RESPONSE TO REVIEWERS' COMMENTS

Anonymous Referee #1

This study claims to provide a high resolution (4km by 4km) dataset of phosphorus inputs, timing and application methods for the USA using interpolation methods and existing datasets at the county and state level from 1850 to 2022. They make an admirable attempt at doing this and could provide an important dataset for those interested in nutrient balances for this country. However I believe the uncertainties could be better explained in the Discussion esp. related to areas not fertilized, and temporal variability in uncertainties given this is such a long term dataset taking data from multiple sources. Below I note some areas of their manuscript which could be elaborated on further to help the reader understand the uncertainty and accuracy of their estimates.

Response: We appreciate the reviewer's positive comments and suggestions for enhancing our manuscript's clarity and addressing the uncertainties, which greatly improve the quality of the manuscript. Please see our responses to the comments as follows.

*I believe the 4*4 km resolution the authors state gives a false sense of accuracy considering data at the state and county level are used for their estimates. Isn't the accuracy of their estimates determined by their lowest resolution data (i.e. at the state level)? Given the methods employed by the authors I believe it is quite a stretch to say it has 4*4km resolution. More Discussion should be made on this point, and perhaps the authors should refer to their study actually offering 'pseudo 4*4 km resolution' with state level accuracy. This would better indicate to users the uncertainty in their estimates and that really the accuracy is at the state level.*

Response: We thank the reviewer for this constructive suggestion! We agree that the accuracy of our product is at the county level. The crop distribution map provides the spatially explicit location of each crop at 1 km × 1 km resolution. Although the spatialization process assigns the consistent number to the same crop within each county, it displaces the variety of P management information across crops. We have carefully clarified the related process to avoid misunderstanding in lines 209-214.

Lines 209-214: “To characterize the variation in spatial P management information, we assigned the state-level (1850-1929) and county-level (1930-2021) crop-specific P management data generated above to 1 km × 1 km gridded maps based on historical crop type distribution maps of the CONUS from 1850 to 2022 developed by Ye et al. (2024). It is worth noting that the P management information remains consistent for the same crop within a given county but varies across crops, while 1-km annual crop type and area maps help add spatial heterogeneity of P fertilizer input within a county.”

Lines 93-96. Please include in Discussion, likely uncertainties in P consumption temporally. I assume there will be more uncertainty in the historic estimates from the 1800’s than the latter surveys?

Response: We thank the reviewer for pointing out this uncertainty. The uncertainties in temporal P use vary among different scales. We have summarized the data availability for different time periods and scales in the supplementary (Table S1, S2-S5). At the national scale, data for P fertilizer consumption from 1850 to 1900 are sourced from Mehring et al. (1957), whereas state-level and county-level P fertilizer consumption data are available after 1930 and 1950, respectively. State- and county-level missing data prior to the unavailable periods was interpolated using the available P consumption data from the upper-level scale as a reference. As suggested, we have addressed these uncertainties in Section “4.3 Uncertainty” regarding data availability for temporal data construction in lines 379-385.

Line 379-385: “The reconstructed P fertilizer management data extends back to 1850. However, compared to the national P fertilizer use information, the state- and county-level data are only available from the 1930s onwards. Due to the absence of earlier data, we interpolated the state-level P fertilizer consumption data back to 1850 by assuming they have the consistent interannual variations with the national data. This approach to addressing the temporal gaps may introduce larger uncertainties in the state-level temporal trajectories before the 1930s.”

Line 142. Where did you get data for the fertilized cropland percentage. Please add this to the method.

Response: Thank you for pointing out this. The fertilized cropland percentage data is paired with the P fertilizer use rate data, representing the percent of cropland that receives P fertilizer. In the Methods section, we have updated our description of the data sources for fertilized cropland percentage in lines 139-141.

Line 139-141: "We obtained the state-level crop-specific P application rates of 9 crops from 1954 to 2022 from the same data sources as national crop-specific P application rates (Table S4). This includes the information of P application rates in the fertilized croplands and percentage of fertilized croplands."

To further clarify the sources of these data, we have revised the title of Supplementary Table S4 to "Data sources for national and state-level average crop-specific P fertilizer application rate and percentage of fertilized croplands" to provide more details.

Line 148. How did you account for areas of wheat not fertilized?

Response: Please refer to the previous response. The percentage of fertilized cropland for wheat in each state was also derived from the same data sources as those for other main crops, as listed in Supplementary Table S4. Due to the lack of information on where croplands are fertilized, we assumed all the croplands in each state, including the area that was not fertilized, was fertilized but with a lower rate by multiplying the rates in the fertilized cropland with the percentage of fertilized cropland.

Line 156-157. Again how did you account for areas of other crops that received no fertilizer at all?

Response: Please refer to the previous two responses. We assumed other crops in one given county receive P fertilizer at the same rate, in order to keep the total fertilizer consumption consistent with historical census data without knowing where other crops were or were fertilized within a county. The uncertainties caused by this assumption have been included in the discussion section 4.3 Uncertainty, lines 386-390.

Line 186. You claim in your abstract that 40% of cropland has remained unfertilized in the last decade, but on line 186 you suggest you do not have spatial information to locate fertilized area. So how do you know the same 40% area has been left unfertilized? Based on line 186 it seems like you are showing average application rates across all area and not accounting for non-fertilized areas. Lines 195 onward you mention USDA-ERS data for % cropland fertilized, but how did you get % area fertilized before the USDA-ERS data before 1996?

Response: We thank the reviewer for highlighting the unclear description. The fertilized percentages for application timing and method differ from the percentage of fertilized croplands mentioned in the previous sections. The USDA-ERS reported the application rate and fertilized area percentage for each timing and each method within each state. We used this information to partition the annual P use into different timings and methods. To clarify, we have revised our description in Lines 187-192. These percentages specifically indicate the area that received fertilizer for different timings and methods, and therefore, they do not conflict to the overall fertilized cropland percentage mentioned elsewhere. The available data for the percentages of timing and method spans from 1996 to 2013. We assumed that the same application method strategy was used before 1996 and after 2003. we revised our description on P fertilizer application method in lines 209-210.

Lines 187-192: "The raw data includes crop-specific P fertilizer application rates and percentages of the fertilized cropland for each of the 4 timings in each state. We calculated the P fertilizer consumption at each timing by multiplying the application rate with the area percentage and total cropland area. The fraction of the P fertilizer consumption at each timing was used to split the annual P fertilizer application rate generated in Sect. 2.1 into 4 application timings."

Lines 199-200: "For the years before 1996 and after 2013, we assume farmers adopt the same application methods of years 1996 and 2013, respectively."

Line 319: Can you explain the brief decline in 1980's. Was there policy changes or a shock to the supply/demand for P that aligns to your estimates? This would be a nice way to cross check your estimates to make sure they make sense in terms of trends

Response: This is a good catch and suggestion, and we appreciate it. In the 1980s, many developed countries, including the US, experienced a decline in the use of P fertilizer due to several factors, such as the increasing P fertilizer use efficiency, increased use of animal manure, and the 1980s farm crisis (Scholz et al. 2013; Bouwman et al. 2017; Zhang et al. 2018). Figure 2(b) and Figure S2 indicate that the P fertilizer rate and consumption of corn have decreased since 1980s, contributing to the overall decline in P use in the US. We have added some discussions in lines: 338-341 to reflect this.

Lines 338-341: "Following a brief decline in the 1980s due to improved fertilizer use efficiency, increased use of animal manure, and farm crisis (Scholz et al., 2013; Bouwman et al., 2017; Zhang et al., 2018), P consumption has stabilized with annual fluctuations primarily caused by changes in grain demand and fertilizer prices (US-EPA, 2024)."

Bouwman, A. F., Beusen, A. H. W., Lassaletta, L., Van Apeldoorn, D. F., Van Grinsven, H. J. M., Zhang, J., & Ittersum Van, M. K. (2017). Lessons from temporal and spatial patterns in global use of N and P fertilizer on cropland. Scientific reports, 7(1), 40366.

Scholz, R. W., Ulrich, A. E., Eilittä, M., & Roy, A. (2013). Sustainable use of phosphorus: a finite resource. Science of the Total Environment, 461, 799-803.

Zhang, W., & Tidgren, K. (2018). The current farm downturn vs the 1920s and 1980s farm crises: An economic and regulatory comparison. Agricultural Finance Review, 78(4), 396-411.

Section 4.3. Discussion should be made about how uncertainty in areas not fertilized could influence average fertilizer rates.

Response: We agree with reviewer for addressing the uncertainty in fertilized area percentage. The discussion has been added in lines 395-399.

Lines 386-390: "(3) Due to the lack of information on where croplands are fertilized, we assumed all the croplands in each state were fertilized but at a lower rate by multiplying the rates in the fertilized cropland with the percentage of fertilized cropland. This could lead to underestimation of P fertilizer use rate in fertilized areas and overestimation in non-fertilized area, especially when the state-level fertilized cropland percentage is low."

Anonymous Referee #2

Understanding and assessing the spatiotemporal patterns in crop-specific phosphorus (P) fertilizer management is crucial for promoting crop yield and mitigating environmental problems. This manuscript combined the top-down and bottom-up method as well as data source to rebuild the crop-specific P fertilizer inputs from 1850 to 2022. I believe it could be highly interesting for readers and related researchers. Before publication, there are still some problems as follows:

Response: We appreciate the reviewer's interest in this work and for the insightful comments.

In the line 157-165, you mentioned that "the summed P consumption of 9 major crops exceeds the state total P amount in some states", and "the negative rates of the Other Crops were replaced by the average". Thus, the total amount of P consumption could be increased, and do you have updated the increased parts for the county level or the state level?

Response: We thank the review for pointing out the unclear description. In our analysis, when "the summed P consumption of 9 major crops exceeds the state total P amount in some states", we adjusted only these nine main crops to align with the total consumption, without changing values in total P consumption. This approach is based on our assumption that total P fertilizer consumption data from sales (top-down source) are more reliable than other data sources. The specific steps are as follows: if, in any state, the sum of P fertilizer consumption of nine main crops exceeds the total state P fertilizer consumption, which result in a negative values of P fertilizer consumption in other crops (total P fertilizer consumption minus P fertilizer consumption of nine main crops), we replaced negative values of P fertilizer rate for other crops with either a 10-year moving average or the interpolated values, and further adjust the values of main crops to match the total P fertilizer amount. We have revised the description in lines 161-173.

Lines161-173: "We adjusted the crop-specific application rates of major crops to match the state total P consumption by assuming that total P consumption data from top-down source is more reliable. First, we reconstructed the positive application rates of Other Crops in each state. If the 10-year moving average of the positive application rates of the Other Crops was available, we used it to replace the negative rates of the Other Crops. Otherwise, if the moving average was unavailable, we interpolated the gaps using the area-weighted mean of Other Crops across all states within the corresponding region as the reference trend. The selection of Eq. (1) and Eq. (2) for interpolation depends on the availability of the beginning and ending year of the gap. After excluding the P fertilizer consumption of cropland pasture, Other Crops, permanent pasture, and non-farm uses from the state total P consumption, we used the remaining total consumption to scale the crop-specific P fertilizer application rates for major crops."

In your study, you have estimated the crop-specific P application rate, and then you have converted the unit of P use from cropland area to land area. It could be very confused. If one grid with less cropland but higher P application rate, it could be presented very low P use.

Response: We appreciate this point. As the reviewer noted, it is true that a grid with less cropland but a high P fertilizer rate will appear to have a low P rate on the map when we use total land area for spatialization instead of cropland area. We have compared the P application rate maps using total land area versus cropland area, and both maps have their pros and cons. For the maps using cropland area, a high fertilization rate in grids with low percentage of cropland may mislead the readers by showing a high level of P fertilizer input in such areas. Ultimately, we opted to convert the cropland area to land area for the following reasons: (1) It presents a clear overall spatial patterns of P application rate, with hotspots representing both high-levels of P fertilizer use rate and larger cropland acreage. (2) It facilitates future studies in identifying and comparing the levels of P fertilizer received by per unit land area on map, using the same land basis. Potential users may use this P fertilizer database to drive ecosystem/environmental models to quantify plant growth, environmental quality, etc. In such cases, presenting the P application rate across all land areas simplifies the way to use the database and minimizes potential errors (e.g., discrepancies arising from using different land use datasets) for other researchers. (3) The application rate can be easily transferred to consumption by timing the map to gridded land area with no need to consider the cropland density in each grid. Vice versa, this data product can be converted to P fertilizer use rate on per unit cropland area by lining up with our crop type and area database (Ye et al., 2024). We included this statement in the figure captions.

The result section is not enough to present your studies, especially for changes and reason on the magnitude and spatiotemporal of P fertilizer use. The increase of P fertilizer use can be due to crop change or the increase of application rate, and thus I believe it could be some points on these reasons.

Response: We agree that the changes in P fertilizer use can be attributed to various factors. In the Result section 3.1, we concisely illustrated the patterns of P fertilizer use change across crops over time and space. In the Discussion section 4.2, we systematically examined the potential causes contributing to these spatiotemporal patterns. From 1850 to 1940, the increasing application rate among crops was the primary drivers of the rising P fertilizer use. After 1940, both changes in application rate and spatial cropland distribution significantly influenced the temporal change in P application rate. As suggested by reviewer in the below comment, we have added a stacked area plot of P consumption by different crops from 1930 to 2022, providing an additional perspective on the contribution of different crops.

The section of "Patterns of P fertilizer application timings" and "Patterns of P fertilizer application methods" are too short, and I suggested to add some interesting results.

Response: We appreciate this suggestion. Our current results just show the shares of different timings and methods across crops and space. To present the practice-specific application rate, we calculated the P fertilizer rate for different timing and method by multiplying annual P fertilizer application rate with the respective fractions for each timing and method. We replaced the original figures depicting the fractions of application timings and methods (previously Figures 7 and 8) with a newly plotted figure because it is more informative and meaningful. The original figures have been renumbered to Figures S4 and S5. Please see our statement about P fertilizer rates in different timings and methods in lines 275-282 and lines 290-295.

Lines 275-282: "In contrast to the wider distribution of different timing ratios, the hotspots of P application rate for 4 timings were found in the Midwest, the Great Plains, and the rice-belt due to generally low application rate in other regions (Fig. 7). Intense P fertilizer was applied in the fall in the Midwest (> 0.6 g P m^{-2}) (Fig. 7a), particularly in Iowa and Illinois. Spring application was concentrated in the corn-belt and rice belt with rates greater than 0.5 g P m^{-2} (Fig. 7b). Farmers in the Northern Great Plains, Kansas, Indiana, and Wisconsin favored application at planting (Fig. 7c). After planting applications were minimal (< 0.2 g P m^{-2}) in the rice-belt and Nebraska (Fig. 7d)."

Lines 290-295: "Due to the intense use of P fertilizer in the corn-belt and rice-belt, the hotspots of P application rate (> 0.6 g P m^{-2}) for 3 methods were found in various regions within these two belts (Fig. 8). Non-broadcast application is prevalent in the Northern Great Plains, Kansas, and Minnesota (Fig. 8a). Intense application of P fertilizer via broadcast with incorporation was observed in Minnesota and Illinois (Fig. 8b). The corn-belt and rice-belt received most of their P fertilizer through broadcast without incorporation (Fig. 8c)."

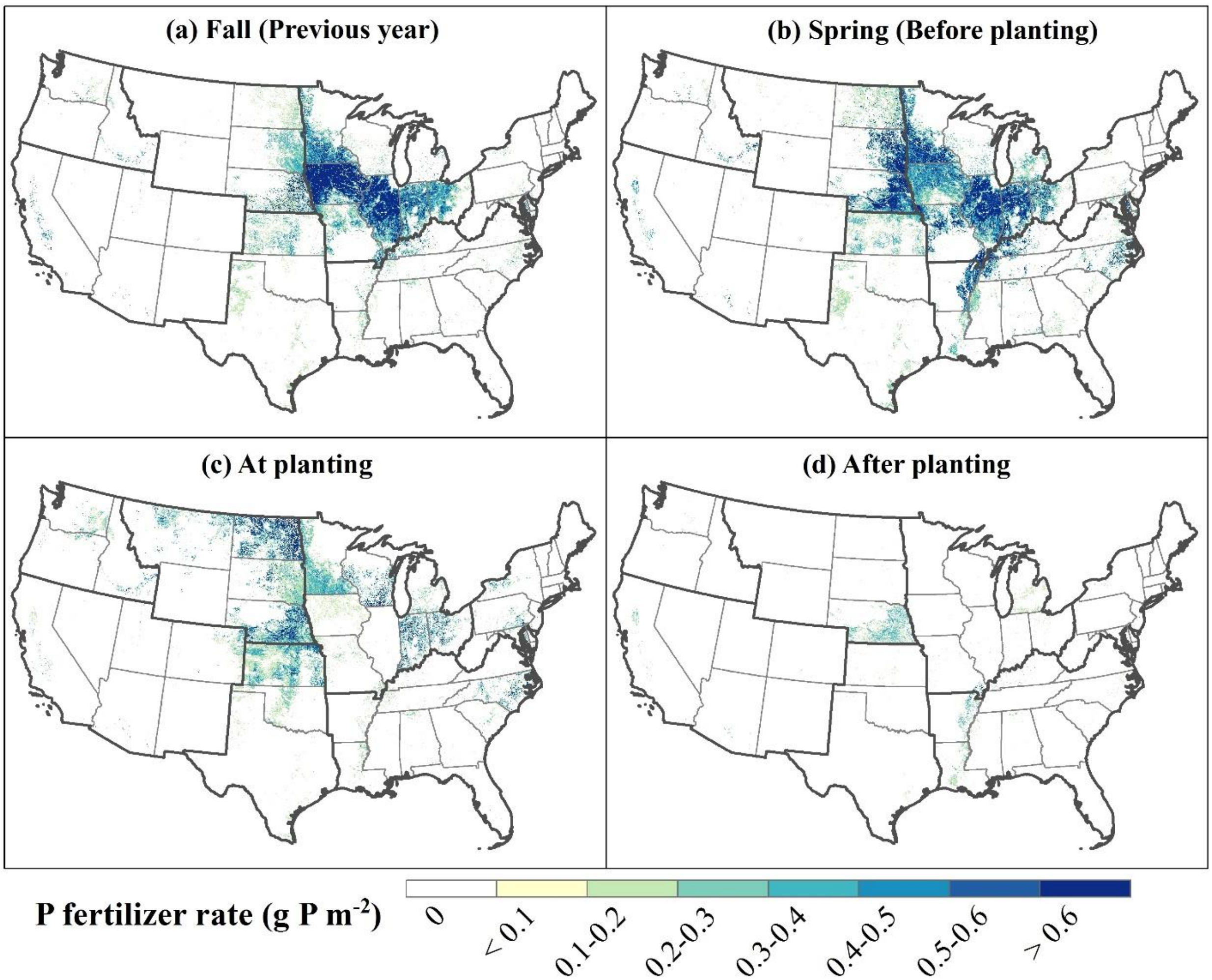


Figure 7. Spatial distribution of P fertilizer application rates at four application timings across the contiguous US in 2020.

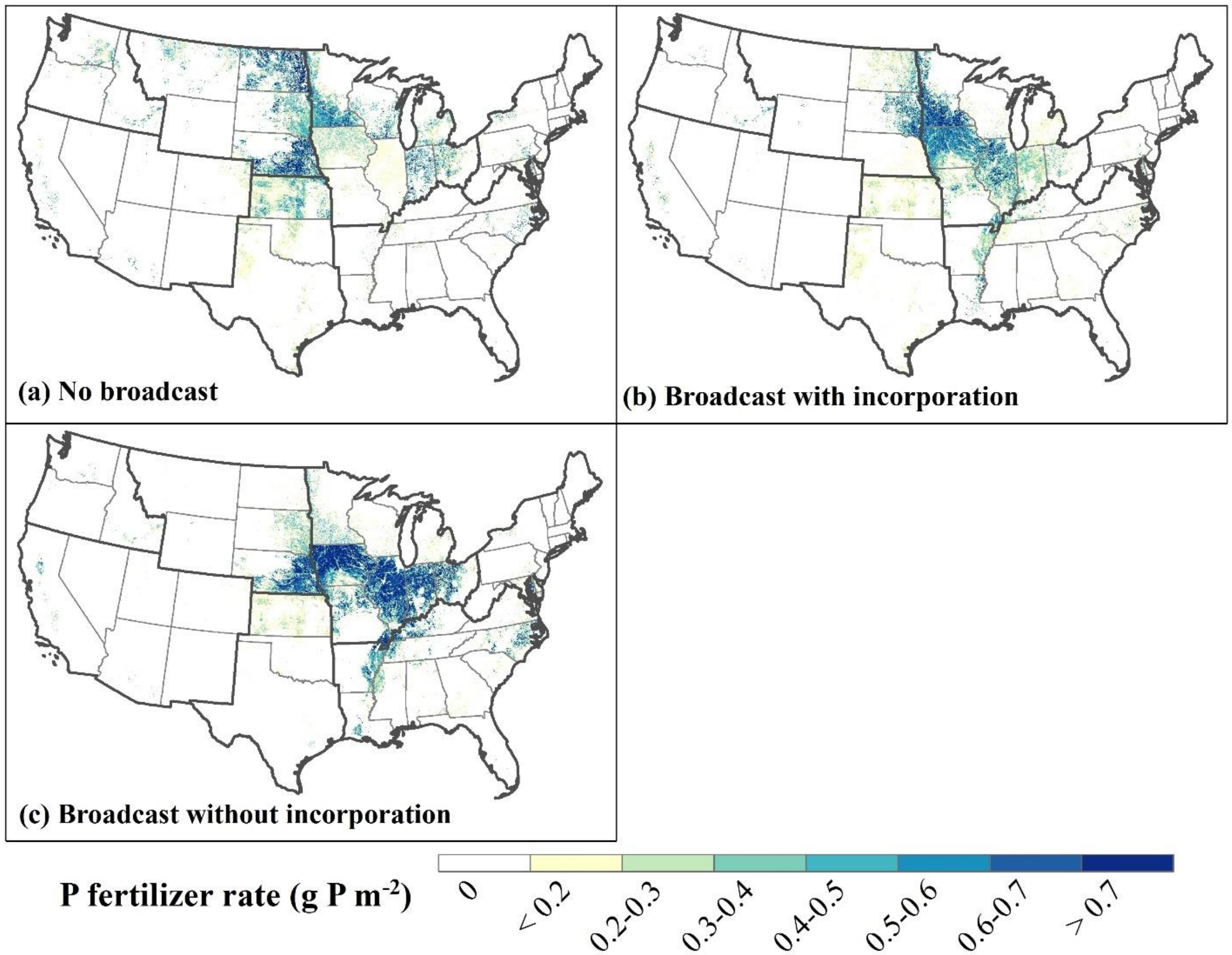
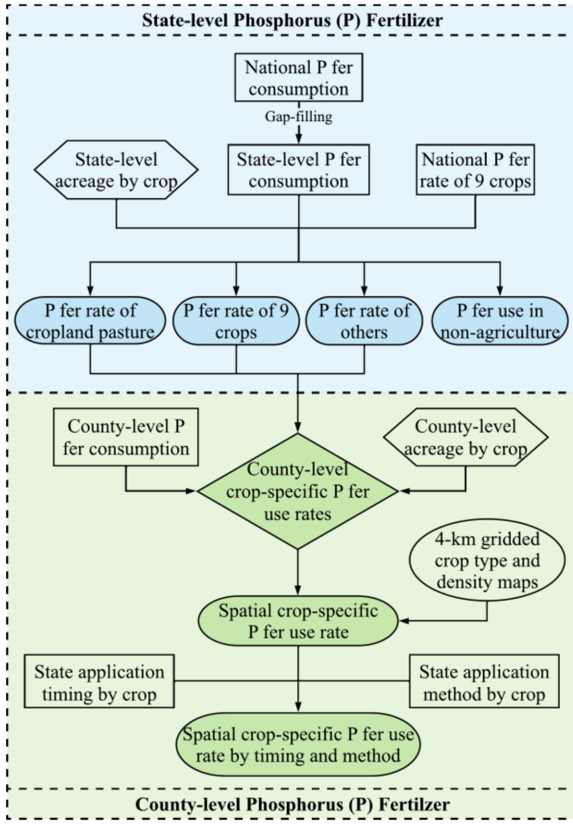


Figure 8. Spatial distribution of P fertilizer application rates in three application methods across the contiguous US in 2020.

Figure 1 is not easy to readable, suggest to improve it.

Response: We thank the reviewer for this suggestion. We have revised Figure 1 to enhance its readability by simplifying the original looping structure and adopting a hierarchical layout. Please see our attached figure below:



It is highly confused in Figure 2 (b). The light-colored bars denote the application rate on fertilized area and dark-colored bars show the application rate on all cropland. Thus, the light-colored bar should be higher than the dark-colored bar. However, the light-colored bar and the dark-colored bar are cumulative, and thus I am confused for the light-colored bar? Is it from the bottom (0 g P m-2) or the top of the dark-colored bar.

Response: Thank you for this observation. In Figure 2, the light and dark colors indicate the P fertilizer rates on treated cropland and all cropland, respectively, both starting from zero on the y-axis and they are not cumulative stacked bars. To avoid any misunderstanding, we have clarified the interpretation of the bar plot in the figure captions. Please refer to lines 556-558.

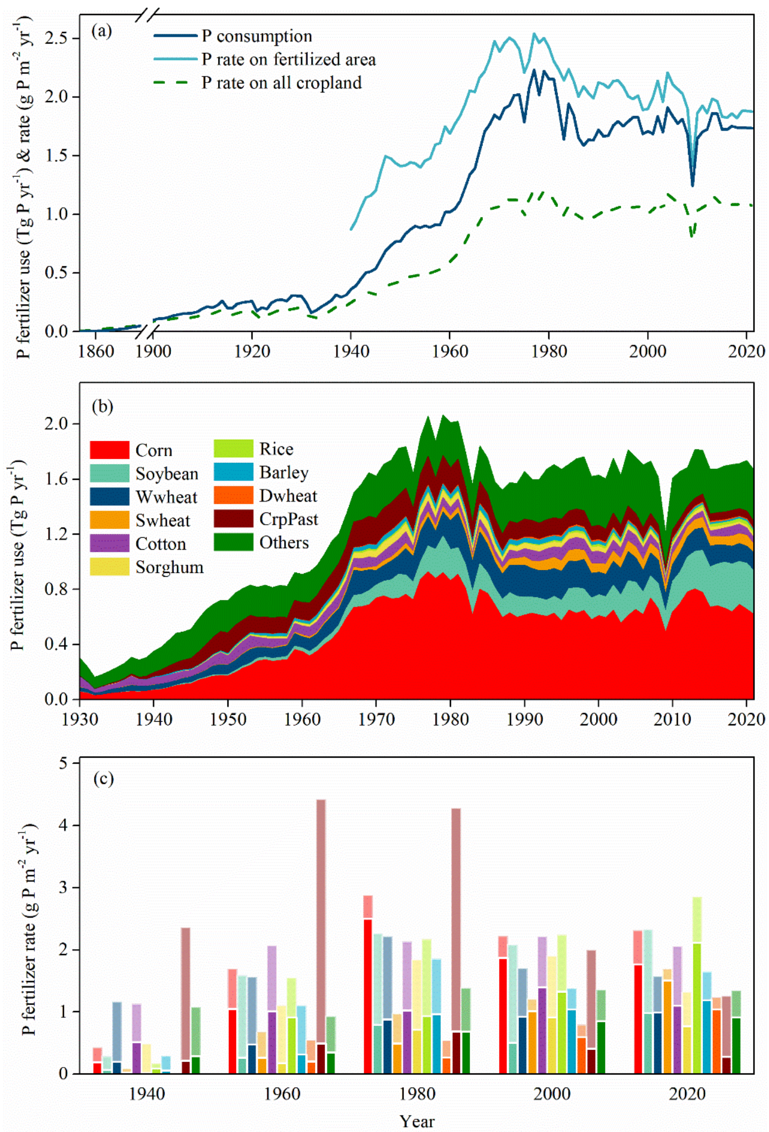
Lines 556-558: “In panel (c), light-colored bars denote the application rate on fertilized area and dark-colored bars show the modified application rate with the assumption that the county-level P fertilizer consumption was distributed on all the croplands. Both start from zero on the y-axis.”

I suggested the spatial distribution of P fertilizer application rates change to the total P consumption per grid.

Response: Thank you for the suggestion. After careful consideration, we have decided to continue representing our final map using the P fertilizer rate rather than total consumption in each grid for the following reasons: 1) Our P fertilizer application rate maps represent the rate on land area rather than cropland per grid. Therefore, the total P consumption can be obtained by multiplying our P rate maps with gridded area. Please see our response to reviewer #1. We are using the 'Albers Conical Equal Area' coordinate system in spatialization, in which each grid has the same land area (16 km^2), so converting P fertilizer rate into P fertilizer consumption does not alter the spatial pattern of our final map; 2) Information on total consumption for each state and county is already available in our tabular dataset (https://doi.org/10.5281/zenodo.10700822).

Can you add the country level of P fertilizer consumption and 9 major crops from 1950 to 2022.

Response: We appreciate this good suggestion. we have included the P fertilizer consumption data for all nine major crops and Other crop from 1930 to 2022 in Figure 2.



I suggest the unit P application rate should be changed to "kg P/ha".

Response: Thank you for your suggestion to change the unit of P application rate to "kg P/ha." The suggested unit is more common in agronomy, especially for N application rate. However, after careful consideration, we have decided to retain the original unit of "g P/m²." The g P/m² unit is metric-based and is more commonly used in ecological and environmental studies, facilitating detailed analysis at smaller scales. This metric unit is particularly beneficial for comparing results across diverse studies and regions, enhancing the granularity and applicability of our findings. We believe that maintaining this unit will provide clarity and consistency with existing literature.

There are some small errors in your manuscript as follows: - Line 224, conversely should be "Conversely"- 3.2 Patterns of P fertilizer application methods should be 3.3

Response: Thank you for pointing out this. We have corrected all the typos in our manuscript.