other models and LUH2 in terms of magnitude, range and spatial distribution. The results are added to the supplement in Figures S11-S17. We added a description of these results to the main text in section 2.2.

Given the variables available in the CMIP archive, we had to make the calculation $\text{cropFrac} \times \text{c3PftFrac}$ or $\text{cropFrac} \times \text{c4PftFrac}$ to enable us to do a comprehensive model intercomparison. We have added a note to the discussion that models' reporting of their C₃ and C₄ crop fractions (cropFracC3 and cropFracC4) would allow for more robust analysis of the role of croplands in carbon flux simulation and the differences in the photosynthetic pathways.

Comment 2

Also, attributing C₃/C₄ GPP using the product of total GPP with C₃/C₄ fractions is problematic. Although the authors noted this overestimated C₃ GPP, the issue was broader and could influence all subsequent analyses, e.g., range of C₄ GPP (12–27% in Fig. 5i).

Response to Comment 2

We agree with the referee that the analysis would be improved with specific information on C₃/C₄ GPP from the models. However, we could only make use of the variables made available by the modelling groups, and this information was unfortunately not available.

We noted that the calculations may overestimate the proportion of GPP assigned to C₃ vegetation, based on the findings of Luo et al. 2024. However, in the absence of full information, our approach should provide a reasonable approximation – because in pixels where plants with both pathways co-occur, the differences in GPP between C₃ and C₄ components will generally not be large due to the extra cost invested by C₄ vegetation in the CO₂ concentrating process (Still et al, 2000, Ehleringer and Bjorkman 1976, and Ehleringer 1978). Nonetheless, it is unfortunate that the modelling groups did not provide enough information for us to do a more exact analysis. We suggest that the GPP and Cveg of C₃ and C₄ vegetation should be explicitly reported in future.. This relationship will likely become even less straightforward when scaled beyond the canopy level.

Comment 3

Section 3.3 states “The increase in GPP in crops is linked to the area increase, while the GPP change in natural vegetation is decoupled from the change in area”. This is an interesting point, but I did not see any evidence supporting this statement.

Response to Comment 3

We have revised the manuscript to make the evidence for this point clearer.

If you look at Figure 4 (a) for instance, total crop area increased by 200 % compared to Figure 4 (b), in which natural vegetation on average decreased by 7 %. Then compare the changes in the vegetation area in the above figures to the change in the GPP in Figure 5 (a) and (b). Total crop GPP increased by 209% on average, however, for CNRM-CM6.1 with a temporally fixed vegetation cover, the increase in GPP is only 18 %. For natural vegetation, even though there is a mean 7 % decrease in total natural vegetation cover, we see on average ~18 % increase in GPP. This increase is likely mostly driven by the CO₂ fertilization effect on vegetation with the C₃ photosynthetic pathway.

We have created a figure (Figure S9 - S10) showing regression lines and correlation coefficients demonstrating the relationship between the vegetation area and GPP for crop and natural vegetation.

I also suggest authors to reframe their study to discuss why models all dependent on LUH2 still disagree strongly on area and fluxes.

We have added some more text regarding the disagreement with LUH for models incorporating LUH data in **Lines 175 – 182**. We also added more information in the supplementary material.

Referee 1 Minor Comments and Responses

Line 13: Change “affect” to “affects”

Done

Line 18: What does this mean by ‘the data-based estimate’?

This has been changed to satellite-based estimate from Potapov et al 2022.

Line 19: I did not see the value of “17%” over the Results

This is based on Luo et al 2024 see Figure 4 (i) and Luo in the reference and the correct value is compared to 20 ± 3 %.

Line 85: Clarify how cSoil was used

Soil carbon content is calculated for C₃ and C₄ cropland and natural vegetation. The results are available in the supplementary material. We have made it clearer how cSoil was used and what is in the supplementary material.

Table 1: Provide the spatial resolution of each model

We have added the spatial resolution of each model.

Line 101: It would be helpful to provide details about the preprocessing differences among models that all relied on LUH2

Some details about this are available in the supplementary material, but we are unable to provide information on all pre-processing that may have been done for each model.

Line 103: Ensure consistent use of CNRM-CM6-1 or CNRM-CM6.1.

Corrected.

Line 110: This paper did not include any analysis about ‘ecosystem carbon content’

Response: This is referring to carbon content in vegetation and soil. It has been restated as ‘vegetation carbon content and land carbon content’ for clarification in the final manuscripta and the figure showing the result for this analysis is in Figure S3 and Figure S4.

Line 143: Why was 12.5 ‰ chosen for isotopic discrimination? Is this value spatially robust?

Response: 12.5 ‰ is the midpoint between the two peaks in Figure 1 from the database of leaf carbon isotope discrimination published by Cornwell et al (2018). The values to the left of 12.5 ‰ in the figure correspond to the values of stable carbon isotope discrimination in vegetation with the C₄ photosynthetic pathway while values to its right correspond to stable carbon isotope discrimination in vegetation with the C₃ photosynthetic pathways. The mean values of these are then calculated and used for the analysis. They are shown in Figure 1: 6.3 ‰ for C₄ and 20.7 ‰ for C₃. We have revised the text to clarify this point.

Line 150: Why is the isotopic analysis based on 1970–2014, while other analyses span 1850–2014?

Response: The isotope analysis spans the whole of the period from 1850 to 2014, as shown in Figure 7. We used 1970–2014 for C₄, C₃ and total crop in this section (Line 155 to Line 183) to focus on the period of largest change since the Green Revolution and how that change is captured in the CMIP6 models.

Line 156: What does this mean by ‘lack of precipitation in UKESM1’

Response: In the Sellar 2019 reference cited, it is shown that the UKESM1 underestimates precipitation in India. We have revised the text to make this clearer.

Figure 2: Change “earth” to “Earth” and “For” to “for.” Also, subfigures should be labelled (a)–(e).

Done.

Figure 3: Clarify the y-axis label

Done.

Line 177: The number (–19 to +3%) differs from the Abstract

This is good point. The values of –28 to +10 % from the satellite that is quoted in the abstract was not in the body of the text and so could mislead the reader. However, the –19 to +3 % mentioned here is a different value comparing models crop area to LUH2 crop area, which is different from the satellite-based estimate. We have now included both in the text to avoid confusion, as follows: “however, the total area of crops in these models differed from LUH2 by –19 to +3 % and it also ranged from –28 to +10 % of satellite-based estimate (Fig. 4, Table S1)”

Line 194–195: Provide full names of the MPI models. Also, use UKESM1 rather than UKESM2.

Done

Figure 4: Provide data sources for ESA CCI, Still, and Luo.

The data sources are provided in the Data Availability section with the following statement: ‘For the ESA CCI, LUH2, Still, Potapov and Luo data used in Figure 4, see Harper et al (2023), Hurtt et al (2020), Still et al (2003), Potapov et al (2022) and Luo et al (2024) respectively. For Gibbs, Spawn and Erb data used in the Figure 6 above see Gibbs and Ruesch (2008), Spawn et al (2020), Erb et al (2018) respectively and Graven et al (2024) for all these three data in in one file at <https://www.science.org/doi/10.1126/science.adl4443>. For the Keeling_vsCO2, Keeling_vstime used in Figure 7 see Keeling et al 2017. And for the GCB data used in Figure S4 see Friedlingstein et al (2025)’. The data can be accessed through the papers in the references.

Line 223: Should be Fig. 5c, not Fig. 6c

Corrected.

and Line 245: Should be “Fig. 6b.”

Line 273: Corrected.

Line 285: how uncertainty in actual crop area is quantified?

Response: This has been rephrased as ‘the uncertainty in input crop area data source.’

Line 298–305: This could also be related to differences in the natural vegetation composition

This point has been added to the manuscript ‘and may be also be linked to iscrepancies in the natural vegetation composition’.

References

The references for all the works cited here have been added to the main manuscript.