Reviewer I comments:

The manuscript entitled 'Phenology, fluxes and their drivers in major Indian agroecosystems: A modeling study using the Community Land Model (CLM5)' benchmarked model simulated carbon, water, and energy fluxes across croplands in India at both site and regional level; following model validation, the authors examined impacts of climate change, elevated CO2, nitrogen fertilization, and irrigation on the long-term trends (1970-2014) of matter and energy fluxes across Indian croplands by conducting four model simulations. The authors concluded that N fertilization and irrigation are top drivers for the increasing trends of carbon fluxes with additional effects from elevated CO2. This work has potential management implications for agricultural production and food security under changing climate. The work is straightforward but needs some clarifications in modeling methods; the results section can also be improved to be more concise. See my comments below.

Thank you for recognising the potential implications of the study. We have addressed the comments below. Our responses to the comments are in black color, any additions to the revised manuscript are shown in green color.

1. CTRL experiment setup: it seems that the control experiment is using transient climate and CO2 concentration but unclear to me which years of data is used for driving the simulations. Was it 1965-2014? And what forcing data was used for the spin-up runs? In addition, in lines 201-203, field observations were collected from experiments with varying N addition and irrigation treatments, but only control treatment was used. Does this baseline treatment match with the control settings used to drive model simulations regarding N addition and irrigation frequency and intensity?
   - Yes, in the CTRL simulation the transient run is from 1965-2014 using the atmospheric forcings from GSWP3 data. This information will be added to the text and Table 1 of the manuscript.
   - The forcing data used for spin-up was 1901-1920.
   - Yes, the nitrogen application in the control field experiments match the nitrogen fertilisation application in the model, which is carried out during the early stages of the crop. Coming to irrigation, in the field experiments the irrigation is applied across the growing period (usually spaced by 15-20 days). In CLM5, irrigation is applied whenever soil moisture falls below the threshold. However, our comparison of the irrigation pattern and amount in Reddy et al., 2025 matches closely with other modeling studies (Biemans et.al., 2016).

2. Cropland definition in model vs reality (L324-327): when compare model simulated matter and energy fluxes FLUXCOM products at regional scale, the authors came up with a 10% crop cover threshold to define grid cells for model-data comparison. This brings up a question: are we confident that 10% threshold is good enough to ensure observed ecosystem fluxes (of which ~ 80% can come from non-crop vegetation in real world if only 20% of the grid cell is covered by crops) can represent the average behaviour of cropland? It seems to me that in the model, there are only crops being

simulated. Also, please cite the data source used to define cropland (e.g., what data is used to classify vegetation cover)

- The explanation provided in the manuscript was not sufficient to clarify what was being compared and why was it compared. The regional scale evaluation from line 324 is aimed at comparing the CLM5 simulation of fluxes against the observations. The model simulated fluxes are from all the vegetation in the grid cell. The FLUXCOM estimates also represent all vegetation. We wanted to compare only the regions with reasonable crop growth (although they might contain other vegetations). This reasonable crop growing region is tested by varying the threshold of crop % in the grid cell and 10% has resulted in the region that resembles the observed crop maps for rice and wheat. This information will be added to the results section so that readers clearly understand the reasons for the comparison.
- The data source to define the croplands is the Land Use Harmonized version 2 (LUH2) transient dataset, product of the Land Use Model Intercomparison Project (LUMIP; https://cmip.ucar.edu/lumip) as part of the Coupled Model Intercomparison Project 6 (CMIP6). The historical component of the transient LUH2 dataset has agriculture and urban land use based on HYDE 3.2 with wood harvest based on FAO, Landsat and other sources, for the period 850-2015. This information will be provided for the readers in the revised manuscript.

3. Results need to be shortened and tighten up: L260-270 are results from Reddy et al. 2025. While I understand the purpose is to convince readers to believe that the current model parameters are much improved for simulating Indian crops, I'm not sure if it is necessary to highlight this here as this is the not results of the current work. My suggestion is to use one sentence to state that current model parameters have been calibrated and validated in Reddy et al. 2025 and move all the details into supplementary if needed.
   - Thank you for the suggestion. We agree that iterating the results from Reddy et al., 2025 would not add a lot of value to the readers. A one-line summary will be provided in the revised manuscript and the rest will be moved to the supplementary material.

4. There are a lot of figure caption-style of writing when documenting results (e.g., L274-275, L301, L330 etc.). These should be moved to the corresponding figures as caption instead of being documented as results.
   - The details of the figures mentioned in the lines 274-275, 301, and similar text will be moved to their respective figure captions.

5. When documenting the trends and drivers on simulated trends (e.g., section 3.2 and 3.3), most of the patterns in carbon fluxes and crop physiology are consistent. So, I think it can be more concise to combine results instead of documenting them separately. For instance, L390-430 can be combined into one paragraph by documenting the trends of GPP, AR, and NPP, and then how climate, CO_2, N fertilization, and irrigation influence them correspondently. For instance, CO_2 has significant positive influences

on all carbon fluxes with effect size being 9, 3, 6 gC/m2/year for GPP, AR, and NPP respectively.

- Thank you for the suggestion. The results will be merged into a smaller number of paragraphs in the revised manuscript. For example, the section 3.2.1 Rice crop carbon fluxes which was earlier 4 paragraphs and 33 lines, will be reduced to 2 paragraphs and 19 lines. The new section 3.2.1 will read as: "Figure 8i shows the increasing trend in GPP, AR, and NPP from the 1970 – 2014 period during a growing season for rice as 18, 3, and 15 gC/m2/year2, respectively. Figure 8 (ii to v) shows the impact of each of the drivers on the observed positive trend. Climate has no significant impact on the observed annual GPP, AR and NPP trends (Figure 8ii). CO2 has a statistically significant positive impact on the yearly GPP, AR and NPP trends, with values of 11, 5, and 6 gC/m2/year2 (Figure 8iii). Nitrogen fertilization has a statistically significant positive impact on the annual GPP and NPP trends, with values of 5, and 10 gC/m2/year2 (Figure 4aiv and 4civ), while have a significantly negative trend on AR with a value of -5 gC/m2/year2 (Figure 8biv). Irrigation has a statistically significant impact on GPP, AR, and NPP with trends of 10, 3, and 7 gC/m2/year2 (Figure 8v).

  Increasing CO2 has the largest impact on the annual GPP of rice, followed by irrigation. CO2 has the most significant positive impact on AR in rice-growing regions, while nitrogen fertilization has a large negative impact on AR. This implies that rice crops tend to respire less in high nitrogen environments. Nitrogen fertilization has the largest impact on the NPP during the growing season of rice, followed by irrigation and CO2. NPP, the carbon taken up by rice crops during their growing season, has seen the largest increase over the study period owing to the impact of nitrogen fertilization on GPP and AR. Nitrogen fertilisation has led to increasing GPP and decreasing losses through AR during the study period."

6. In several places the authors have stated how well CLM can capture the seasonality of cropland function (e.g., L314, L618, L621), but seasonal pattern is not shown in any of the figures included in main. Maybe there can be a better way to visualize the results if that's something authors would like to highlight.
   - A new figure showing the seasonal performance of CLM5 terrestrial fluxes of crops will be added to the supplementary. This will support the statements made across the manuscript. Please see the response to Reviewer 1: minor comment 10, for details of the figure that will be added to the supplementary material.

Some other comments:

1. In abstract, the authors kind of sell themselves short when speak about the broader impacts of the work (L23-26). I think using cross-scale data for model benchmark is not the most important impact (as a lot of other work has done). The authors can focus

on their findings of changing climate, rising CO_2, and management practices effects on crop yield, and how this can help agriculture activity planning in the face of global change.

- The abstract will be rewritten. Please see response to Reviewer II, general comments 1.

2. L50: this sentence reads a bit awkward in terms of its logic. Maybe rephrase as “the investigation … revealed a significantly longer growing period compared to….”
   - Changed in the manuscript.

3. L185: equilibrium states regarding what? Soil carbon stock? Aboveground biomass? Please specify
   - The criteria in CLM are that less than 3% of the land surface be in total ecosystem carbon disequilibrium. Since the region considered for simulation is Indian subcontinent, this criterion is reached in the about 200 years (figure shown below).

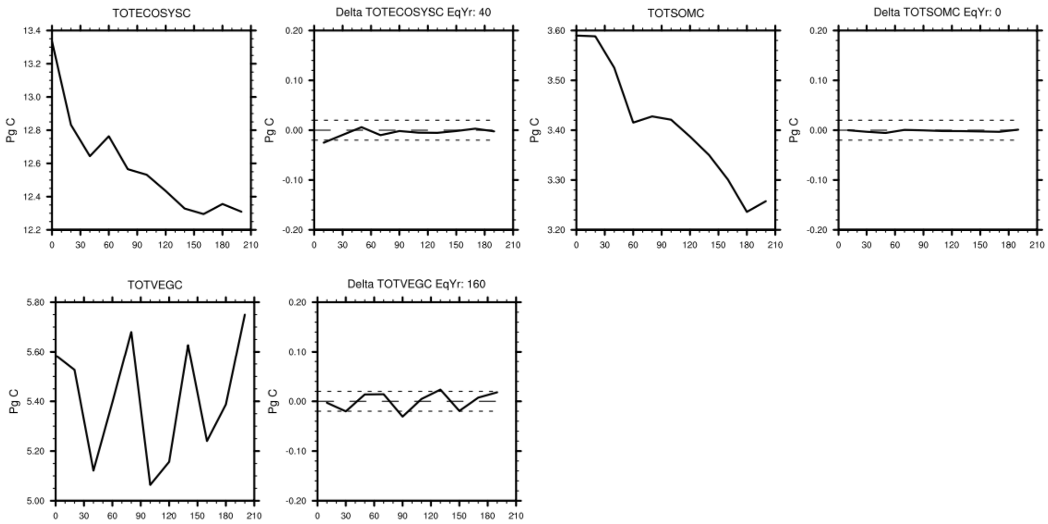

Figure 1: The spinup of the CLM5 model for 200 years in the accelerated mode and the time taken for various land variables to reach equilibrium.

- This information will be added to the supplementary.

4. 2.3.1 Crop physiological parameters: when I saw parameters, I thought it is model parameters associated with crop physiology (e.g., Vcmax, SLA). But I then realized that it refers to model variables such as LAI, dry matter. Please consider changing to crop physiological variables to avoid confusion.
   - Thanks for pointing this out. The section title and the text in the section will be changed to “crop physiological variables”.
5. L240: change to ‘corresponding fluxes observations’ to be concise.
   - Changed in the revised manuscript.
6. L303: CLM5 simulations are close to observations only in Feb. and Apr.?
   - Yes, simulated fluxes are close to observations in Feb. and Apr. The bias is less in Jan. This information will be reflected in the manuscript.

7. L392: 18gC/m2/year? Same typos in L399, 400 and many other places throughout the manuscript.
   - The carbon fluxes have the units gC/m^2/year, as we are reporting the cumulative fluxes and, in this section, we are reporting the trend over 50 years. Therefore, the units have ended up as gC/m^2/year^2.
8. L488: not wheat but rice?
   - Thanks for pointing out this mistake. Corrected in the revised manuscript.
9. Fig. 10, 12, 14, 15, 16 don't have captions. All figures should have its stand-alone figure captions.
   - Corrected in the revised manuscript.
10. L618: I don't see any figures demonstrating the simulated seasonality of crop physiology.
   - The realistic seasonality of crop physiology in L618 is not shown in this manuscript but is an outcome of Reddy et al. (2025). This sentence will be changed to make this clear to the readers.
   - The following figure is added to the supplementary material to facilitate the readers understand the simulated seasonality of carbon fluxes.

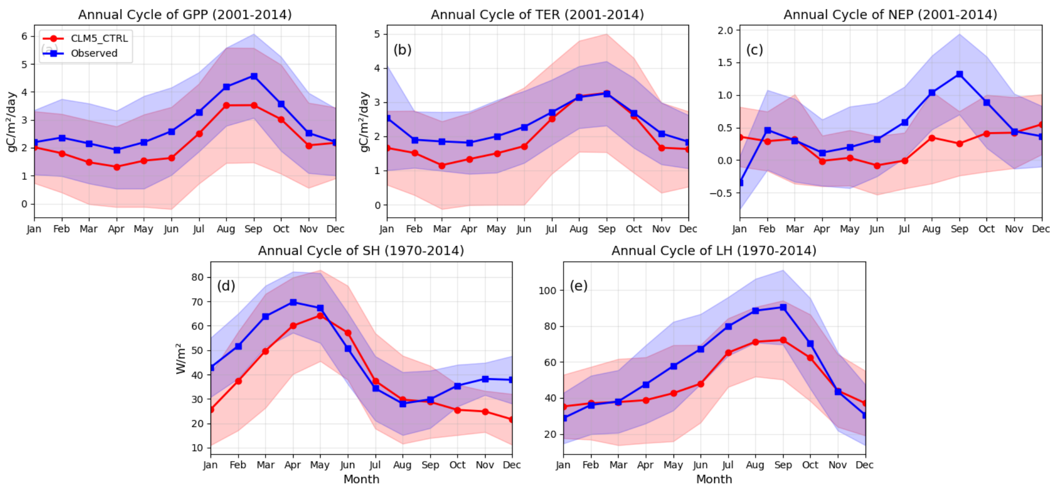

Figure 2: Mean seasonal cycles of carbon and energy fluxes simulated by CLM5 and fluxes from observations. Panels show the climatological annual cycles of (a) gross primary production (GPP), (b) total ecosystem respiration (TER), and (c) net ecosystem production (NEP) for the period 2001–2014, and of (d) sensible heat flux (SH) and (e) latent heat flux (LH) for the period 1970–2014. Solid lines indicate monthly means simulated by CLM5 (red) and derived from FLUXCOM observations (blue). Shaded envelopes represent ±1 standard deviation of the monthly fluxes for CLM5 and observations.

Reviewer II comments:

General comments

This manuscript presents a well-executed and ambitious modeling study that substantially advances our understanding of long-term phenological and biogeochemical trends across

India's major agroecosystems. However, several weaknesses limit its clarity and impact, including:

1. **Abstract**: The Abstract is somewhat long, scattered, and lacks a clear structure. I suggest following the standard mini-paper structure, including:
    1. brief background introduction,
    2. the research questions or issues to be addressed,
    3. a brief description of methodology, and
    4. the key numerical results.
   - We thank the reviewer for the suggestion. The revised abstract is:
     "Agroecosystems cover over half of Indian land surface, yet the long-term and spatial variability in crop physiology and terrestrial fluxes from croplands is not well understood. Most previous studies rely on site-scale eddy covariance observations, and the only regional assessment over Indian agroecosystems (Reddy et al., 2023) focused solely on wheat with limited calibration. Reddy et al. (2025) calibrated CLM5 using multi-site data to simulate Indian wheat and rice. In this study, we use this capability of CLM5 to provide the first comprehensive regional analysis of long-term (1970–2014) trends in crop variables and terrestrial fluxes across major croplands of India. Further, numerical experiments are conducted with CLM5 to evaluate the role of climate, CO_2, nitrogen fertilisation, and irrigation in driving the trends. The results show that LAI, yield, and dry matter of the crops increased more than twofold since the 1970s, with carbon uptake doubling and respiratory losses decreasing during this period. Nitrogen fertilisation and irrigation have the largest impact on the observed trends of crop variables and terrestrial fluxes, followed by CO_2. This study highlights the important role of management practices in increasing crop productivity and carbon uptake under a changing climate and demonstrates that a robust modeling framework is now available for testing management strategies across Indian agroecosystems."

2. **Introduction**: The Introduction is too long and needs to be more concise. Some terms/phrases are repeated. For instance, the description of knowledge gaps overlaps substantially with the objectives, and knowledge gaps are usually followed by specific objectives. These two parts should be placed closer together and rephrased to avoid redundancy.
   - Thanks for pointing out the redundancy in introduction. We have now greatly altered and trimmed this section, and we believe the introduction is more concise and readable.
   - The introduction will be rewritten as follows:
     " The exchange of water, energy, and carbon between the terrestrial ecosystems and the atmosphere play key role in shaping the water, energy and carbon cycles (A FEW KEY REFERENCES). Agroecosystems are one of the largest components of terrestrial ecosystems and have significant influence on the land-atmosphere

interactions (Liu et al., 2016; Lokupitiya et al., 2016; Ingwersen et al., 2018). Almost 56% of the Indian harvested land area is comprised of croplands (Zanaga et al., 2021), 80% of which is by wheat and rice. Wheat is harvested in northern and central part of India during rabi season (November to April) and constitutes to 30 Mha (million hectares), while rice is harvested across India in the kharif (June to October; 39 Mha) and rabi (5 Mha) seasons (ASG-2023, 2024). Due to the large spatial coverage and long growing season, terrestrial fluxes from wheat and rice croplands dominate regional land-atmosphere interaction processes. Agroecosystems are influenced by natural factors, including temperature, radiation, precipitation, and atmospheric CO_2, as well as human management factors like irrigation, nitrogen fertilization, tillage, and residual management (Chenu et al., 2017). Changes in natural and management drivers have varied impacts on agroecosystems (Gahlot et al., 2020; Lombardozzi et al., 2020; Reddy et al., 2023). Hence, it is important to understand the dynamics of the fluxes and their drivers in Indian agroecosystems.

Studies over the past two decades used eddy covariance observations to investigate terrestrial fluxes in croplands across Asia, Europe, and North America (e.g., Saito et al., 2005; Chen et al., 2015; Wagle et al., 2021). However, findings from mid-latitude wheat systems with long vernalization periods are not representative of short, warm growing seasons observed in India. A few studies examined the terrestrial fluxes within Indian agroecosystems (Patel et al., 2011; Bhattacharya et al., 2013; Kumar et al., 2021; Patel et al., 2021), usually at one site, which fail to adequately represent the diverse climatic growing conditions and regions of India. For example, the sites in Patel et al. (2011, 2021) and Kumar et al. (2021) are in the northern part of India, which has colder temperatures and is well irrigated. These are not representative of all wheat-growing regions of India most of which experience warm temperatures and low water availability (Gahlot et al., 2020). Additionally, these studies examine short time periods of 1-3 growing seasons failing to provide any long-term information about the diverse crop growth and fluxes from Indian agroecosystems. Despite their importance, Indian agroecosystems lack (1) regional scale estimates of crop phenology, productivity, and terrestrial fluxes, (2) long-term trend assessments, and (3) attribution of observed changes to natural and management drivers.

Land Surface Models (LSMs) have come a long way, from their initial versions of simplified representations providing boundary conditions to the atmospheric models to currently very complex models, with accurate representation of the land surface and competition for resources amongst various land types (Fisher and Koven, 2020). Models provide a powerful framework for addressing the above-mentioned gaps in Indian agroecosystem studies. Gahlot et al. (2020) and Reddy et al. (2023) investigated the impact of natural and management drivers on crop phenology and carbon fluxes in Indian wheat agroecosystems using the Integrated Science Assessment Model (ISAM) at a regional scale. The major limitation of these studies is they use only one site for calibration and simulation of wheat. They fail to provide a complete picture of crop physiology and fluxes of Indian agroecosystems.

Land model benchmarking studies showed that the Community Land Model version 5 (CLM5) offers advanced representations of terrestrial processes and performs better than other LSMs (Collier et al., 2018). Reddy et al. (2025) calibrated CLM5 using multi-site data from different climatic regions of India. Building on the improved CLM5 model, the current study aims to (1) evaluate the CLM5 simulation of crop phenology and terrestrial fluxes against a new and long term site scale dataset (1970-2014) and widely used regional scale datasets (FAOSTAT and FLUXCOM); (2) investigate the long-term and spatial trends of crop physiology and fluxes; and finally, (3) understand the impact of natural and management drivers on the observed trends of crop physiology and fluxes.

By enhancing our understanding of the spatial and temporal dynamics of crop productivity, energy, water, and carbon fluxes in a highly diverse and climatically sensitive region like India, this study provides valuable insights for future food security planning and sustainable land management. The approach demonstrated in Reddy et al. (2025) and in this study can serve as a blueprint for extending such analyses to other tropical and subtropical regions, where data limitations and complex agroecosystem interactions are observed. Ultimately, this research contributes to global efforts in predicting agricultural resilience, optimizing resource use, and mitigating the impacts of climate change on vulnerable agroecosystems."

3. **M&M**: The Methodology is described in great detail, but the structure is cumbersome, and essential elements—such as model limitations in flooded rice systems—appear too late in the paper.
   - We felt the details about the model and its processes is necessary for readers to understand the various uncertainties in the model simulation of wheat and rice crops in Indian region.
   - Yes, we agree that the limitation of CLM5 not simulating flooded rice is discussed much later in the manuscript. This issue is now added to the methods section while describing the irrigation module in CLM5 in section 2.1.4.

4. **Results**: The Results section is extremely long and difficult to follow, dominated by dense figure panels with minimal synthesis.
   - Please see our response to Reviewer I- main comment 5.
   - Figures 4 to 7 of the original manuscript will be moved to the supplementary and the following figure (Figure 3) will be added to the manuscript. This figure will describe the overall performance of variables simulated by CLM5. The current results of the manuscript will be followed while referring to the figures in the supplementary.

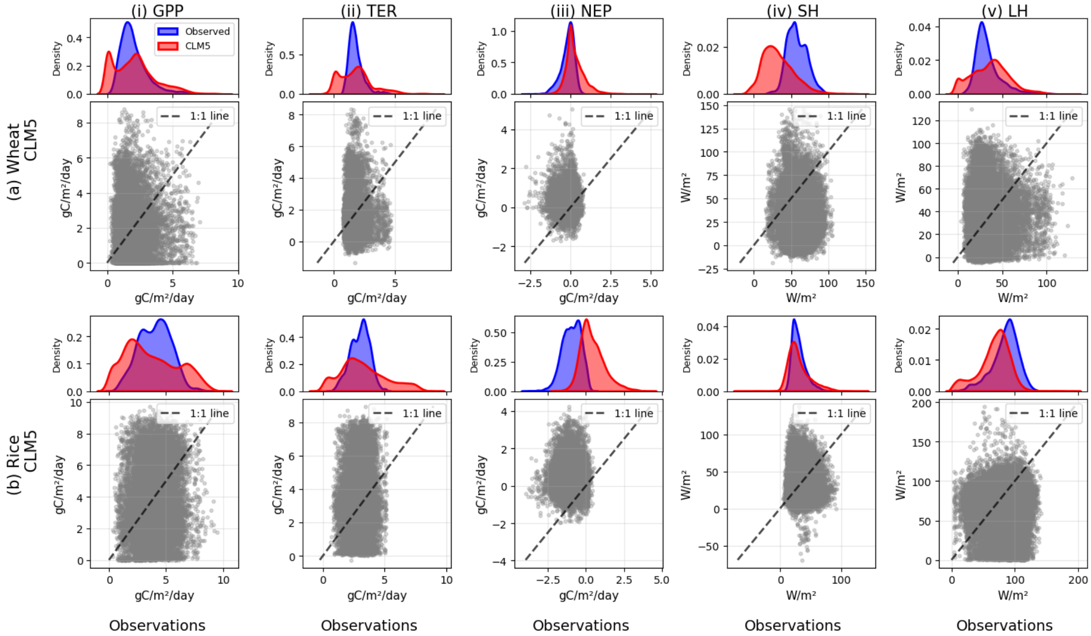

Figure 3: Comparison of observed and CLM5 simulated fluxes for (a) wheat and (b) rice agroecosystems. Probability density functions (upper panels) and scatter plots (lower panels) show observed (blue) and CLM5-simulated (red) (i) Gross Primary Production (GPP), (ii) total ecosystem respiration (TER), (iii) net ecosystem production (NEP), (iv) sensible heat flux (SH), and (v) latent heat flux (LH). The dashed line in the scatter plots denotes the 1:1 relationship.

- Similarly, figures 8, 10, 12, 14, 15, and 16 from the original manuscript will be moved to the supplementary and the following figure (Figure 4) will be added to the revised manuscript. This should drastically reduce the length of the manuscript, and concise a lot of information in a single figure.

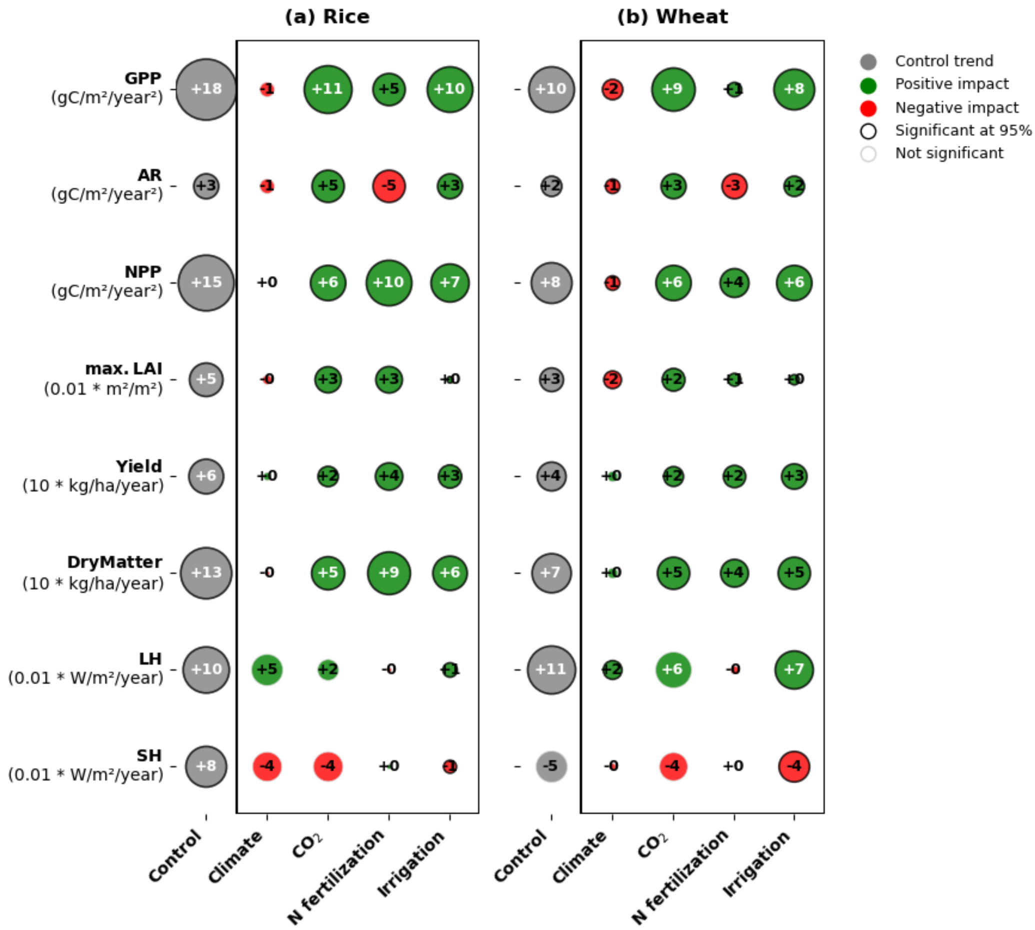

Figure 4: Attribution of long-term trends in carbon fluxes, crop variables, and surface water and energy fluxes for (a) rice and (b) wheat agroecosystems. Grey bubbles show linear trends (1971–2015) in carbon fluxes (GPP, AR, and NPP), crop variables (max. LAI, yield, and dry matter), latent heat flux (LH), and sensible heat flux (SH) from the CLM5 control (CTRL) simulation. Colored bubbles within the rectangular boxes represent the contributions of individual drivers: climate, CO_2 concentration, nitrogen fertilisation, and irrigation (trend of CLM5_CTRL – CLM5_S_{driver}). Bubble size is proportional to the magnitude of the trend, with green and red indicating positive and negative contributions, respectively. Bubbles outlined with an edge denote trends or driver impacts that are statistically significant at the 95 % confidence level ($p < 0.05$).

5. **Discussion**: The Discussion section is combined with the Conclusion section, which differs from the standard format of scientific papers. Please explain why these two sections were merged.
   - The discussion and conclusion in this manuscript needed to be together as the concluding points were arising from the discussions and did not want to separate them.
   - Another reason was the length of the manuscript (which was already long), pushed us towards having one section at the end of results.

Specific comments

1. **Introduction**: I suggest reframing this section into 4–5 paragraphs. Begin with why understanding the dynamics of crop phenology, fluxes, and their drivers in Indian agroecosystems is so important. Follow this with the challenges—specifically that current evaluations are limited to regional-scale estimates, which restrict our understanding of carbon fluxes, crop phenology, etc. The introduction to the CLM5 model should be mentioned earlier.
   - Please see response to Reviewer II- General comment 2.

2. **M&M**: Although the information in the M&M section is important, I suggest adding a conceptual figure and a summary table for clarity. For example, consider the conceptual figure of the DNDC (Denitrification–Decomposition) model—this type of figure is a good example for summarizing Sections 2.1.1 to 2.1.4. For Section 2.3 "Evaluation of CLM5," I suggest adding a summary table describing the data sources used for validation (e.g., papers, theses, public datasets, or data repositories).
   - Adding a conceptual figure of agriculture and their fluxes in CLM5 is done in many previous studies (Lawrence et al., 2018; Lombardozzi et al., 2020). Instead of repeating, we will cite the figures in the revised manuscript.
   - Adding a summary table of all the dataset used to evaluate the CLM5 model will be helpful to the readers. We already have one table in supplement showing the source of cumulative seasonal carbon flux estimates. Now we have added another table in the methods section, which shows all the datasets used in the study.

3. The Results section is technically rich but dense and could be streamlined with short summary paragraphs and/or reorganized figures.
   - We agree. Please see our response to Reviewer I- main comment 5.
   - We will reorganise the figures and summarise the results section as mentioned in responses to 'Reviewer 2: general comments 4' and 'Reviewer 1: general comments 5'. This will drastically reduce the manuscript length and contain the figures that are necessary to derive the conclusions.

4. Verb tense inconsistencies further distract from the narrative flow. Past tense should generally be used throughout the paper; present tense can be used in the Conclusion section.
   - We apologise for the inconsistency in the verb tense usage. This is thoroughly checked in the revised manuscript.

5. Avoid starting a sentence with an abbreviation. Instead, use the full term.
   - Followed in the revised manuscript.

6. P4 L119 – "The overall bias in simulating crop growth has improved from 0.51 to 0.24 and 0.48 to 0.25." These improvements need clarification (e.g., units). If these are unitless values, that should be stated explicitly.

- Yes, the bias reported across the manuscript is unitless (please refer to equation used). This will be highlited in the manuscript to help readers while understanding the results.

7. P8 L224 – The citation for Patel et al. should be modified to: "Patel et al., 2011 and 2021."
   - Changed in the revised manuscript.

8. P10 L277 – Please change to "$p < 0.05$."
   - Changed in this and all other instances of reporting the p-value.

9. P11 L296 – Please explain the statement "The CLM5 simulations overestimate the fluxes during the early months and are close to observation estimates in the reproductive and maturity months" in the Discussion section.
   - For the wheat crop, the early months are December and January and the reproductive months are February, March and April. In figure 3 of the original manuscript, we can see in the panels (a) and (c) the simulated fluxes are closer to observations. We believe that the statement at L296 has come before the explanation of the figure. This will be moved to a more appropriate position in the revised manuscript.