## **KEY:**

Editor/Reviewer Comments  
Author Response  
Already in Text  
Modified Text  
**Comments from Reviewer #3**

**First Review/Response ()**

**Reviewer: 1**

Comments to the Author

The manuscript tries to determine phosphorus use efficiency by cereal crops by using data collected from FAO. The manuscript is very well written but there are some improvements that are needed. I believe the work is good but there are some revisions needed before I can recommend the manuscript for publication.

I am attaching a pdf file with some comments/revisions. However, the most important point I see from your work is that there is a huge difference in the PUE estimated based on the two methods. I was expecting that you would recommend what method is best and why future work should focus on using this method. The balance method is the most appropriate method in my opinion.

We agree with the use of the difference method, and have now validated the approach, especially for Macro statistics.

I say this because in soils where P is limiting, the addition of P will increase yield and also P uptake as a function of P application rate. For example, in corn the application of say 70 kg P2O5 ha will result in the uptake of 70 kg P2O5 ha-1. Although research using labeled P has shown that not 100% of the applied labeled P is recovered, the total amount of P removed from the field equals that applied. So the balance method seems to be the only method that captures this. You should be able to find enough work in the literature to support this and make the recommendation for the consistent use of one method only as opposed to many.

Agreed, we have tried to highlight the difference method

See attached the specific comments

13- indicate value calculated by difference method

This is now included. Thank you

14- indicate value calculated by balance method

This is now included. Thank you

13-14 – saying high or low doesn’t inform the reader the magnitude. Adding values is much easier to see what you mean

Included accordingly. Thank you

21- “that P deficiency” is it deficiency or unavailable

Correction made, this is more appropriately termed unavailable.

30- “solution is generally low” – what do you mean by low? 0.5 mg L-1 or 30 mg L-1 indicate the value.

Thanks for pointing this out. This is now delineated on page 2.

32-40 – In general the references used here are fairly old. There are newer Literature that uses state of art instruments such as XANES and have provided much better data consider revising.

Good point. New reference for Sato et al. (2005) was added.

42 – “several major soil orders are likely to be deficient in P” such as give citation

Brady and Weil (2008) has been included.

46-47 – “Consequently, these soils are to become dominated by Fe and Al, further increasing the fixing capacity of a soil and reducing the availability of P for plant uptake” it should be - Consequently, the soil solution of these soils is to become dominated by Fe and Al, further increasing the fixing capacity of the soil and reducing P availability for plant uptake.

Corrected accordingly. Thank you

48-50- “Additionally, soils such as Aridisols, Alfisols, and Mollisols are also associated with P deficiency, because these soils usually accumulate Ca that interacts with P forming insoluble compounds, once again deceasing P availability for plant uptake” provide citation.

Baligar et al. (2001) added. Thank you

51-54 – “The fixing capacities of soil have a direct impact on the dynamics of P, which in turn influences P losses from the soil to the environment, often resulting in eutrophication of water bodies. Losses of soil P can occur mainly by runoff of dissolved and particulate P (adsorbed and/or precipitated), leaching and subsurface run-off” – provide citation.

Hart et al. (2004) added.

56- Sims et al., 1998 – its 20-year-old any recent work?

Good point. Nonetheless, this work was iconic.

62-64 – “Considering the significance of P fertilizers for agricultural production and its relationship with population growth, it is understandable that PUE needs to be improved, principally in view of the non-renewable nature of P reserves” – perhaps add here how each method is calculated, or at least which methods are used, positive and negative aspects of each method, and citation.

Procedures for the computation of each method were included accordingly.

66 – “This same value for P, on a global scale, is not included in the literature” – rephrase to “The PUE, on a global scale, is not included in the literature”

Corrected. Thank you

68 - “PUE depends on the method” – method??

Good point, as this is redundant and not of use in this paragraph (deleted accordingly)

93 – “Using macro-data and assumptions established in previous research” – like what research? Add citation

Included, the Agronomy Journal 1999, 91:357 reference.

97-98 consider adding a subscripts to differentiate the methods: PUEB and PUED

This is a great suggestion and clearly better communicates the importance of these approaches.

97-104 – very confusing present one equation at a time and talk about it then present the second and talk about it.

As per your suggestion, these are now discussed independently.

104-114 – this sound more like discussion than methods

This has been altered accordingly and that was needed

119-134 – this section needs more clarification very confusing the way you handle PUE. It’s hard to know if you are talking about PUE diff or PUE bal.

This has now been changed to reflect balance (PUE-B) and difference (PUE-D) methods

146 – “rate of 228,698 Mg yr-1 (FAOSTAT, 2016)” how did you estimate this rate of increase is usually %, is this what you mean.

That sentence was poorly structured and has now been improved.

183-184 “Adjusting the soil pH above 5.5 and increasing base saturation to 50% are well-known strategies to improve P availability” in what soils?

Good point. This sentence has been restructured so as to communicate the value of altering soil pH and base saturation.

189-201 what about recent work liquid fertilization is a game changer

The use of different liquid P fertilizers has been shown to be advantageous and that is now cited accordingly.

**Reviewer: 2**

Comments to the Author

The paper is well written and makes a significant contribution to our knowledge on P. An even larger impact could be made if the authors included some meta-analyses of the data and attempted to determine the impact on PUE if the management techniques mentioned were implemented.

12- “P fertilizer consumption over 53 years” – about 7% increase per year

Included. Thank you

13-14 “difference method, and higher” – How much higher

Values included. Thank you

15 – “exists to promote improvement in the use of P fertilizers” – How?

This sentence has been omitted and no longer appears in the abstract.

46 – “Consequently, these soils are likely to become dominated” – delete consequently

Deleted. Thank you

80- “collected for maize, rice, wheat, sorghum, barley, millet, oats, rye, triticale and other cereal” provide scientific names for all crops.

Thanks for pointing this out, scientific names included

113 – why not use meta analyses for the statistical analyses

Thank you for the suggestion. Consistent with comments from the other reviewers, we have chosen to retain the present analysis/interpretation.

217 – “collected at a 0.30 m2 resolution obtained at a 1 m 2” superscript 2 need space between resolution obtained

Corrected. Thank you

226 - This paper provides a synopsis of previous reports and research. To make a more significant contribution, the authors could analyze the techniques for improving efficiency and then, using meta analyses, come up with the best estimate for how PUE could be improved using best management practices.

**Reviewer: 3**

General

The paper reviews literature from worldwide studies of phosphorus use efficiencies (PUE) in cereal crops, and provides an estimate of the global average PUE. There is considerable interest in an accurate estimate of PUE for global crop production. Thus the topic is relevant and timely, and a sound agronomic research paper is required. This in fact has potential to be a very highly cited paper, and thus requires rigorous review. The title, abstract and content are well-written, concise and clear in general, with the exception of one section around lines 209-217.

Thank you for your comments, especially the value of writing a good abstract.

The analysis in the manuscript as presented, however, provides only a single number as the estimate, without adequately describing its method of calculation in summary statements and in the abstract. The single number chosen is by the difference method, which on lines 69 to 71 is stated to be a less preferred method than the balance method advocated by Syers et al. (2008), which is considered an authoritative paper on the topic of PUE. Both the calculations and the method of presentation need to be revised in order to prevent serious misperceptions arising from communication of the essence of this article to the many audiences interested in this information. The current concluding statement “This work reports that world PUE is near 16% using the difference method” poses risk of being interpreted as “84% of applied P is wasted” or “84% of fertilizer P is lost” which is not likely the authors’ intent. This can be corrected by reporting results for both the balance and the difference method, and more specifically identifying what is meant by each.

Clarification of this value (16% PUE) is essential. No miscommunication can be tolerated as you have delineated. As suggested, definitions of the balance and difference methods have been partitioned. Critical to the understanding of using macro/world values (especially for PUE and/or recovery) is that the same total rates and removal estimates are/will be the same in ensuing years. This in turn negates “residual effects” as we understand them in short term, 2-4 year experiments. Discussion associated with macro/world estimates has been clarified in the text and that was clearly needed. Thank you for pointing this out.

Specific comments by line number

9 – 61% of the “total agricultural land” is incorrect – it should be of “total harvested cropland.”

Corrected. Thank you for pointing it out.

11 – The description of the increase in P fertilizer use gives the impression of a linear increase, while Figure 1 clearly shows a curve with declining growth rate, as well as an important period of decrease in the late 1980s and early 1990s.

The total differences (1961 to 2013) were the targets for this sentence. For the abstract, we would like to leave this the same. The altered response, over this time period is important but not critical within this context.

13 – The abstract does not provide sufficient information for the reader to interpret the difference between the difference method and the balance method. Since an abstract needs to be understandable on its own these terms need definition and/or description if they are to be used in the abstract. Also, “higher” is hardly adequate to describe the difference when estimates for the balance method are several fold higher than those by the difference method.

Actual values are now reported so as to avoid the incorrect use of “higher” as you noted. Differences in the balance and difference methods are more clearly defined within the text.

14 – The current phrasing suggests the non-renewable nature of P is an opportunity; in reality it would constitute a driver of the need to improve PUE.

Sentence has been deleted

16 – It is noted in the abstract that difference and balance methods give different results. Reporting only one thus requires a choice. Why does the author choose to present only the lower figure, particularly since several of the references cited conclude that the balance method is the preferred and more useful form of PUE to consider? Presenting only a single figure, without adequate definition of the method used, has high potential to mislead.

Thanks for pointing this out. Both values are now reported in the abstract.

24-28 – The references cited prior to 2010 are all out of date, since they were prior to the major revision published by IFDC in 2010 and subsequently accepted by the USGS. I suggest the earlier references be ignored, and that the authors consider referring to some or all of the following: USGS (2016): Annual Mineral Yearbook- Phosphate Rock [http://minerals.usgs.gov/minerals/pubs/commodity/phosphate\_rock/mcs-2016-phosp.pdf]. Van Kauwenbergh, IFDC (2010): World Phosphate Rock Reserves and Resources [http://pdf.usaid.gov/pdf\_docs/Pnadw835.PDF]. Van Vuuren D.P. et al (2010): Phosphorus demand for the period 1970-2100: a scenario analysis of resource depletion; Global Environmental Change v20. Scholz RS et al (2014): Comment on: “Recent revisions of phosphate rock reserves and resources: a critique” by Edixhoven et al. (2014); Earth Syst. Dynam. [http://www.earth-syst-dynam.net/7/103/2016/]

References before 2010 remain in the document, however, post-2010 references that you mentioned have been added.

29 – The phrase “Phosphorus is abundant in soil” is rather vague and may support misperceptions. A more specific statement, such as “Total phosphorus in surface soils varies from 0.005 to 0.15%” (Soil Fertility and Fertilizers, 8th edition, Havlin, Tisdale, Nelson, Beaton; Chapter 5, Phosphorus) would be more appropriate.

This paragraph has been reconstructed accordingly.

35 – The calcium compounds should be listed in order of decreasing solubility.

Thanks for pointing this out. Correction made

36 – Suggest a change: “Fe and Al will react with P forming strengite and variscite, respectively” to “Fe and Al will react with P, forming secondary minerals such as strengite and variscite, respectively”

Corrected. Thank you

59 – It is not only fertilizers that increase P losses when applied non-incorporated into soil. The same is true of manures, composts, and biosolids. Suggest “fertilizers” be changed to “P sources” or “P inputs.”

Corrected. Thank you

60 – The term “crop removal index” requires definition and description.

Crop removal index has been changed to crop requirement

60 – The word “which” seems to refer to the increased risk of P movement. It is the actual P movement that would be detrimental to aquatic systems.

Which was removed. Sentence structure altered for clarity

65 – Nitrogen use efficiency, like PUE, requires careful definition. The NUE referred to here is calculated as fertilizer N recovered in grain, which should be stated explicitly. It is not the same NUE as the more commonly used recovery efficiency (RE) calculated as the increase in crop above-ground N uptake as a proportion of the N applied, nor as the partial nitrogen balance (PNB) calculated as the N removed by crop harvest divided by the amount of N applied. It should also be noted that a wider range of nitrogen use efficiencies has been reported by others, e.g. Kitchen and Goulding, 2001, Chapter 13 in Nitrogen in the Environment: Sources, Problems and Management [http://www.sciencedirect.com/science/article/pii/B9780444504869500157], Ladha, J.K., H. Pathak, T.J. Krupnik, J. Six, and C. van Kessel. 2005. Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects. Advances in Agronomy 87: 85-176, and Cassman et al (2004) [AMBIO: A Journal of the Human Environment 31(2):132-140. <http://dx.doi.org/10.1579/0044-7447-31.2.132>]

As noted, NUE and PUE estimates need to be clearly delineated, and where additions and removals are carefully considered. We have added some of the important references mentioned and that articulate added issues surrounding nutrient use efficiency and N partitioning.

This now includes,

Cassman, K.G., A Dobermann and D.T. Walters. 2002. Agrosecosystems, nitrogen-use- efficiency, and nitrogen management. AMBIO. A Journal of the Human Environment. 31(2):132-140.

Wuest, S. B., and K. G. Cassman. 1992. Fertilizer-Nitrogen Use Efficiency of Irrigated Wheat: II. Partitioning Efficiency of Preplant versus Late-Season Application. Agron. J. 84:689-694.

67 – The reference cited (Roberts, 2007) does not appear to support the statement about PUE and lack of on-farm trials.

This paper has been removed, following your comments.

68 – A range of methods is also advocated for nitrogen use efficiency – see Kitchen and Goulding (2001, cited above), Cassman et al. (2002, cited above), Dobermann (2005) [http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1319&context=agronomyfacpub], and Dobermann (2007) [Nutrient use efficiency- measurement and management. 22 pp. Proc. of International Fertilizer Industry Association (IFA) Workshop on Fertilizer Best Management Practices. Brussels, Belgium. March 7-9, 2007.

We greatly appreciate the added references that have been provided. Several of the Cassman papers have now been included. This was clearly missing.

69-71 – Noting that the balance method is advocated over the difference method, the use of the difference method needs justification. Also, this statement implies that a figure calculated by the balance method should also be presented for comparison in the summary statements and in the abstract of the paper.

A concise justification has been included in Materials and Methods.

83-86 – it is not clear from the description whether a fixed ratio of cereal to cropland was used for the entire period, as compared to calculating the proportion of the area in cereals each year. The proportion may have shifted over time, as noted in lines 152-153.

Thanks for pointing this out, the ratio between total cereal and total world area was calculated for each year. It is now corrected in the manuscript.

83-87 – Using the sum of all harvested cropland area as denominator may lead to an overestimate of the proportion of global fertilizer going to cereals, because input to pasture, grassland and grazing land would not be included in harvested area. The International Fertilizer Association estimates about 49% of global fertilizer use going to cereals (Assessment of Fertilizer Use by Crop at the Global Level 2010-2010/11. Patrick Heffer, International Fertilizer Industry Association (IFA) International Fertilizer Industry Association (IFA) - 28, rue Marbeuf - 75008 Paris – France ifa@fertilizer.org - [www.fertilizer.org](http://www.fertilizer.org))

References included were almost exclusively wheat, maize, and rice, with one P recovery value coming from Barley. Also, the cited values primarily came from “difference method” estimates (10 of 14). The average difference and direct method estimates were 20 (50 values) and 13 (10 values) %, respectively. Average PUE’s reported for maize, wheat, and rice were 25, 15, and 22, respectively using the difference method.

Area estimates for maize, wheat, and rice fall between 163 and 246 million ha’s (2014 values). Depending on how this is weighted as was suggested, the average value will remain very similar since the wheat, maize, and rice production values are similar (www.fao.org/faostat).

100-101 – The wide range of recovery values evident in Table 2 suggests that this average recovery needs to be calculated with a careful weighting of crops and growing conditions. Crop species, cultivars, and the levels of soil available P have large influence on recovery. It is not clear from the description whether an appropriate weighting was used, whether it changed over the time period, or whether a fixed value of 20.7% was used for all crops and all years. In addition, the variance and confidence interval of the recovery should be calculated and carried through to the calculations of PUE.

The average 20.7% value used, is now indexed in Table 2. Statistical analysis associated with reference values reported in this table are not in order.

124-134 – Some of the references cited for comparison to the calculated global PUE were actually used in the calculation (listed in Table 2), so it is a tautology to say they are “in agreement.” For the references cited that were not used in the calculation of the global mean P recovery (e.g. Steen, 1998; Shabnam and Iqbal, 2016) a reason should be presented as to why they were not included in the calculation.

Shabnam and Iqbal 2016, and Steen 1998 papers are now referenced. However, values from these papers were not used. Phosphorus recovery from the Shabnam and Iqbal paper were from isolated acidic soils. The Steen manuscript failed to identify the crops used.

142-144 – The opportunity for improvement requires a more complete description of the interpretation of the two forms of PUE (difference and balance).

Associated text has been modified to more clearly delineate difference and balance methods

Given the chemical reactivity of P with soil and its constituents, it is unrealistic to expect PUE by difference method to get close to 100%, and its prospects for improvement need to be set in the context of maximum recorded levels and the conditions, including modification of soil available P levels, required to achieve them. Additionally, discussion is needed on the time frame of assessment of P recovery – Syers et al 2008 points out on page 89 and 90 that PUE estimates by the difference method can increase substantially when long term rather than single year responses are considered. The relationship of PUE by balance method with soil test P level and its implications for future PUE also needs to be described.

This commentary really gives rise to an additional paper that addresses a different objective. Estimating world PUE for cereals was the goal of this manuscript and that has been embraced by 2 of the 3 reviewers. PUE differences coming from estimates over different time periods is not and was not targeted. In addition, understanding that P applied and P removed from one year to the next using macro values are likely to be similar.

146 – It is clear from Figure 1 that “an average rate” of increase in world fertilizer P consumption is not an appropriate description of the curvilinear trend that also included a substantial reduction during the late 1980s and early 1990s.

The range in P consumption was the target concept that needed to be communicated. As, you noted, the inconsistent trend before 2000 is noteworthy and this decrease is now addressed in the Results and Discussion section.

156-164 – The description of trends in cereal production are important and useful. A description of the trends over time in the calculated PUEs (both by difference and removal) should be added.

This would comprise a very different objective. The point included here is clearly of value, but not the target of this work.

180-182 – It should be noted that not all studies (or soils) show reduction in P loss with reduced or no tillage. See Quincke et al Agron. J. 99:1104–1110 (2007); Sharpley J. Environ. Qual. 32:1375–1384 (2003); Dodd and Sharpley 2016 Nutr Cycl Agroecosyst DOI 10.1007/s10705-015-9748-8; Gaynor and Findlay J. Environ. Qual. 24:734-741 (1995); and Smith et al Soil & Tillage Research 95 (2007) 11–18

This is an excellent point. A reference to the Sharpley, 2003 work has been included.

189 – The difference in efficiency between broadcast and banded applications is not as simple as “efficient – inefficient.” The difference depends on the level of soil available P and rate of P application, and other factors. (Randall and Hoeft, 1988; Nkebiwe et al, 2016, Field Crops Research 196 (2016) 389–401).

Another great point. The reference to some of the Sander work at Nebraska was considered prudent.

191-201 – The discussion on potential improvement of PUE with foliar fertilizers needs to include considerations of whole-system efficiency, addressing the question of whether foliar fertilizer can realistically be expected to maintain soil available P, and at what levels of soil test P it can adequately correct crop P deficiencies.

This comment is also of value. But, some of this is a part of the literature review we felt was relevant and useful.

209 – Current phrasing implies that Wittry and Mallarino measured improvements in overall environmental health arising from variable rate application of P. This is not the case.

We have altered this sentence so as to better reflect what they reported.

209-213 – Current phrasing is unclear and partly redundant.

Altered accordingly

214 – It seems “access” should be “assess.”

Corrected. Thank you

217 – Unclear on resolution 0.3 or 1.0 square meters?

Corrected. Thank you

220 – The fact that in this study, P rates recommended increased with variable rate application contrasts to the observation of rate reductions in Wittry and Mallarino. This contrast should be discussed.

We request to leave this component as has been reported by these specific authors.

223-224 – the (im)practicality of sampling for soil available P at the square meter level needs to be discussed.

Sentence added

231-233 – Not enough evidence has been presented to support just these two methods as complete replacements for broadcast application. Banding with the seed allows only limited rates of application, whereas banding beside the seed row offers opportunity to replenish crop removal where required. In addition, in soils testing below critical levels, optimum PUE and yield are not obtained without application of sufficient P to increase soil test P levels. As noted in Syers et al (2008) “Phosphorus use efficiency depends on soil P status” and “To build up soil P to the critical value, it may be necessary to accept a lower recovery of added P for some years.”

Agreed. This macro estimate is not tied to any specific method, but your point is entirely accurate. Added sentence on the value of methods associated with initial soil test levels has been included.

236-237 – persuasive evidence relating PUE improvement to mitigation of environmental risk has not been presented, so this statement, appearing in a conclusive position, needs more support and clarification. Obviously in situations where soil P has been built up by high rates of manure or fertilizer application, improving PUE would contribute to reducing P losses, but the balance method PUE could be at least as useful at tool for achieving this as the difference method PUE, which is more difficult to estimate at the farm level. Dodd and Sharpley (2016, cited above) noted “the effect of reducing farm inputs and source management on [particulate] P transfer was negligible” and “a study by Withers et al. (2009) suggested the reduction of STP in P enriched soils will have limited impact on PP loss because STP represents only a small proportion of the total P present in soils.”

This is a good point. Nonetheless, a common thread in Dr. Sharpley’s work cemented the need to focus on environmental P issues, simultaneously with agronomic demands. An added paper from Sharpley et al. (1994) has thus been referenced.

239 – A more objective concluding statement would include the balance method as well as the difference method, particularly in view of the balance method being advocated by Syers et al (2008). In addition, the study has presented the trend over time, which is of great interest. Comments above on the calculations involved may result in changes to the numbers presented, but this reviewer’s assessment of the data currently presented in Table 2 would result in a concluding statement along the lines of “Between 1961 and 2013, phosphorus use efficiency for global cereal crop production declined initially but has increased to surpass earlier levels. The amount of P removed by crop harvest declined from around 97% of fertilizer input to as low as 60% before increasing to current levels of over 100%. The amount of P in cereal grain estimated to be directly taken up from applied fertilizer decreased from around 20% to less than 15% before increasing to current levels of over 20%.”

While not employing your exact words, this work does show what you have highlighted.

Table 2 – it is clear that reported P recoveries vary substantially, ranging from 2.6% to 43%. The paper needs to more thoroughly discuss the reasons for these differences, and also the methodology for calculating an average P recovery that is then apparently applied as a constant over a time period (1961-2013) in which the crop species composition, yield levels, and available soil P levels all changed.

Large differences in P recovery have been further highlighted and these were noted, and reported in Table 2.

Table 3 – it is unclear what role the standard deviation, minimum, maximum and confidence limits play in the calculation. Are these to represent variability over time? Has variability over time in P recovery been assessed, or has it been assumed to be constant over the time period? It does not appear that these statistical data represent the uncertainty in the estimates of crop production quantities, grain P uptake, and coefficients for P recovery from applied P.

These values are simply to describe the certainty / uncertainty around mean estimates. Other macro statistical manuscripts, especially those dealing with efficiency, have similarly included these values.