

Interactive comment on “Global Phosphorus Recovery for Agricultural Reuse” by Dirk-Jan D. Kok et al.

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The authors would like to thank the anonymous referee for the constructive feedback and welcomed contributions. In the below, we would like to present our a summary of our response and the motivations for some of the decisions made.

1. The referee suggests presenting a motivation as to why we chose to use minimum production costs for production nodes and maximum bid prices for demand nodes instead of average costs/optimal prices. The referee wonders whether this potentially leads to an overestimation of trade, resulting in the misbalance of 109% total production to demand.

The rationale for this based on the assumption that both the producers and consumers

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maximize their profits. A producer will then be willing to recycle P only if it is able to at least recover its cost of producing it. Meanwhile, a consumer will only be able to buy as long as its profit is above zero. Thus the maximum price of recycled P that it is willing to pay is the marginal value of the crop that it grows, i.e. so-called maximum bid price. The space between these two prices (as long as minimum production cost is lower than the maximum bid price) is the space to negotiate and settle the price at which recycled P is traded.

The 109% imbalance the referee mentions derives from a balance made purely using the statistical throughput figures and population density maps for production, and crop phosphorus requirements and crop harvest area maps for demand. It is a summation of the estimated total livestock (cow, chicken, pig) phosphorus excretion and human phosphorus excretion rates, divided by the sum phosphorus demand of all agricultural areas. Since these production/throughput rates are taken as average (and in reality vary with age, diet, gender, and species for livestock and crops, etc), some error in this balance was imminent. Also, there are some major phosphorus consumers not included, such as the pharmaceutical industry and detergent manufacturers. In reality, these also have an at least 10% share of the actual global phosphorus demand. Including this 10% would likely balance the budget almost perfectly despite the generalizations. However, since we do not account for these actors in this study, we decided to just take the imbalance as is. We will definitely explain this imbalance in more detail in the revised draft to avoid future confusion.

2. The referee remarks the supply and demand curves in Figure A of the Supplementary Materials have inverted axis and ought to be concave instead of convex.

We agree that the figure is not entirely correct, the demand curve is convex while it is expected to be concave (however supply curve is expected to be convex as shown). We will adapt the illustrative figure accordingly. However, we intend to keep the axes as such since it does not influence the economic interpretation.

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3. The referee recommends to elaborate on the costs and implications of applying different technologies for different development regions. The authors agree that this is indeed insufficiently discussed in the manuscript. Although much of this discussion was intentionally left out to shorten the length of the manuscript, we agree that it is an important aspect of our study and therefore needs to be elaborated upon in the next revision of the article.

4. The referee suggests to rework the model description which is currently difficult to follow. The authors recognize that the model description can be improved and will attempt to do so in the revised version.

5. The referee has doubts about how realistic the model is, and cannot find justification for selecting the simulation years 2005, 2006, 2011 and 2015. The referee recommends running the model for all years.

The authors acknowledge that the model performance can be validated more rigorously. We will present model estimates for all the years. Also, we will include a model sensitivity analysis (see referee #1 comment) in the next draft.

6. The referee asks how labour wage is determined.

In the study, we assume a globally homogenous labour wage of 17 [\$ h-1] for truck drivers and cargo ship personnel. Although trucking wage in the U.S. is estimated at around 20 [\$ h-1], we arbitrarily assumed a slightly lower value considering that wages in the vast majority of the world are likely lower. We will explain this in the revised draft.

7. The referee asks to explain what 'resource cost' stands for.

The production cost of a production node has two main components: 1) The technology investment cost (fixed value for each technology) and, 2) a resource cost. While the investment cost is fixed per x number of people (i.e. 1 mio \$ per 500,000 people), the resource cost varies with the amount of product recovered (i.e. the cost of magnesium chloride for struvite precipitation ~ 740 [\$ t-1] P recoverable). We will explain in greater

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detail what the 'resource cost' entails in the revised version of the manuscript.

8. The referee notices that the study does not consider external phosphorus costs such as CO₂ emissions and energy demands, and recommends to explicitly mention these.

The authors acknowledge that these costs are relevant for consideration and discussion. Some assessment with regards to the difference in total CO₂ emissions was included in earlier versions of the model, but was later abandoned to reduce the (still very large) scope of the model. The authors will briefly discuss these external costs in the revised version.

9. The referee wonders if environmentally extended world input-output (EEIO) studies on phosphorus could make a valuable contribution to a more precise and realistic representation of phosphorus supply, demand, and in particular trade.

The authors believe that all studies on phosphorus, of whatever nature, can at this time make extremely valuable contributions to the effort of stimulating the transitioning to a sustainable phosphorus market in general, and that EEIO studies can play an especially important role in this at a national spatial resolution. However our model runs at finer resolution, so EEIO based datasets can be used to constrain sub-national (grid) scale estimates of P supply and demand. We will discuss this possibility in our revised version.

10. The referee mentions that two important aspects for the far-future scenario that are missing in his view: 1) the high prices of phosphorus, and 2) the availability of new and cheaper technologies.

The authors acknowledge that discussion of these dimensions is not present currently. Although the prices of phosphorus are determined to rise in our future scenario (in accordance to the referee's intuition and other study predictions), we do not account for a decrease in recovery costs due to technological innovation, or the introduction

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of new technologies to the market. Since the degree of innovation and extent of new technological developments are uncertain, we ignored this aspect all together in order to not complicate the study further. The authors definitely agree, however, that this merits much more attention and therefore this concept will be discussed in the revised version.

11. The referee references three additional sources that should be cited with regards to phosphorus recovery. The authors will consider these publications and cite them in the manuscript where relevant.

12. The referee recommends to introduce early on that the economic feasibility of P recovery varies in space as it depends on the concentration of P in wastewater, which is related to the population and livestock density.

The authors would like refer the referee to section 1.1, line 19 of page 2, where this concept of spatial variability is introduced quite early on. To bring this to greater attention, however, we will see if we can draw the link to population density also at this point, without adding to many additional words or unnecessarily overcomplicating the introduction.

13. Similar to referee #2, the referee (#3) is led into confusion by improper definition and inconsistent use of terminology. The authors recognize this issue and will address this in the revised version.

The authors would like to sincerely thank the anonymous referee for his well-grounded feedback. We hope we have understood correctly- and responded adequately to the referees questions, and we look forward to improving the manuscript accordingly.

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