Carbon fluxes in spring wheat agroecosystems in India

K. Narender Reddy, Shilpa Gahlot, Somnath Baidya Roy, Venkateshwara Varma Gudimetla, Vinay Kumar Sehgal, and Gayatri Vangala

We thank the referees for their thorough reviews and the editor for allowing us to respond to the referees' comments. We did additional work involving rerunning the model and acquiring new data to properly address the referees' comments. One common critique from both referees was the limited model evaluation against observed data. Addressing this issue was a major challenge because site-scale crop phenology, yield, and other observations are not readily available in India and almost none in the public domain. That is why we decided to look for unconventional sources for crop data. We realized there are many agricultural institutions across India where students conduct field experiments on crops grown in India and report the data in tabular form in their thesis. The theses are rarely published, and data from these field experiments are never made public. Accessing the theses was an issue until recently when an online thesis repository, KRISHIKOSH, was established where many old theses were uploaded. We took this opportunity to extract data from these theses and digitize them in machine-readable format. In all, we have digitized data covering 25 growing seasons from 9 spring wheat sites [Table 1]. We used this data to evaluate our simulations for the revised manuscript. We will also make the data available in the public domain so that other researchers can use it.

The digitization took longer than anticipated, so we thank the editor for giving us extra time to revise this manuscript. Mr. Gudimetla Venkateshwara Varma contributed significantly to finding, extracting, digitizing, and analyzing crop data. Hence, we would like to add him to the list of authors.

Below, we provide a point-by-point response to the referees' comments. The comments are in red font, our responses are in black font, and the proposed changes to the text are in green font.

Referee I Comments:

1) **The manuscript documented a regional modelling effort using the ISAM to quantify carbon fluxes from the spring wheat agroecosystems in India. Overall, the manuscript is well organized, and the topic interests the community. However, the following major concerns should be addressed before the manuscript can be considered for publication.**

   We thank the referee for the encouraging comments.

2) **First, there is no validation of spring wheat yield in the manuscript, which is a major carbon flux out of the agroecosystem. I strongly suggest the authors to add the validation of yield at both site and regional scales to demonstrate that the yield can capture the variation of this important carbon flux. Related to this suggestion, please also add how the model simulates yield formation processes in the method section.**

   a) Both referees have asked for a more thorough model evaluation. We evaluated the annual yield simulated by ISAM at the regional scale using data from FAO-EarthStat and the site scale using the dataset we digitized [Table 1]. The results show that the yield simulated by ISAM replicates the pattern observed in most parts of the wheat growing regions, however, having a bias in a few regions. The comparison at the site scale gives us confidence about the model as it agrees with the observations (Pearson's *r* = 0.57) [Figure 1]. We will add a new subsection describing the validation of the ISAM model.

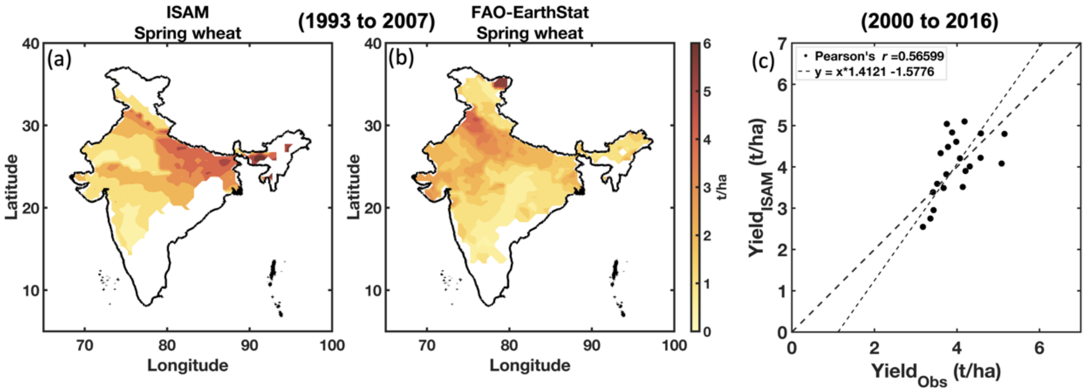

Figure 1: Comparison of spring wheat yield across the wheat-growing regions of India simulated by ISAM (a) against FAO-EarthStat (b) data for the 1993-2007 period, and (c) scatter plot of yield observations at site scale [Table 1] and ISAM yield simulations (over the period 2000 to 2016).
Note: The bootstrap linear regression of observation and model data is mentioned in the figure. The linear fit's intercept, slope, and correlation are the mean of 10000 bootstrap values.

b) This work is a follow-up to Gahlot et al. [2020]. The model simulations were conducted for that study. That study looked at spring wheat production and its drivers. In this study, we are looking at the carbon fluxes and their drivers using the outputs of the same simulations. Here, we ran simulations to extract variables at higher frequencies to evaluate the simulated yield and LAI against observations. However, the model configuration remained the same as in Gahlot et al. [2020]. Hence, for brevity, we have not provided a detailed description of the model and configurations here but instead, refer the referees and the readers to Gahlot et al. [2020]. We will clarify this in the revised manuscript.

However, we understand the paper will be easier to read if we add relevant details. Hence, we propose to add the following text: "The initial reproductive stage in ISAM marks the onset of the storage organs. The allocation of assimilated carbon to the storage organ begins, and the vegetative development of the plant stops. The next stage, the post-reproductive stage, marks the solidification of grains and increased nutrient allocation to the grains while ensuring capable roots support the plant. After the crop reaches maturity, the total grain allocation from the initial reproductive stage to maturity is converted to yield. Various factors like light availability, temperature stress, and nitrogen availability act as limiting factors to crop growth, and nutrient allocation is promoted in the crop so that the impact of these factors is minimized [supplement material, Gahlot et al., 2020]".

3) **Second, for the long-term simulation of the agroecosystem, crop rotation is a critical factor as it will affect the soil biogeochemical cycling and thus the long-term soil fertility. However, this part is mainly unaddressed in the current manuscript. Besides spring wheat, what other crops are planted in the cropping systems in reality, and how was that handled in the ISAM modelling efforts? Without simulating the typical crop rotation, I don't think the carbon fluxes can be reliably simulated by the model.**

Crop rotation is a farming practice in which a different crop is grown in alternate years to promote soil fertility. However, in India, most farmers do not practice crop rotation. A more common practice is multiple-cropping, where spring wheat is grown across the country during the rabi season (winter, November/December to March/April), and rice is grown during the Kharif season (monsoon, April/May to October/November) on the same land. We understand that crop rotation and multiple cropping can affect carbon fluxes. In an ongoing study, we are incorporating multiple cropping (rice-wheat) to study how individual crops of a multi-cropping system might affect the carbon and energy fluxes. We will add this in section 4 (Discussions) of the manuscript.

4) **Third, changes in crop cultivars and management practices (as well as their spatial variations) are not well considered in the manuscript. For long-term simulation, these factors are critical aspects that cannot be neglected, especially when the focus is related to carbon.**

These are both very important factors for spring wheat agroecosystems. In our study, we already include nitrogen fertilization and irrigation, the two main management practices used in India. The details of implementing these practices are given in Gahlot et al. [2020]. Results show that these management practices strongly affect yield [Gahlot et al., 2020] and carbon fluxes [this study].

Many studies show that using different cultivars can change spring wheat yield, but there are no studies on the effects on carbon fluxes. Thus, studying the impact of cultivars on carbon fluxes is an exciting and open question. This effect was not incorporated in our study. Developing spatiotemporal maps of cultivar use and collecting site-scale carbon flux and phenology data for various cultivars will take a lot of work. The community should strive to create such datasets to better understand and simulate the effect of different cultivars. We will discuss this issue in section 4 (Discussions) of the manuscript.

5) **Fourth, the authors are using the dynamic planting date predicted by the model, however, the authors are not evaluating whether the simulated sowing date reflects reality. The authors should have access to several crop calendars and good knowledge of the local farming seasonality. I would suggest the authors validate the predicted sowing date as it is such a critical factor affecting the spatial pattern of carbon fluxes shown in Fig. 3. Otherwise, I cannot have more confidence in the spatial patterns of carbon fluxes, which are not well interpreted by the authors.**

This is a good point. We acquired the relevant data and evaluated the predicted sowing dates against observations. We find that the sowing dates simulated by ISAM are in good agreement with the GGCMI phase 3 data [Jägermeyr et al., 2021] in most wheat-growing regions except the north-western region [Figure 2]. However, our simulations compare well with data from the Jobner site in the northwest [Jobner LAI plots in Figure 3]. This suggests that perhaps the GGCMI data in the northwest is biased.

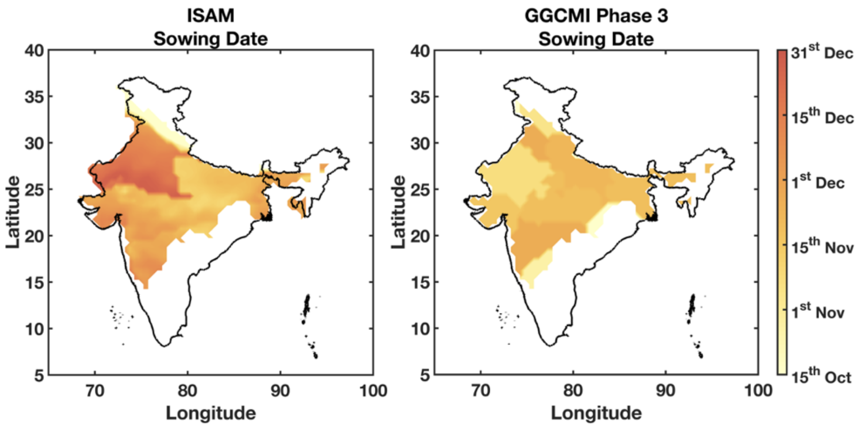

Figure 2: ISAM simulated sowing date of spring wheat (mean: 1980-2016) against GGCMI spring wheat sowing data

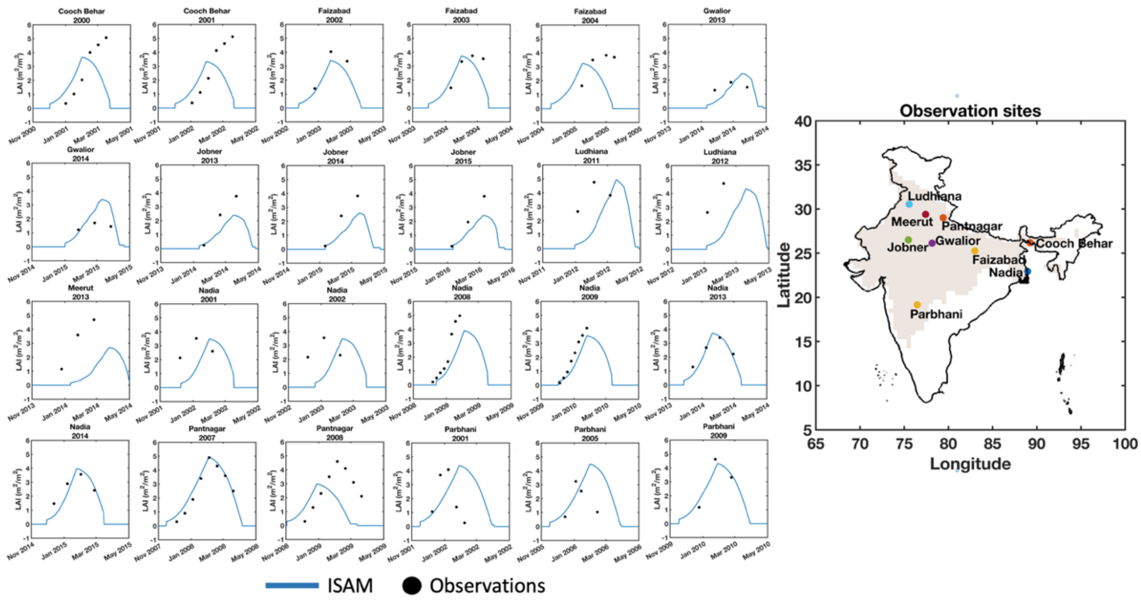

Figure 3: Comparison of site scale crop phenology (LAI) against the ISAM simulations. The map shows the locations of the sites.

In addition to validating crop sowing dates, we have also looked at how the dates varied across decades [Figure 4]. The sowing dates have shifted by nearly two weeks in the eastern Indian Gangetic plains (significant at 95%) over three decades. This shift also coincides with the higher yields in this region. The western parts of the wheat-growing regions also have a shift in the growing season (significant at 95%), resulting in a loss of yield (not significant at 95%). We will add this to the text and support it with figures.

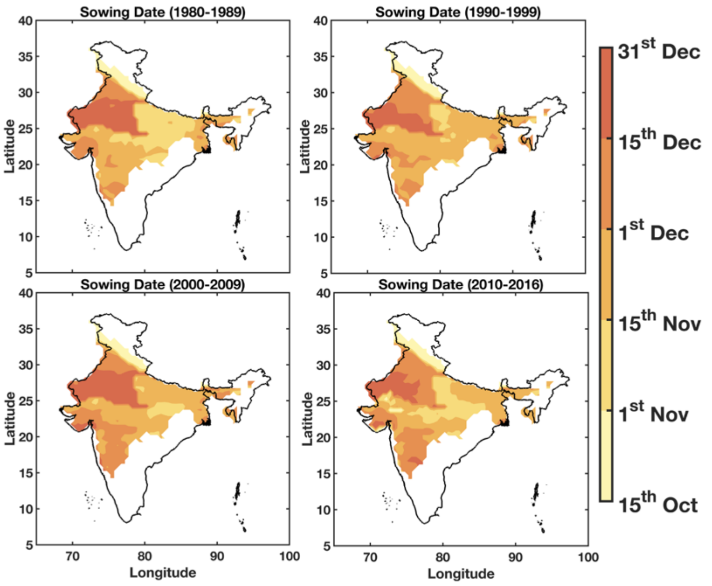

Figure 4: Variation in sowing dates of spring wheat simulated by ISAM during different decades

6) **Finally, before showing the spatial pattern and temporal trends of carbon fluxes, there are so many other intermediate variables which should be checked, such as leaf area index, biomass, and crop yield.**

In response to comments 2 and 6, we will include spatial yield plots from the control run in the revised manuscript. We will also incorporate the spatial patterns of LAI and biomass.

In addition, we will also include site-scale plots of LAI [Figure 3] that show our model simulations agree with the seasonality and values of the observations in most of the growing seasons.

Other comments:

Figure 1: Why did the authors only show monthly data here? Daily time series of carbon fluxes can also be added here.

We focus on the decadal scale variation in carbon fluxes from the wheat-growing regions. That is why monthly data is appropriate. Furthermore, we do not have access to the hourly data.

L124 and L134: what's the criteria of steady state of soil parameters? The authors should demonstrate that by plotting the data.

The steady-state soil parameter criteria used in the study are similar to Yang et al. [2009]. We would add this information to the revised manuscript.

Figure 2: what is leading to the systematic bias here?

We thank the referee for pointing this out. We investigated this issue in detail. We found that the sowing dates simulated by ISAM are in the second week of December, as opposed to the last week of November in the observed data [Patel et al., 2011 and 2021]. Because the crops in Patel et al. [2011 and 2021] are sown earlier, they are phenologically ahead of ISAM crops by

2-3 weeks. Hence, there is a positive bias in the observations. In the revised manuscript, we will modify this plot so the comparison is made for the same 'days after sowing' instead of on the exact dates. We will replace Figure 2 in the manuscript with the following figure.

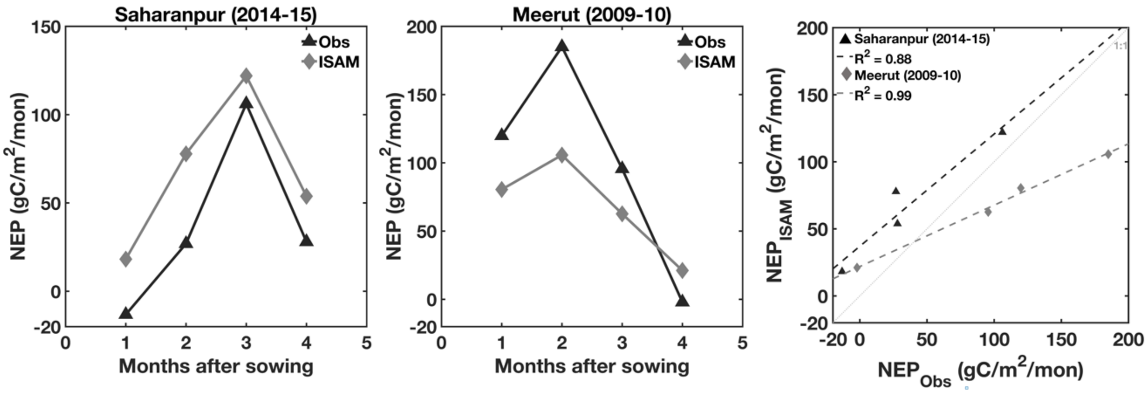

Figure 5: NEP simulated by ISAM compared against the observations [Patel et al., 2011 and 2021]

Figure 4: Is the Ra here too low? The rule of thumb is that NPP=0.5GPP, which indicates that Ra~0.5GPP.

Amthor and Baldocchi (2001) reported a Ra/GPP range of ~0.3-0.6 for crops like wheat. Our value of 0.26 is slightly lower than that. Many studies [Table 2] report a Ra value of ~0.5GPP. These are all winter wheat with a vernalization period and a growing length of more than 200 days; in our case, it hardly crosses 150 days. Interestingly, Zhang et al. [2020], who reported Ra values similar to ours, also consider full irrigation identical to our study, while the other studies are not irrigated.

Referee II Comments:

1) **Authors of this manuscript use ISAM model calibrated over a wheat site to explore the carbon flux change over Indian spring wheat region since 1980. They further performed factorial simulations to attribute the carbon flux change. Overall, the manuscript addresses an interesting topic, but the quality of the study and the presentation need to be improved before it could be acceptable.**

   We thank the referee for the encouraging comment.

   We will add the validation of ISAM simulated yield [Figure 1] and LAI [Figure 3] to establish confidence in our simulations. We will also add the spatial trends in carbon fluxes (the 1980s to the 2010s) to improve our understanding of the carbon fluxes in Indian wheat-growing regions. We hope that with these additions and expanded discussions, this manuscript will meet the high standards of the Earth System Dynamics journal.

2) **Some critical details of the model and modelling experiments were missing from the manuscript. For example, the author stated that ISAM_dyn_wheat with dynamic phenology, carbon allocation, and vegetation phenology. However, how these modules were formulated remains unknown.**

   The current study is a follow-up to Gahlot et al. [2020]. The model simulations were conducted for that study. That study looked at spring wheat production and its drivers. In this study, we are looking at the carbon fluxes and their drivers using the outputs of the same simulations. Here, we conducted some simulations to extract LAI at higher frequencies to evaluate the simulated LAI against observations. However, the model configuration remained the same as in Gahlot et al. [2020]. Hence, for brevity, we had not provided a detailed description of the model and configurations but referred the referees and the readers to Gahlot et al. [2020]. In the revised manuscript, we will add more to describe the relevant sections of the model that are required to understand the current study. This will include a description of the phenology and yield calculation described in our response to comment two by Referee I. We will also add details on the ISAM_dyn_wheat module and the numerical experiments. ISAM_dyn_wheat is built on the default ISAM_C3_crop by adding dynamic planting, new allocation parameters, and a heat stress module specific to Indian spring wheat.

3) **The authors simulate three decades' change of cropland carbon flux, but how change in crop varieties and management practices was accounted remain unknown. If these changes were not accounted, the simulated change in the carbon flux could be far away from the reality.**

These are both very important factors for spring wheat agroecosystems. We already include nitrogen fertilization and irrigation, the two main management practices used in India, in our study. The details of implementing these practices are given in Gahlot et al. [2020]. Results show that these management practices strongly affect yield [Gahlot et al., 2020] and carbon fluxes [this study].

Many studies show that using different cultivars can significantly change spring wheat yield, but there are no studies on the effects on carbon fluxes. Thus, studying the impact of cultivars on carbon fluxes is an exciting and open question. This effect was not incorporated in our study. The spatiotemporal maps of cultivar use and site scale carbon flux and phenology data for various cultivars are unavailable and will be challenging to develop. The community should strive to create such datasets to understand better and simulate different cultivars' effects. We will discuss this issue in the Discussions section.

4) **Carbon fluxes over croplands heavily depend on phenology and managements. These conditions could vary largely from year to year. While the authors recognize the importance in accounting them, in calibrating and validating their model, the phenology and flux data driving the model come from different years. This should introduce biases/uncertainties.**

Yes, validating the carbon flux simulations with data from different growing seasons than the crop phenology data would have introduced bias. We used the same management practices over the two years to minimize errors. During the revision of the manuscript, we compared the seasonal carbon uptake of ISAM and datasets by Patel et al. [2011 & 2021], which reported carbon fluxes for Saharanpur and Meerut [Figure 5].

We have added this to our manuscript, and we could observe that the seasonality is well simulated, but the ISAM simulations have bias. The bias is likely due to the difference in the sowing dates followed at the sites and the ones simulated in ISAM.

5) **While calibration of the crop model in a site with good observation is helpful for robustness of model simulation results. However, using the model calibrated on one site to represent the entire Indian spring wheat region is far from giving readers good confidence. There are many satellite observations and statistics available to test model**

performance (e.g. LAI, FPAR, and yield), which should be used to validate the model in regional applications.

We understand the need for more extensive validation of the model. We have extended the ISAM yield and crop phenology validation against the gridded data and site scale observations [Figures 1 and 3]. We would add these to our revised manuscript.

6) Attribution of carbon flux change to climate variations at regional scale have strong spatial heterogeneity. A simple bar figure is not very informative, in particular for changes in climatic variable.

We agree with the referee that spatial heterogeneity is an essential aspect of the results that have not been looked at in the current version of the manuscript. We will add the spatial trends in GPP, TER, and NEP [Figures 6 and 7] and expand the results section explaining the patterns observed.

We observe that there is a significant increase in carbon fluxes in the Indo-Gangetic plains compared to all other wheat-growing regions. We could attribute the spatial pattern in carbon fluxes to the impact of individual climate variables [CO2] and temperature by comparing the spatial trend patterns of the factorial simulations. Higher temperatures alone caused a reduction in carbon fluxes in recent years [Figure 7: 2nd row]. As temperatures rise, crops absorb less carbon from the atmosphere during the spring wheat season. Higher [CO2] alone has resulted in a very low increase in NEP change between the 2010s and 1980s [Figure 7: 1st row], and the change is not significant in most parts of the wheat-growing regions. These issues will be discussed in the revised manuscript.

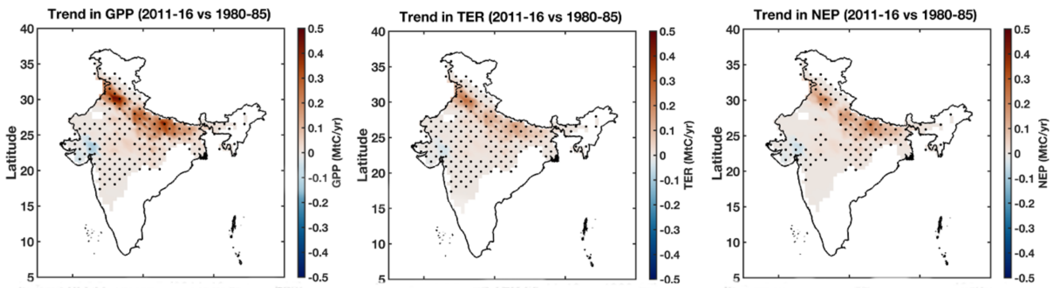

Figure 6: The spatial trend in fluxes from spring wheat. The stippling shows the grid cells with a significant trend at 95%.

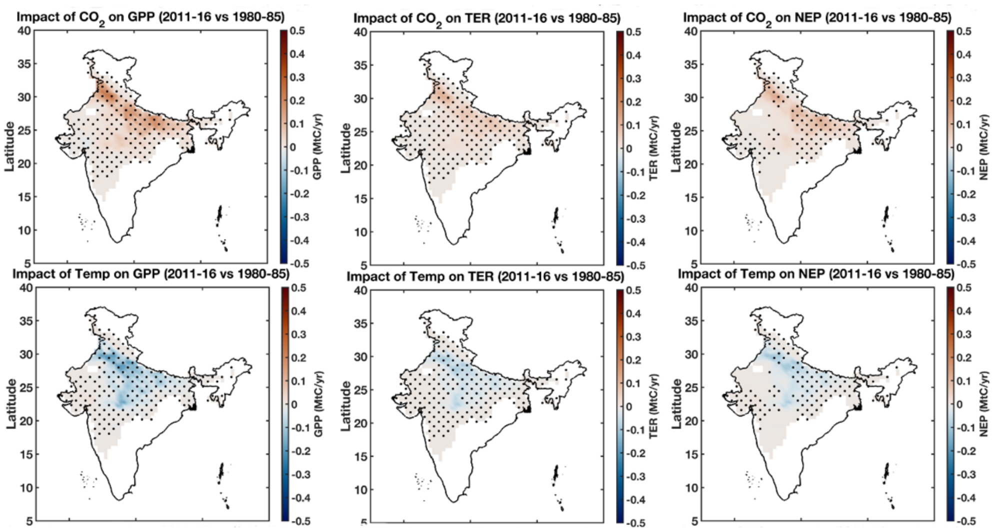

Figure 7: Impact of [CO2] and temperature on the observed carbon fluxes. Impact on trend is calculated as Impact of [CO2] = Trend in CTRL run - Trend in S_CO2 run.

References:

Amthor, J. S., and Baldocchi, D. D.: Terrestrial Higher Plant Respiration and Net Primary Production, Terr. Glob. Product., 33–59, https://doi.org/10.1016/B978-012505290-0/50004-1, 2001.

Aubinet, M., Moureaux, C., Bodson, B., Dufranne, D., Heinesch, B., Suleau, M., Vancutsem, F., and Vilret, A.: Carbon seques-tration by a crop over a 4-year sugar beet/winter wheat/seed potato/winter wheat rotation cycle, Agr. Forest Meteorol., 149, 407–418, https://doi.org/10.1016/j.agrformet.2008.09.003, 2009.

Demyan, M. S., Ingwersen, J., Funkuin, Y. N., Ali, R. S., Mirzaeitalarposhti, R., Rasche, F., Poll, C., Muller, T., Streck, T., Kandeler, E., and Cadisch, G.: Partitioning of ecosystem respiration in winter wheat and silage maize modeling seasonal temperature effects, Agr. Ecosyst. Environ., 224, 131–144, https://doi.org/10.1016/j.agee.2016.03.039, 2016.

Gahlot, S., Lin, T. S., Jain, A. K., Baidya Roy, S., Sehgal, V. K., and Dhakar, R.: Impact of environmental changes and land management practices on wheat production in India, Earth Syst. Dynam., 11, 641–652, https://doi.org/10.5194/esd-11-641-2020, 2020.

Jägermeyr. J., Müller. C., Ruane. A. C., Elliott. J, Balkovic. J., Castillo. O., Faye. B., Foster. I., Folberth. C., Franke. J. A., Fuchs. K., Guarin. J. R., Heinke. J., Hoogenboom. G., Iizumi. T., Jain. A. K., Kelly. D., Khabarov. N., Lange. S., Lin. T., Liu. W., Mialyk. O., Minoli. S., Moyer. E., Okada. M., Phillips. M., Porter. C., Rabin. S. S., Scheer. C., Schneider. J. M., Schyns. J. F., Skalsky. R., Smerald. A., Stella. T., Stephens. H., Webber. H., Zabel. F., and Rosenzweig. S.: Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat. Food 2, 873–885, https://doi.org/10.1038/s43016-021-00400-y, 2021.

Moureaux, C., Debacq, A., Hoyaux, J., Suleau, M., Tourneur, D., Vancutsem, F., Bodson, B., and Aubinet, M.: Carbon balance assessment of a Belgian winter wheat crop (Triticum aestivum L.), Glob. Change Biol., 14, 1353–1366, https://doi.org/10.1111/j.1365-2486.2008.01560.x, 2008.

Suleau, M., Moureaux, C., Dufranne, D., Buysse, P., Bodson, B., Destain, J. P., Heinesch, B., Debacq, A., and Aubinet, M.: Respiration of three Belgian crops: Partitioning of total ecosystem respiration in its heterotrophic, above- and below-ground autotrophic components, Agr. Forest Meteorol., 151, 633–643, https://doi.org/10.1016/j.agrformet.2011.01.012, 2011.

Wang, Y. Y., Hu, C. S., Dong, W. X., Li, X. X., Zhang, Y. M., Qin, S. P., and Oenema, O.: Carbon budget of a winter-wheat and summer-maize rotation cropland in the North China Plain, Agr. Ecosyst. Environ., 206, 33–45, https://doi.org/10.1016/j.agee.2015.03.016, 2015.

Zhang, Q., Lei, H., Yang, D., Xiong, L., Liu, P., and Fang, B.: Decadal variation in CO_2 fluxes and its budget in a wheat and maize rotation cropland over the North China Plain. *Biogeosciences*, *17*(8), 2245–2262. https://doi.org/10.5194/bg-17-2245-2020, 2020.

Tables:

Table 1: The site details, growing season, and the yield used for the ISAM simulations.

S No	**Site Name**	**Latitude**	**Longitude**	**Sowing Year**	**Yield (kg/ha)**	**Growing Season Length (days)**
1	Cooch Behar	26.19	89.23	2000	3753.67	120
2	Cooch Behar	26.19	89.23	2001	3882.7	121
3	Faizabad	25.26	82.99	2002	4182.33	142
4	Faizabad	25.26	82.99	2003	5082	129
5	Faizabad	25.26	82.99	2004	5152	121
6	Gwalior	26.14	78.15	2013	4309.875	113
7	Jobner	26.51	75.28	2002	4140	129
8	Jobner	26.51	75.47	2013	3676.75	127
9	Jobner	26.51	75.47	2014	3520.25	131
10	Jobner	26.51	75.47	2015	3896	135
11	Ludhiana	30.54	75.56	2011	4571.67	170
12	Ludhiana	30.54	75.56	2012	4579.33	169
13	Meerut	29.4	77.42	2011	3742.495	138
14	Meerut	29.4	77.42	2012	4072.33	142
15	Meerut	29.4	77.42	2013	4206	142
16	Nadia	22.95	88.95	2001	3420	92
17	Nadia	22.95	88.95	2002	3433	124
18	Nadia	22.95	88.95	2008	3175	134
19	Nadia	22.95	88.95	2009	3356	137
20	Nadia	22.95	88.95	2013	3782	126
21	Pantnagar	29.02	79.4	2007	3982.33	126
22	Pantnagar	29.02	79.4	2008	3603.67	126
23	Parbhani	19.16	76.47	2001	2907.22	109
24	Parbhani	19.16	76.47	2005	4450	120
25	Parbhani	19.16	76.47	2009	2761	106

Note: A comprehensive crop dataset for the modeling community to calibrate and validate crop models over the Indian region is included in the current study. Here we show the yield and growing season length data of 9 spring wheat sites across 25 growing seasons.

Table 2: Comparison of the carbon flux ratios in various studies

S No	NPP/GPP	Ra/GPP	TER/GPP	Reference
1	0.7385	0.2615	0.5006	This study*
2	0.76	0.24	0.59	Zhang et al. (2020)
3	0.56	0.44	0.60	Aubinet et al. (2009)
4	0.52	0.48	0.57	Aubinet et al. (2009)
5	0.51	0.49	0.71	Demyan et al. (2016)
6	0.54	0.46	0.61	Moureaux et al. (2008)
7	0.55	0.45	0.57	Suleau et al. (2011)
8	0.57	0.43	0.66	Wang et al. (2015)