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."