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# World Phosphorus Use Efficiency in Cereal Crops

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## ABSTRACT

A current estimate of global phosphorus use efficiency (PUE) for cereal production is not available. The objectives of this paper were to estimate PUE for cereal crops grown in the world and to review methods for improvement. Phosphorus use efficiency was determined using world cereal harvested area, total grain production, and P fertilizer consumption from 1961 to 2013, in addition to assumptions established from previous literature. World PUE of cereal crops was calculated using both balance and difference methods. Using the balance method, cereal grain P uptake is divided by the P fertilizer applied. Alternatively, the difference method accounts for P coming from the soil and that is subtracted from applied P. Utilized in this analysis is the estimate that cereal production accounts for 61% of the total harvested cropland. Cereal grain yields increased from 1.35 to 3.90 Mg $h^{-1}$ between 1961 and 2013. In 1961, the world's fertilizer P consumption was 4,770,182 Mg and increased to 16,662,470 Mg of P fertilizer by 2013. This represents a 3.5× increase in P fertilizer consumption over 53 yr. Phosphorus use efficiency estimated using the balance method was 77%. Using the difference method, PUE for cereal production in the world was estimated to be 16%.

## Core Ideas

- A current estimate of global P use efficiency for cereal production is not available.
- This study shows that world P use efficiency for cereal crops is low.
- Using the difference method, average world P use efficiency from 1961 to 2013 was 16%.

Phosphorus is the second most limiting nutrient in crop production after N. Batjes (1997) estimated that P deficiencies can be found in nearly 67% of world land designated for crop production. Hinsinger (2001) reported that crop production is reduced due to P deficiency on an estimated 5.7 billion hectares of land. Due to the non-renewable nature of P resources, appropriate management should be considered to lengthen the life-span of phosphate reserves. According to Roberts and Stewart (2002), P reserves will last 343 yr at current mine production rates. Heffer et al. (2006) concluded that based on current consumption, P reserves are sufficient for approximately 100 yr. Similarly, Smil (2000) projected that P reserves will be depleted in the next 50 to 100 yr. The International Fertilizer Development Center (IFDC, 2010) estimated that global P reserves range between 300 and 400 yr. Van Vuuren et al. (2010) stated that depletion of phosphate rock is not imminent. Recently, Van Kauwenbergh et al. (2013) estimated that the world has over 300 yr of P reserves (phosphate rock) and 1400 yr of resources. However, Edixhoven et al. (2014) expressed concerns about recent updates due to indistinct definitions for reserves and resources. Edixhoven et al. (2014) was challenged and criticized by Scholz and Wellmer (2016) stating that biased interpretations had been drawn. However, considering finite, non-renewable and the non-substitutable nature of P, increasing PUE remains important.

Phosphorus is abundant in soil; however, the concentration of plant available P in the soil solution is generally low (Clarkson and Grignon, 1991). These values were 0.1 to 10 μM as reported by Hinsinger, (2001). Marschner (1986) stated that P concentration in soil solution and P-buffer capacity are among the most relevant factors responsible for the availability of P to plants. Soil pH influences chemical properties and biological processes, including solubility, mobility, and availability of nutrients and trace metals. According to Lindsay et al. (1989), in alkaline soils, P can precipitate with Ca forming insoluble hydroxyapatite, octacalcium phosphate, and dicalcium phosphate. In acidic soils, P can precipitate as minerals of Fe, and Al (strengite and variscite, Sato et al., 2005). Both of these minerals decrease the availability of P for plant growth (Lindsay et al., 1989). Clay fractions such as amorphous hydrated oxides of Fe and Al, in addition to gibbsite, goethite,

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**Abbreviation:** PUE, phosphorus use efficiency.

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and kaolinite are responsible for the greatest P fixation (Kamprath, 1972). As a result, P is one of the most limiting nutrients for crop production.

Parent materials and the environment are fundamental factors that influence the overall availability of naturally supplied P. Several major soil orders are likely to be deficient in P. Accounting for 51% of the soils in the world, Oxisols, Ultisols, and Spodosols are those that are highly weathered, and found in regions that receive significant amounts of rain (Brady and Weil, 2008) (Table 1). Consequently, cations such as Ca, Mg, and K are leached from the soil profile and pH decreases. The soil solution can in turn become dominated by Fe and Al, further increasing the fixing capacity of a soil and reducing the availability of P for plant uptake. Additionally, soils such as Aridisols, Alfisols, and Mollisols are also associated with P deficiency (Baligar et al., 2001), because these soils usually accumulate Ca that interacts with P forming insoluble compounds, once again deceasing P availability for plant uptake.

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 (Hart et al., 2004). Even though P is considered immobile in the soil, leaching and subsurface run-off can occur in deep sandy soils, soils with high organic matter content, and overfertilized soils that have accumulated P (Sims et al., 1998). Anthropogenic factors are the main contributor to P losses. According to Brady and Weil (2008), tillage practices usually increase the amount of P lost by particulate P, while non-incorporated P inputs increase P losses as dissolved P in surface run-off. The risk of P movement is increased when P in the soil is accumulated beyond the crop requirement, and can subsequently be detrimental to aquatic systems (Sims et al., 1998).

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. To improve PUE, a benchmark or estimated level for cereal production was sought. Similar research generated an estimate of nitrogen use efficiency (NUE) for cereal production in the world, and that was reported to be near 33% (Raun and Johnson, 1999).

On a global scale, PUE has not been reported in the literature, although Syers et al. (2008) did provide definitions of the direct, difference, and balance methods for estimating P fertilizer use efficiency. The direct method includes recovery estimated using isotopic differences and a radioactive $^{32}P$ source (Johnston and Syers (2009). Johnston and Syers (2009) also reported that P recovery seldom exceeds 25% using the direct method; hence, the remaining 75% of P in the grain was assumed to have come from the soil. Mclaughlin and Alston (1986) reported PUE's of 18 and 19% for wheat cultivated in the growth chamber using the direct method.

Syers et al. (2008) advocated the use of the balance method over the difference method, mainly due to residual effects of P, which can be beneficial for improving yields in subsequent years. However, Johnston and Syers (2009) went on to report that the balance and difference methods would result in different recovery values. Phosphorus use efficiency determined using the balance method was computed as follows.

Balance method:

$$PUE_B = \frac{\text{Cereal grain P uptake}}{\text{P Fertilizer applied in cereal crops}} \times 100$$

The difference method for estimating PUE, followed that of Syers et al. (2008) and is included below.

Difference method:

$$PUE_D = \frac{\text{Cereal grain P uptake - P removed from the soil}}{\text{P Fertilizer applied in cereal crops}} \times 100$$

For $PUE_D$, P removed in the grain coming from the soil was calculated by multiplying the total cereal grain P removed by 79.3%. This value was based on an average P fertilizer recovery of 20.7% (Table 2). It should nonetheless be noted that the cited P recovery levels were highly variable regardless of the method used. The assumption that 79.3% comes from the soil was determined using average PUE estimates, employing direct and difference methods for maize (*Zea mays* L.), rice (*Oryza*

Table 1. Possible macronutrient deficiency and mineral toxicity associated with major soil orders.†

| U.S. taxonomy soil order | FAO soil group | Soil order global distribution %‡ | Potential macro-nutrient deficiency | Element toxicity |
|---|---|---|---|---|
| Andisols (Ancepts) | Andosol | 0.7 | P, Ca, Mg | Al |
| Ultisols | Acrisol | 8.5 | N, P, Ca | Al, Mn, Fe |
| Ultisols/Alfisols | Nitosol | | P | Mn |
| Spodosols (Podsols) | Podsol | 2.6 | N, P, K, Ca | Al |
| Oxisols | Ferreasol | 7.6 | P, Ca, Mg | Al, Mn, Fe |
| Mollisols (ustolls) | Kastanozem | 6.9 | P, K | Na |
| Mollisols (rendsols) (shallow) | Rendzina | | P | |
| Vertisols | Vertisol | 2.4 | N, P | S |
| Aridisols | Xerosol | 12.7 | P, K, Mg | Na |
| Aridisols/arid entisols | Yernosol | | P, K, Mg | Na, Se |
| Alfisols/ultisols (Albic) (poorly drained) | Planosol | 9.6 | Most nutrients | Al |
| Alfisols/ultisols/molisols (Natric) (high alkali) | Solonets | | N, P, K | Na |

† Table adapted from Baligar et al. (2001).
‡ Brady and Weil (2008).

*sativa* L.), and wheat (*Triticum aestivum* L.) found in the literature, and reported in Table 2.

Estimates of cereal PUE in this paper do not account for residual effects or the benefit of P coming from fertilizer that was applied in previous years. World values for P removal encumber the reality that similar amounts of total P will be applied in ensuing years. The objective of this paper was to estimate global P fertilizer use efficiency for cereal crops using harvested area, fertilizer consumption, and production quantity from macro-data acquired from the Food and Agriculture Organization Statistics Division (Food and Agriculture Organization, 2016).

## MATERIALS AND METHODS

Fifty-three years of world cereal harvested area, cereal production, and world fertilizer P consumption data was obtained from the FAOSTAT database (http://faostat3.fao.org/home/E; accessed 23 Aug. 2016). Cereal harvested area (ha), and cereal production (Mg) data was collected for maize, rice, wheat, sorghum (*Sorghum bicolor* L.), barley (*Hordeum vulgare* L.), millet (*Pennisetum glaucum* L.), oat (*Avena sativa* L.), rye (*Secale cereale* L.), triticale (*Triticale hexaploide* L.), and other cereal crops. Other cereal crops consisted of a summation of area and production for minor cereal crops such as canarygrass seeds (*Phalaris canariensis* L.), buckwheat (*Fagopyrum esculentum* Moench), fonio (*Digitaria exilis* stapf), mixed grains, and quinoa (*Chenopodium quinoa* Willd.).

Using macro-data and assumptions established in previous research (Raun and Johnson, 1999), a relationship between fertilizer taken up by cereal crops and the amount of P removed in the grain was used to determine global PUE for cereal crops. Phosphorus use efficiency was thus computed using the balance method ($PUE_B$) and the difference method ($PUE_D$):

The procedure to estimate PUE (balance and difference methods) was accomplished by calculating the ratio between total cereal harvested area (sum of the harvested area of all cereal crops) and world harvested area (all agricultural crops) to estimate the percentage of harvested agricultural land under cereal production for each year from 1961 to 2013. Subsequently, world fertilizer P consumption was multiplied by the percent of the global area under cereal production. This was used to estimate the amount of P fertilizer taken up by cereal crops. Phosphorus uptake of cereal grain was calculated using crop specific grain P content obtained from the U.S. Department of Agriculture (USDA) (http://plants.usda.gov/npk/main; accessed 23 Aug. 2016). Cereal grain P uptake (Mg) was calculated by multiplying the crop specific grain P content,

Table 2. Studies reporting P fertilizer recovery for cereal crops using the difference and direct methods.

| Crop | Description | Estimation method | Reported P recovery | Reference |
|---|---|---|---|---|
| | | | % | |
| Wheat | Broadcast application of 20, 40, 80, and 160 kg P $ha^{-1}$ | Difference | 30, 18, 10, 6, 10 | Alessi and Power (1974) |
| | Banding with seed | | | |
| Wheat | $^{32}P$-labeled fertilizer | Direct | 11.6 | Mclaughlin et al. (1988) |
| | $^{33}P$-labeled fertilizer | | 5.4 | |
| Wheat | $^{32}P$-labeled fertilizer on growth chamber | Direct | 18 | Mclaughlin and Alston (1986) |
| | $^{33}P$-labeled fertilizer on growth chamber | | 19 | |
| Barley | $^{32}P$-labeled fertilizer on plowed pasture | Direct | 21, 10 | Mattingly and Widdowson (1958) |
| | $^{32}P$-labeled fertilizer on arable land | | 15, 14 | |
| Rice | Two genotypes grown in acid soils | Difference | 33 | Baligar et al. (2001) |
| Maize | $^{32}P$-labeled Phosphate Rock | Direct | 2.6 | Franzini et al. (2009) |
| | $^{32}P$-labeled TSP | | 10.5 | |
| Maize | Two hybrids fertilized with 44 and 132 kg P $ha^{-1}$ | Difference | 37.5, 17.4 | Zhang et al. (2004) |
| | | | 36.3, 16.0 | |
| Wheat–maize | NP treatments, 15 yr average of five locations | Difference | 19, 26, 28, 43, 35 | Tang et al. (2008) |
| | NPK treatments, 15 yr average of five locations | | 18, 32, 43, 36, 23 | |
| Rice | Application of 16 kg P $ha^{-1}$ at each cropping cycle | Difference | 21 | Pheav et al. (2003) |
| | Fresh application of 16 kg P $ha^{-1}$ in a specific crop season | | 20 | |
| Maize | Soil mixing of 30, 60, and 90 kg $P_2O_5$ $ha^{-1}$ (two varieties) | Difference | 30, 32, 20, 25, 17, 19 | Hussein (2009) |
| | Fertirrigation of 30, 60, and 90 kg $P_2O_5$ $ha^{-1}$ (two varieties) | | 34, 39, 24, 28, 19, 25 | |
| Wheat | P use efficiency in cereal production in China | Difference | 10.7 | Ma et al. (2011) |
| Rice | | | 13.1 | |
| Maize | | | 11.0 | |
| Wheat | Average of experiments established from 1986 to 1989 with P rates of 5, 11, 20, and 38 kg $ha^{-1}$ | Difference | 10.5, 7.0, 4.6, 2.6 | Holford and Doyle (1993) |
| Average | | | 20.7 | |

by the production of that given crop. For "other cereal crops" an average grain P content of all cereal crops was used.

The "summary" and "means" procedures in SAS 9.3 (SAS Institute, Cary, NC) were used to calculate descriptive statistics for world harvested area, consumption of P fertilizers in cereal production, P removed in the grain, and estimated PUE over 53 yr.

## RESULTS AND DISCUSSION

Over a 53 yr period, (1961–2013, Fig. 1), world fertilizer P consumption increased by 228,698 Mg $yr^{-1}$ (Food and Agriculture Organization, 2016). In 1961, the world's fertilizer P consumption was 4,770,182 Mg and has increased to 16,662,470 Mg of P fertilizer today (Fig. 1). This represents a 349% increase in P fertilizer over 53 yr. It should be noted that P consumption was variable in the late 1980s and early 1990s. Cereal crops are major sources of P removal, as maize, rice, and wheat are staple foods in many countries around the world. It was calculated that cereal harvested area accounts, on average, for 61% of the total agricultural harvested area (Food and Agriculture Organization, 2016) (Table 3). However, in 2013 this value was lower than the average and only 53% of the world's harvested area was designated for cereal production, with a corresponding area of 699,971,846 ha (Food and Agriculture Organization, 2016).

Since 1961, global cereal production has increased significantly, largely driven by increases in maize, rice, and wheat production. Cereal production in 2013 was 2,735,736,892 Mg (Food and Agriculture Organization, 2016) with a 53-yr cereal production average of 1,761,247,509 Mg. Maize production increased by a factor of four while rice and wheat increased roughly threefold when comparing the production of 1961 to 2013. The area used for maize and rice, increased moderately while the area under wheat production remained constant. In the last 53 yr, increases of approximately 311% in world cereal yields have been observed. Higher yielding crops are most likely due to improved genetics and management practices. World cereal yield was approximately 1.35 Mg $ha^{-1}$ in 1961 and 3.90 Mg $ha^{-1}$ in 2013 (Food and Agriculture Organization, 2016).

The lowest $PUE_B$ was observed in1988 with 59%, and the highest at 111% for 2008 (Fig. 2). The average $PUE_B$ was 77% from 1961 to 2013. In 2013, $PUE_B$ was calculated to be 104% (Fig. 2). Syers et al. (2008) noted that P recoveries calculated using the balance method are always greater than when computed using the difference method. Syers et al. (2008) implied that if PUE computed using the balance method exceeds 100%, it means that P reserves are being depleted. Roberts and Johnston (2015) stated that PUE often exceeds 80% with the balance method. They further interpreted results obtained from the balance method, where a PUE of 100% implied little or no change in plant available P, less than 100% meant that fertilizer input was more than crop removal and greater than 100% suggests nutrient mining.

For the difference method, it was estimated that from 1961 to 2013 (53 yr), mean world $PUE_D$ was 16% (Table 3). The lowest $PUE_D$ was observed in 1980 and 1988 with 12%, and the highest was observed in 2008 and 2009, estimated to be 23%. In 2013, $PUE_D$ was 21% (Fig. 2). Phosphorus use efficiency from field research has generally been reported to be low, ranging between 15 and 25% if measured after the first year of application (Steen, 1998). Critical to the understanding of using macro/world values is that the total rates and removal estimates will be similar in ensuing years. This same approach was not adequately delineated by Raun and Johnson (1999) who similarly estimated world fertilizer use efficiency in cereals, for N. Nonetheless, this was implied for their calculations to be of value. Embracing this concept in turn negates residual effects for P because P applications will continue at the same/similar rates in years that follow.

The estimated world PUE using the difference method is in agreement with regional/local values reported in previous research. For example, Ma et al. (2011) investigated PUE in wheat, rice, and maize production in China and reported $PUE_D$ values of 10.7, 13.1, and 11.0%, respectively. Shabnam and Iqbal (2016) reported a $PUE_D$ value of 8.0% for wheat grown on an acidic soil. Similar results were obtained using the radioactive isotope $^{32}P$ by Mattingly and Widdowson (1958), where 20% PUE was found in spring barley. Cases reviewed by Syers et al. (2008), noted P recovery

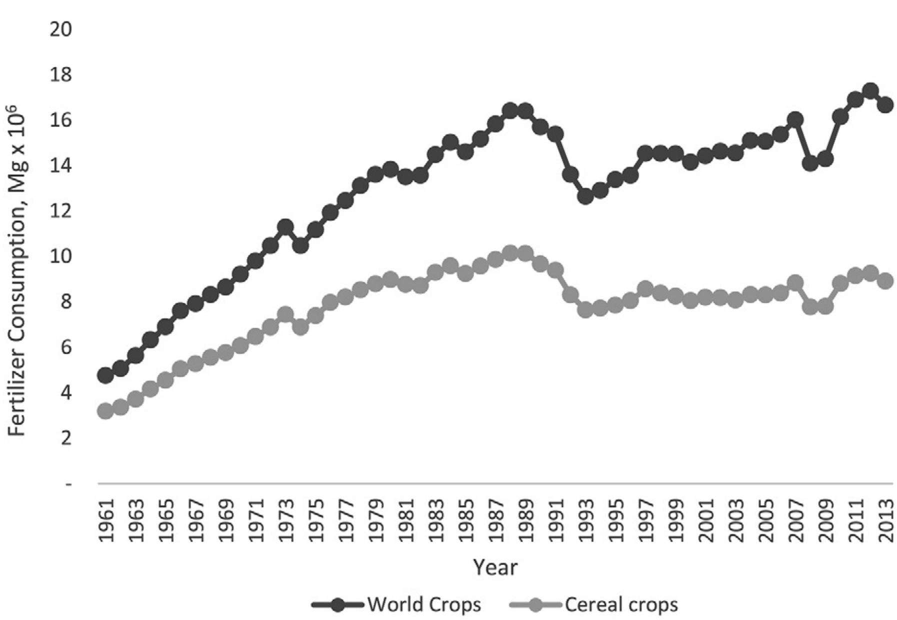


Fig. 1. Fertilizer P consumption for the World and for cereal crops.

Table 3. World harvested area, consumption of P fertilizers for cereal production, P removed in the grain and estimated phosphorus use efficiency (PUE) over 53 yr (FAO, 2016).

| Variables and computation | Item and unit | Mean | SD | Minimum | Maximum | 95% Confidence limit | |
|---|---|---|---|---|---|---|---|
| | | | | | | Lower | Upper |
| | Harvested area, ha | | | | | | |
| | Maize | 131,807,059 | 17,959,100 | 103,496,674 | 180,850,789 | 126,856,918 | 126,856,918 |
| | Rice | 143,902,426 | 11,642,941 | 115,365,135 | 164,031,254 | 140,693,234 | 147,111,618 |
| | Wheat | 220,887,531 | 8,182,868 | 204,209,450 | 239,165,634 | 218,632,053 | 223,143,009 |
| | Sorghum | 45,187,643 | 3,460,867 | 34,338,196 | 52,178,397 | 44,233,710 | 46,141,576 |
| | Barley | 66,519,003 | 10,845,236 | 47,339,191 | 83,694,982 | 63,529,686 | 69,508,320 |
| | Millet | 38,258,934 | 4,065,742 | 27,781,542 | 45,640,447 | 37,138,277 | 39,379,592 |
| | Oat | 21,577,297 | 8,016,903 | 9058,263 | 38,260,751 | 19,367,565 | 21,577,297 |
| | Rye | 15,056,837 | 6,969,821 | 5040,070 | 30,339,487 | 13,135,716 | 16,977,957 |
| | Triticale | 1348,249 | 1,525,507 | 0 | 4,331,787 | 927,767 | 1768,731 |
| | Other cereal crops† | 7149,769 | 985,161 | 5260,069 | 9,994,810 | 6878,225 | 7421,313 |
| *A* | Cereal | 691,694,749 | 73,654,146 | 551,888,590 | 848,488,338 | 671,393,152 | 699,886,332 |
| *B* | World harvested area, ha | 1132,341,088 | 90,870,356 | 967,561,970 | 1309,775,232 | 1107,294,116 | 1157,388,060 |
| $C=\frac{A}{B}\times 100$ | World area under cereal production, % | 61 | 81 | 57 | 65 | 61 | 60 |
| | Fertilizer P consumption,Mg | | | | | | |
| *D* | World | 12,811,779 | 3,296,571 | 4770,182 | 17,288,945 | 11,903,131 | 13,720,426 |
| $E = C \times D$ | Cereal crops | 7,826,122 | 2,672,006 | 2720,869 | 11,199,989 | 7217,306 | 8296,905 |
| | Production quantity, Mg | | | | | | |
| | Maize | 490,064,281 | 202,172,922 | 204,876,937 | 991,413,624 | 434,338,522 | 545,790,039 |
| | Rice | 471,628,097 | 150,649,524 | 215,646,633 | 737,564,302 | 430,103,945 | 513,152,248 |
| | Wheat | 485,877,275 | 136,863,478 | 222,357,231 | 711,142,394 | 448,153,028 | 523,601,521 |
| | Barley | 141,782,972 | 25,512,623 | 72,411,104 | 178,074,020 | 134,750,822 | 148,815,122 |
| | Sorghum | 59,435,219 | 7,410,164 | 40,931,625 | 77,567,348 | 57,392,724 | 61,477,713 |
| | Millet | 28,042,024 | 2,835,556 | 23,307,950 | 34,814,105 | 27,260,447 | 28,823,600 |
| | Oat | 37,857,976 | 10,563,958 | 19,724,920 | 54,506,300 | 34,946,188 | 40,769,763 |
| | Rye | 26,014,042 | 7,054,518 | 11,959,182 | 38,193,583 | 24,069,576 | 27,958,508 |
| | Triticale | 4747,831 | 5,477,206 | 0 | 15,833,430 | 3238,126 | 6257,536 |
| | Other cereal crops | 15,797,794 | 1,657,520 | 12,825,332 | 18,752,739 | 15,340,925 | 16,254,663 |
| *F* | Cereal | 1761,247,509 | 550,197,469 | 824,040,914 | 2857,861,845 | 1609,594,305 | 1912,900,714 |
| | Grain P uptake, Mg‡§ | | | | | | |
| | Maize | 1519,199.27 | 626,736.06 | 635,118.50 | 3073,382.23 | 1346,449.42 | 1691,949.12 |
| | Rice | 1367,721.48 | 436,883.62 | 625,375.24 | 2138,936.48 | 1247,301.44 | 1488,141.52 |
| | Wheat | 2040,684.55 | 574,826.61 | 933,900.37 | 2986,798.05 | 1882,242.72 | 2199,126.39 |
| | Barley | 467,883.81 | 84,191.66 | 238,956.64 | 587,644.27 | 444,677.71 | 491,089.90 |
| | Sorghum | 219,910.31 | 27,417.61 | 151,447.01 | 286,999.19 | 212,353.08 | 227,467.54 |
| | Millet | 92,538.68 | 9,357.34 | 76,916.24 | 114,886.55 | 89,959.48 | 95,117.88 |
| | Oat | 124,931.32 | 34,861.06 | 65,092.24 | 179,870.79 | 115,322.42 | 134,540.22 |
| | Rye | 98,853.36 | 26,807.17 | 45,444.89 | 145,135.62 | 91,464.39 | 106,242.33 |
| | Triticale | 16,142.63 | 18,622.50 | – | 53,833.66 | 11,009.63 | 21,275.62 |
| | Other cereal crops | 54,414.62 | 5,709.23 | 44,176.14 | 64,592.77 | 52,840.96 | 55,988.28 |
| *G* | Cereal | 6002,280 | 1845,413 | 2816,427 | 9632,080 | 5493,621 | 6510,939 |
| *H* | Grain P uptake from soil, Mg¶ | 4759,808 | 1463,412 | 2233,427 | 7638,239 | 4356,442 | 5163,174 |
| $PUE_B = \frac{G}{E}\times 100$ | Balance method | 77 | 69 | 104 | 86 | 76 | 78 |
| $PUE_D = \frac{G-H}{E}\times 100$ | Difference method | 16 | 14 | 21 | 18 | 16 | 16 |

† Other cereal crops consist of canary seed, buckwheat, fonio, mixed grains, and quinoa.
‡ Grain P content (%) for each crop used was obtained from the USDA (http://plants.usda.gov/npk/main) (accessed 23 Aug. 2016).
§ Grain P uptake is the product of cereal production and %P in the grain. $G = (F \times \%P\ \text{content})$.
¶ Phosphorus removed in cereals coming from soil is assumed to be 79.3% of the total amount of P found in the grain (see Table 2). $H = (G \times 0.793)$.

using labeled $^{32}P$ fertilizer, between 5 and 25%. Our results show that global PUE is generally low using the difference method and comparable to reported P efficiencies on smaller scales.

## Strategies to Improve Phosphorus Use Efficiency

Current understanding of the behavior of P in the soil provides opportunities to counteract low use efficiencies of fertilizer P. Several strategies and management practices have been identified as potential measures to improve PUE. Water and wind erosion are significant factors that contribute to low world PUE and represent an economic and environmental risk. Unfortunately, erosion is not a recent problem and is intensified by certain agricultural production systems. In Europe, erosion persists particularly in sloping lands, coarse-textured soils, and regions which receive significant precipitation (Verheijen et al., 2009). This same work estimated that soil loss due to erosion ranges from 5 to 40 Mg $ha^{-1}$ $yr^{-1}$. When soil is subjected to erosion, P is also lost, further reducing crop productivity and ultimately, PUE (Schröder et al., 2011). An assessment of soil P loss due to erosion was reported by Liu et al. (2008) who suggested that 13, 8, and 3 kg P $ha^{-1}$ are lost on an annual basis from arable land, overgrazed and normal pastures, respectively. Other work has shown that tilling P-stratified soils can decrease P loss when tillage-induced erosion is minimized (Sharpley, 2003). Among the technologies to control erosion are no-till cropping, reduced tillage, crop rotation, terracing, cover crops, and wind-breaks (Pimentel et al., 1995). McGregor and Greer (1982) observed a consistent reduction in erosion among no-till and reduced tillage systems and conventional tillage plots, having reported a mean annual soil loss 22 times greater for conventionally tilled plots compared to no-till plots.

Adjusting soil pH and base saturation are methods to reduce the amount of P that is bound by Al and Fe, further reducing the effects of Al toxicity to plants, which can inhibit uptake, and use of P by the plant (Syers et al., 2008). Fertilization method, source, rate, time of application, and the interaction between these variables can be managed to achieve better PUE. The most frequent method of P fertilization is broadcast applications over the soil surface and is recognized to be inefficient when compared to the application of P in bands (Sander et al., 1990). Peterson et al. (1981) compared broadcast and banded phosphate fertilization in winter wheat in P-deficient soils and reported higher efficiency for banded applications. Liquid P fertilizer has advantages over granular forms of P fertilizer as documented by Lombi et al. (2006). They studied P availability in calcareous soils and compared granular and fluid P fertilizers, and that confirmed P being more available to plants when applied as a liquid. McBeath et al. (2007) also recommended liquid P over granular forms, and their effectiveness for wheat in calcareous soils. Foliar P fertilization is recommended in dry environments, soils with elevated P-fixing capacity, and soils that are marginally deficient in an effort to avoid pathways that promote loss of soil P. Relatively low rates are used for foliar applications; therefore, foliar P fertilization normally improves PUE. Mid-season application of low rates of foliar P on winter wheat improved PUE and was capable of correcting mid-season P deficiency compared to soil applications (Mosali et al., 2006). Further, foliar P fertilization allows for application at critical periods during crop development when the demand for the nutrient is at its peak (Faulkner, 1999). Although foliar fertilization can, be an efficient way to apply P to a crop, this practice is not widely used and P sources accessible to producers are usually not designed for this purpose.

Precision agriculture technologies such as geographic information systems (GIS), remote sensing, and variable rate application can provide more efficient use of fertilizers helping to treat soil variability. Variable rate application is based on recommendations provided by the relation between soil analysis and yield maps connected to a global positioning system (GPS), allowing application of area-specific rates (Kirkby and Johnston, 2008). Mallarino and Wittry (2006) presented results from on-farm trials acknowledging that variable rate application of P resulted in reduced soil test variability and decreased fertilizer application

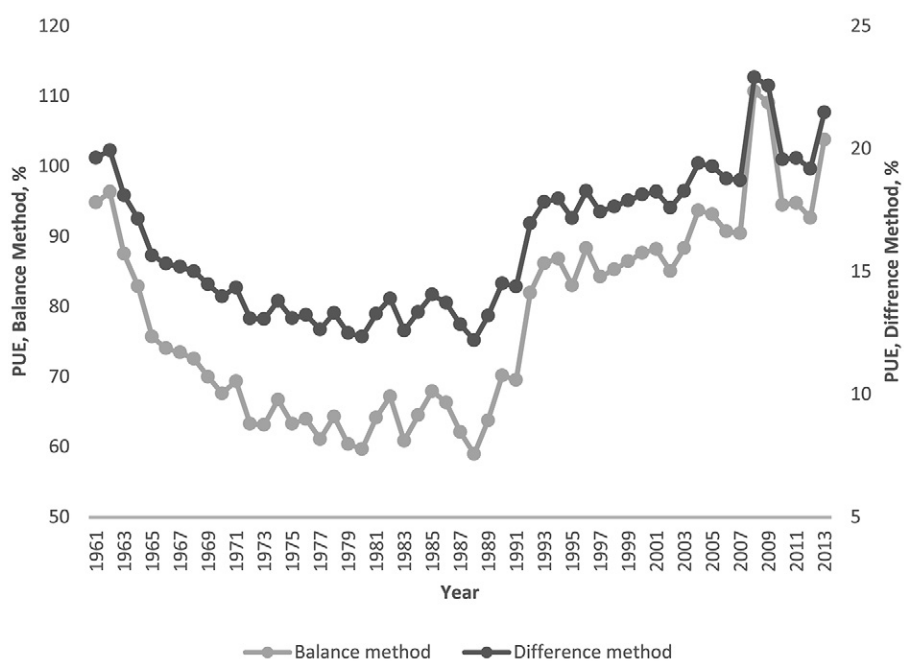


Fig. 2. Historical estimates of world P use efficiency for cereal crops.

for high-testing fields, in addition to benefiting overall environmental health. Work by Wittry and Mallarino (2004) compared variable rate P application to conventionally used uniform rates. Their results suggested that P fertilizer use could be improved when employing variable rate fertilization. This technology discussed by Wittry and Mallarino (2004) resulted in applied fertilizer reductions of 12 to 41% and less soil test P variability when compared to conventional methods and uniform application.

The ability to assess levels of available soil P on a regular basis and recognize spatial variability to make more accurate P recommendations are fundamental to ensure better fertilizer use. Work by Sharpley et al. (1994) cautioned that continued inputs of fertilizer P in excess of crop requirements will ultimately lead to P build-up in soils and that would become environmental problems. Raun et al. (1998) reported significant differences for soil test analyses of both mobile and immobile nutrients, from soil samples collected in a (0.30 $m^2$ grid). Further, it was demonstrated that if the site mean for soil P were used, no additional P would have been needed. Alternatively, when sampling at a 0.30 $m^2$ resolution, recommended P rates would have ranged from 0 to 31 kg P $ha^{-1}$.

Fertilizer P recommendation strategies include build-up and/or maintenance of critical P sufficiency levels to achieve optimum yields. Maleki et al. (2008) designed and implemented on-the-go variable rate application of P based on soil sensing (visible and near-infrared soil sensor) and suggested that the management resolution should be implemented at the meter level (1 $m^2$ resolution). In addition, this work showed significantly higher maize yields and less variability among soil P tests between variable rate and uniform rate treatments. It should nonetheless be noted that soil sampling at the submeter level in agricultural fields is not practical. Furthermore, the value of different methods of applying fertilizer to some extent depend on the initial soil test levels and existing spatial patterns that can be detected using grid sampling techniques (Schepers et al., 2000).

## CONCLUSIONS

Phosphorus deficiencies are wide spread in agriculture, covering 67% of agricultural land (Batjes, 1997). Tiessen et al. (2011) stated that P resources are being depleted and additional P fertilizer is needed to ensure food security. Current knowledge regarding P in the soil and improved application methods could help to offset this problem and promote more efficient use of P fertilizer in the world. Improved awareness of the wide range of P management practices are likely to increase worldwide PUE for cereals. Banding P fertilizer with the seed and foliar P application are viable alternatives that should replace broadcast application and improve PUE. Recognizing P variability and treating at the appropriate scale can also increase PUE and decrease environmental problems coming from excess P use. Noteworthy for this work is that gains in PUE have been realized using improved methods and P sources over the last 30 yr. Based on cereal fertilizer P consumption in 2013, every 1% increase of PUE in cereal production is associated with a reduction of 404,762 Mg in fertilizer consumption. Improved efficiency of P fertilizers can extend the lifetime of P reserves, enhance sustainability of food production, and mitigate environmental risk associated with excessive P fertilization around the world. Furthermore, viable opportunities for improving PUE are reported and that can be employed. Using Food and Agricultural Organization data from 1961 to 2013, PUE for world cereal production using the balance method was 77%. Phosphorus use efficiency estimated for the world using the difference method was 16%.

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## Conflict of Interest

The mention of any trademarked products or equipment utilized in this experiment was for research purposes only and does not act as an endorsement by Oklahoma State University. The authors and Oklahoma State University have no direct financial relation with any of the named manufacturers, thus the authors declare there is no conflict of interest regarding the publication of this manuscript.

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