Spanish Journal of Agricultural Research
22 (1), e0901, 11 pages (2024)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2024221-19941
INIA-CSIC

RESEARCH ARTICLE

OPEN ACCESS

Maize yield and grain quality response to foliar-applied phosphorus in a soil testing high in P

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Abstract

Aim of study: To test the effect of foliar and granular P fertilizer application on maize performance planted under permanent beds from 2012 to 2019 in a soil testing high in P.

Area of study: This field experiment was located in the eastern region of the trans-Mexican volcanic belt.

Material and methods: Three P treatments, foliar and granular (band and broadcast), and a control (0P) plot were allocated in an randomized complete block design in six replications.

Main results: Year-P treatment interaction was significant for yield, agronomic efficiency (AE), and recovery efficiency (RE). Contrastingly, grain quality parameters measured as bulk density and thousand grain weight were only affected by year's main effect. Yield, AE, and RE were generally more responsive to the foliar than the granular P application. These parameters varied in each treatment according to precipitation accumulated in 40 days during the bracketing-silking period (40d PP) and heat units during the grain filling stage [GDD(t-m)]. As 40d PP increased, yield and AE improved, while RE decreased; as GDD(t-m) increased, yield and grain quality improved. Initial soil available P (46 mg/kg) decreased 26% due to foliar P application.

Research highlights: Results suggest that replacing the granular P with foliar P fertilization is an option to mine soil to an acceptable P level without adverse effects on maize performance.

Additional key words: agronomic efficiency; recovery efficiency; soil legacy P; sustainability; precipitation; growing degree-days.

Abbreviations used: AE (agronomic efficiency); GDD (growing degree-days); GDD(t-m) (growing degree-days from tasselling to maturity); RE (recovery efficiency); TGW (thousand grain weight); 40d PP (40 days precipitation during the bracketing-silking period).

Citation: Limon-Ortega, A; Baez-Perez, A (2024). Maize yield and grain quality response to foliar-applied phosphorus in a soil testing high in P. Spanish Journal of Agricultural Research, Volume 22, Issue 1, e0901. https://doi.org/10.5424/sjar/2024221-19941

Received: 01 Nov 2022. **Accepted**: 28 Nov 2023. **Published**: 09 Jan 2024.

Introduction

Phosphorus is an essential nutrient for plant growth, and most cropping systems rely on the regular supply of P-based fertilizer to maintain productivity. This dependence leads to frequent applications of P fertilizers to obtain adequate yields. However, this is expensive and environmentally undesirable as the build-up of soil P leads to P losses to the environment and causes aquatic eutrophication (Bai et al., 2013; Ridoutt et al., 2013). Therefore, the purpose should be to maintain an adequate P sufficiency level to achieve optimum yield (Dhillon et al., 2017); neither excess nor deficiency is advisable (Reid et al., 2019). Before reaching an adequate soil P level in soil testing high, the current soil available P (i.e., legacy P), from past intensive fertilizer applications may contribute significantly to crop production for a considerable time (Van de Wiel et al., 2016). However, despite legacy P represents a long-term source of both dissolved and particulate P, demand for P fertilizer continues to increase (Bai et al., 2013), particularly in developing countries (Syers et al., 2011). Alternatively, applying P to foliage represents a potential source of fertilization to replace the high rates of granular P forms (Dhillon et al., 2017). Nevertheless, soil P evaluations should not be confined to short-term trials as these may often be a substantial limitation in assessing the long-term impact of fertilization practices. Additionally, some of the many uses of long-term trails are that they represent an excellent resource for understanding the sustainability of agricultural practices (Maharjan et al., 2021) and provide resources to assess soil processes where changes occur slowly (Johnston & Poulton, 2018).

Maize (*Zea mays* L.) in Mexico represents the staple food for the population. The importance of maize in this country extends to the cropland occupied in rainfed areas (>50%) (Murray-Tortarolo et al., 2018). Some factors that limit maize production in the highlands of these areas are the low response to increased doses of inorganic fertilizers, the irregular distribution of rainfall, and the amount during the crop season (Torres Flores et al., 2017). Concurrently, the expected grain yield and efficiency dependence on the climate escalate to P fertilizer application strategies when P fertilization continues (McBeath et al., 2011). However, one concern is the inherent low P rates sprayed to foliage as the sole fertilizer source; yield presumably decreases over time, and the effect extends to use efficiency and grain quality parameters (Van de Wiel et al., 2016). Nevertheless, such an effect depends upon conditions like soil P supplying capacity (Tang et al., 2008), crop, and climate (Tang et al., 2011). As climate factors, precipitation around the flowering stage, from just prior to tasseling through the middle of grain filling, has been identified as a factor that can explain a high degree of yield variation in dryland corn (Nielsen et al., 2010). Analogous to precipitation, crops grown at near-optimal temperatures are more likely to reach maximum yields (Murray-Tortarolo et al., 2018). Depending upon the region and the method employed to estimate the heat units expressed in growing degree-days (GDD), corn may need between 1600 and 1900 units to reach maturity growth stage (Zhou & Wang, 2018).

Therefore, on account of the significance of P fertilizer for agricultural production and its relationship with population growth, it is understandable that crop yields need to be improved due to the increasing food demand. Given the non-renewable nature of P resources, the achievement of this goal should consider the appropriate P management to lengthen the lifespan of phosphate reserves (Dhillon et al., 2017). In this view, it is necessary to consider the soil legacy P as a contributor to crop P uptake (Withers et al., 2014). Accordingly, applying liquid P to foliage is a management option that may complement the soil P supply to meet crop needs. Furthermore, this practice is an effective way to supply P late in the season as it provides a potential increase in fertilizer use efficiency (Noack et al., 2010).

Agronomic performance due to P supply may differ depending on several factors, including the source of P fertilizer (Chien et al., 2011). Accordingly, the soil legacy P is an alternate source that can supply the crop and replace the fertilizer application. This source considers only P accumulated above the agronomic recommended level and comes from the excessive rates previously applied. Nevertheless, replacing fertilizer P application with legacy P is a practice that poses the risk of causing detrimental effects on yield. Thus, to avoid this risk, it is necessary to identify the appropriate crop P management. According to the foreground, the objective of the research work was to evaluate the performance of dryland maize fertilized with foliar P as an alternative practice to using the soil legacy P. The hypothesis addressed the differential response between foliar and granular P treatments in soil that initially tested high Bray P-1 (46 mg/kg). For this work, however, the term soil available P replaced the term legacy P.

Material and methods

Site description and experimental design

Field data for this study were collected on dryland maize over seven summer seasons from 2012 to 2019 (2018 missed due to weather conditions) in an experiment established in 2005 under permanent beds and rainfed conditions at the 'Valle de Mexico' experimental station of INIFAP, Mexico. The study site location is in the Eastern region of the trans-Mexican volcanic belt (19°26.7' N, 98°53.2' W, 2280 masl). According to the USDA taxonomy, the soil classification corresponds to a fine-loamy mixed thermic Cumulic Haplustoll (Govaerts et al., 2008). At the onset of the study, soil available P averaged 46 mg P/kg estimated as Bray P-1 extractable, organic matter 24 g/kg with the Walkley-Black method, pH 6.8 (soil:water ratio 1:2), total N 1.1 g/kg following Kjeldahl procedures, and exchangeable K 470 mg/kg extracted with ammonium acetate. The climate is temperate with dry winters; heavy rain events are frequent during the cropping seasons with significant dry spells. As management factors, leaving crop residues as stubble and reshaping beds during winters were the every-year practices.

This study was a single-factor experiment conducted as a randomized complete block design and six replications. Treatments consisted of a single application of 1.1 kg P/ha in liquid form to foliage at the V5 growth stage and 21 kg P/ha in granular form to the soil, banded and broadcast, applied by hand before planting. The application of liquid P fertilizer included a surfactant. Granular fertilizer was incorporated when reshaping beds and during the planting operation. The source of fertilizer was triple superphosphate (45% P_2O_5 per unit of fertilizer). Treatments included a control (0P) plot without fertilizer. Application of glyphosate (726 g a.i./ha) before planting and atrazine (1.8 kg a.i./ha), 30-40d after plant emergence, allowed appropriate weed control.

Plant and soil measurements

Plots were planted to a dent-kernel hybrid (H-40), 4-5 cm deep at about 60,000 seeds/ha at the onset of the rainy season when soil moisture was considered appropriate. The plot size was 10 m long by four beds wide (0.8 m each). Harvest area for grain yield estimation was from ears collected from the two central beds after physiological maturity; removing foreign material, impurities, and broken kernels allowed to draw clean grain samples to perform grain evaluations. Grain yield was adjusted to 140 g/kg moisture basis.

A kernel subsample was taken to determine grain P removal, bulk density (test weight), and thousand grain weight (TGW). Grain P removal was estimated from the P concentration using the vanadium-molybdenum method on digested samples with H_2SO_4-H_2O_2. The product of grain P concentration and grain yield estimated grain P removal (kg P/ha). Test weight was defined as the mass of grain in a volume of 1-L cup, including air space, using a filling hopper. Kernel weight was measured from a 200-kernel subsample and multiplied by five to obtain TGW. The agronomic efficiency (AE) was estimated as follows:

$$AE = [(Yf–Y(0P)]/Fp$$

where Yf is the yield from the treatments with P fertilizer application, Y(0P) the yield from the control (0P) plot, and Fp the amount of P applied (kg/ha). AE indicates the change in yield per unit of P applied (kg/kg P). Stover P removal was not estimated; stover was left on the soil surface as mulch, assuming that most of the P recovery went into grain (Yu et al., 2021). Phosphorus RE was estimated by the balance method as:

$$RE=Gp/Fp$$

where Gp is grain P removal (kg P/ha). This parameter shows the quantity of P removed by the grain for each P unit applied (kg P/kg P).

Composite soil samples to 30 cm depth were collected before planting to estimate soil P content following Bray P-1 procedures. As weather variables, accumulated precipitation during a 40-d period (40d PP) comprised within the bracketing-silking stage (~20 d before tasseling through ~20 d after) and heat units as accumulated growing degree-days estimated as:

$$GDD(t\text{-}m)=\sum(Tmax–Tmin)/2–Tb$$

where GDD(t-m) is the accumulated heat units from tasseling to physiological maturity, (Tmax-Tmin)/2 is the average temperature in 24-hr period, and Tb is the base temperature (10 °C). However, in days when Tmin<10 °C, then Tmin=Tb.

Statistical analysis

Data were subjected to ANOVA using SAS (SAS/STAT® Software, 2017) to test treatment effects as modeling correlation of times with Proc Mixed statistical model approach. Years and treatments were analyzed as fixed effects, while replications nested years were considered random effects. For the Year-P fertilizer interaction, regression analysis with 40d PP and GDD(t-m) as independent variable explained treatment variations over the years. As Eghball et al. (2003) applied, regression procedures allowed the estimation of soil available P decay over the years using the following non-linear equation:

$$Pavai = A\, e^{(b * x)}$$

where Pavai was the level of soil available P, x the time in years (1, 2…7 for 2012, 2013, 2014, 2015, 2016, 2017, 2019, respectively), and A and b non-linear regression parameters.

Results

Long-term annual precipitation for the site is 534 mm and GDD 2590 units, of which nearly 80% and 66%, respectively, occur during the maize crop season (~ 15 May to 15 Oct). However, weather data collected during the crop seasons of the study indicated that these long-term percentages changed; precipitation declined and GDD rose. The Year-P fertilizer interaction significantly affected yield and efficiency parameters; 40d PP and GDD(t-m) as weather factors explained the effect of Years in this interaction. Meanwhile, grain quality parameters were only affected by the main effect of Years (Table 1).

Table 1. Probability values of repeated measurements from the analysis of variance for a randomized complete block design.

Source of variation	Yield	Agronomic efficiency	Recovery efficiency	Bulk density	Thousand grain weight
P fertilizer	0.01	0.02	0.0001	0.36^{ns}	0.28^{ns}
Year	0.0001	0.12^{ns}	0.0001	0.0001	0.0001
Year-P fertilizer	0.04	0.04	0.0001	0.11^{ns}	0.19^{ns}

^{ns}: not significant at p<0.05

Maize yield

The average maize yield ranged from a low of 2624 kg/ha in 2019 to a high of 7533 kg/ha in 2016, when the lowest and highest 40d PP occurred, respectively (Table 2). Average yield as affected by P fertilizer application decreased in the order of foliar > broadcast > control (0P) > band (5856, 5507, 5456, and 4888 kg/ha, respectively) with some variations within crops seasons, mainly in the early seasons after the onset of the study (Fig. 1). According to a multiple regression analysis applied to each P treatment, 40d PP and GDD(t-m) combined effect explained 64-83% of the annual yield variations (Fig. 2). In agreement with the regression coefficients, the effect of 40d PP on yield was more significant than GDD(t-m). Similarly, the influence of 40d PP on grain yield variations was more significant for the P application to foliage and lowest for the control (0P) plot. For example, holding constant GDD(t-m) at 600 units, the yield for those two treatments increased 1540 and 960 kg/ha, respectively, for each 30 mm increase in 40d PP around tasseling.

Agronomic efficiency (AE)

Results showed two crop seasons (2015 and 2019) with negative AEs (Table 2). As defined for this work, negative AEs in these two years indicated that the control (0P) plot yield was higher than the yield from P treatments. Indeed, the annual average of AE showed considerable variation, from-193 kg/kg P in 2015 to 413 kg/kg P in 2014. The effect of P fertilizer treatments on the average AE was higher for the foliar P application (350 kg/kg P) than for the granular band-applied and broadcast (-27 kg/kg P and 6 kg/kg P, respectively) (Fig. 3). However, the variation of AE across 40d PP due to foliar P was more significant (Fig. 4a), while variations for both granular P applications were lower (Fig. 4b). Even though the AE of foliar P treatment showed a tendency to increase as 40d PP increased from 71 to 123 mm, regression procedures failed to identify statistical significance (p=0.13).

Phosphorus recovery efficiency (RE)

Phosphorus fertilizer treatments consisted of the spray of 1.1 kg P/ha to foliage and 21 kg P/ha applied to the soil. Results showed an average RE of 9.3 kg P/kg P; however, the RE of foliar P was consistently higher (Fig. 5a) than granular treatments (Fig. 5b). Recovery due to foliar P ranged between 16 and 38 kg P/kg P, while for granular application, between 0.7 and 2 kg P kg/P. As the Year-P fertilizer interaction was significant (Table 1), replacing the effect of Year in this interaction with 40d PP in regression procedures explained the RE variations. Results indicated a significant effect of 40d PP on the RE of foliar P and broadcast application (Fig. 5a and b, respectively). The effect of 40d PP explained about 70% of RE variations for the foliar and broadcast P application. The band-applied treatment was unaffected by 40d PP. According to the RE-40d PP relationship, as precipitation improved, the corresponding RE of each treatment decreased. Regression coefficients suggested that this reduction (slope) was larger for the foliar P application.

Table 2. Yearly data of accumulated precipitation during the bracketing-silking period (40d PP) (~3 Aug-12 Sep), growing degree-days from tasseling to maturity [GDD(t-m)], yield, agronomic efficiency (AE) and recovery efficiency (RE), and grain quality parameters.

Year	40d PP (mm)	GDD(t-m) (^{o}C)	Yield (kg ha^{-1})	AE (kg kg P^{-1})	RE (kg P kg P^{-1})	Bulk density (kg m^{-3})	Thousand grain weight (g)
2012	108	510	4120	10	9.2	703	---†
2013	115	685	7107	195	6.3	726	270
2014	99	612	4800	413	10.5	762	280
2015	96	668	6792	-193	13.8	770	344
2016	123	612	7533	343	7.7	738	268
2017	104	542	4998	199	10.9	730	271
2018†	---	---	---	---	---	---	---
2019	71	550	2624	-170	4.3	714	154
Mean	102	597	5458	116	9.3	735	282
SE‡	1.2	4.7	167	68.6	1.2	2.1	4.1

† Not measured. ‡ Standard error of the mean

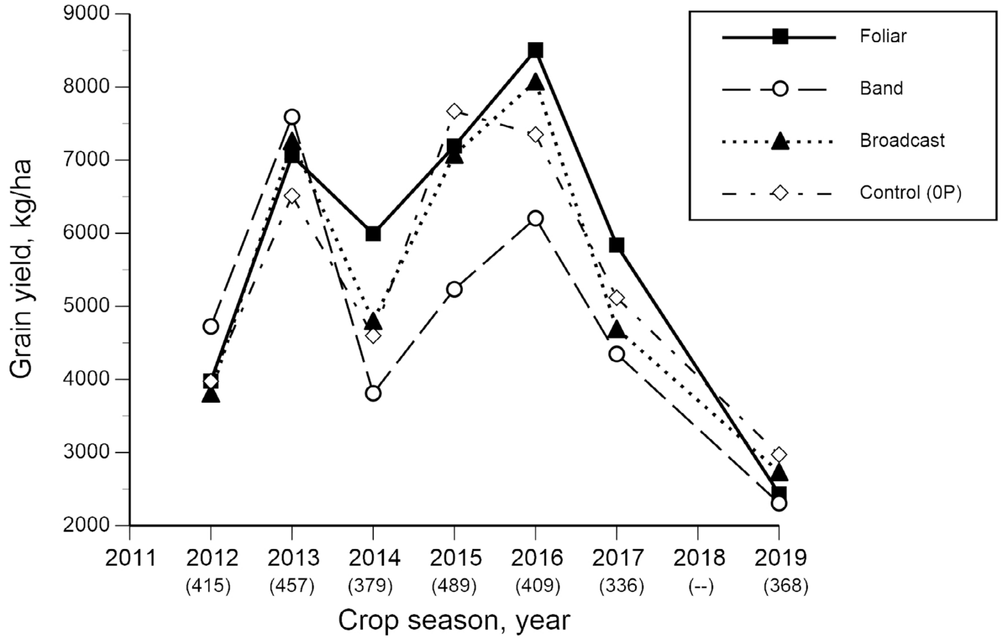

Figure 1. Maize yield variations over crop seasons as affected by P fertilizer treatments applied from 2012 to 2019, except in 2018, which was not harvested due to a hail event. Numbers in parenthesis indicate the seasonal rainfall.

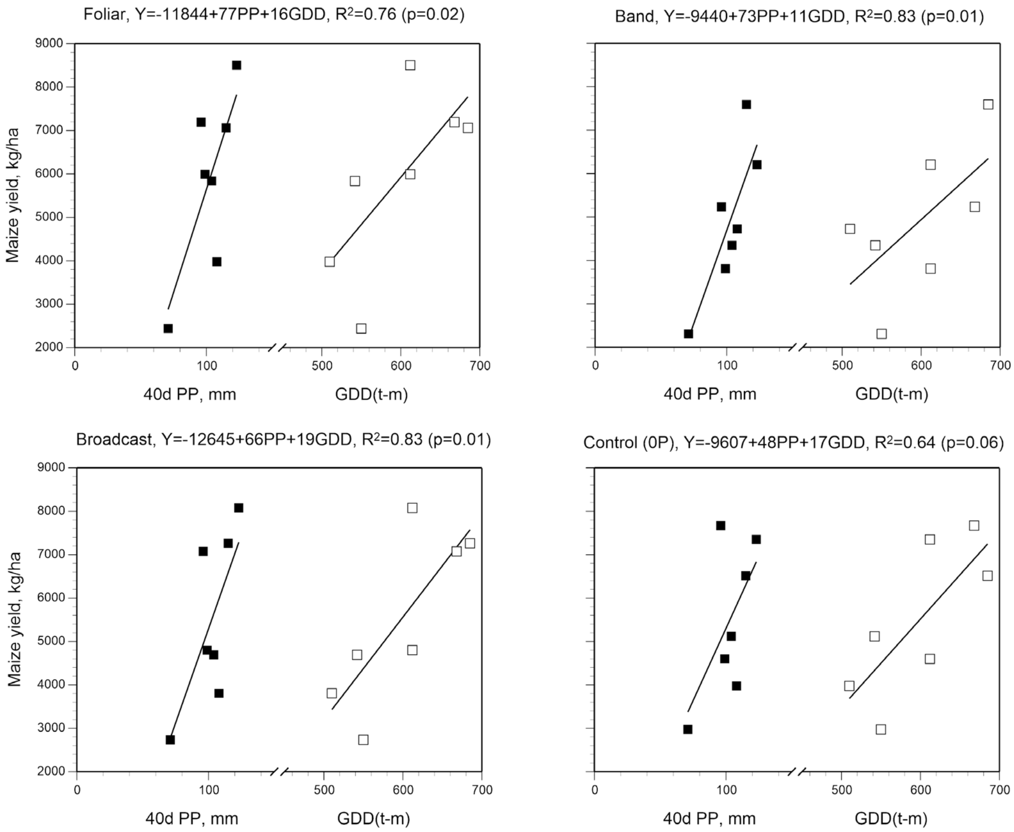

Figure 2. Relationship between maize yield with accumulated precipitation during bracketing-silking stage (40d PP) and heat units from tasseling to maturity stage [(GDD(t-m)]. Equations in each graph show the relationship from a multiple regression analysis with 40d PP and GDD(t-m) as independent variables.

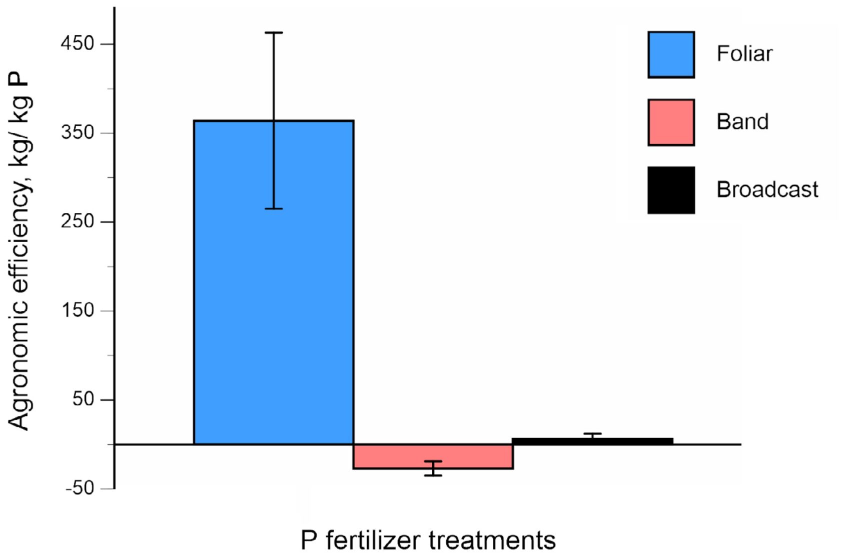

Figure 3. Average P agronomic efficiency (AE) of maize in permanent beds from 2012 to 2019 as affected by three fertilizer P treatments.

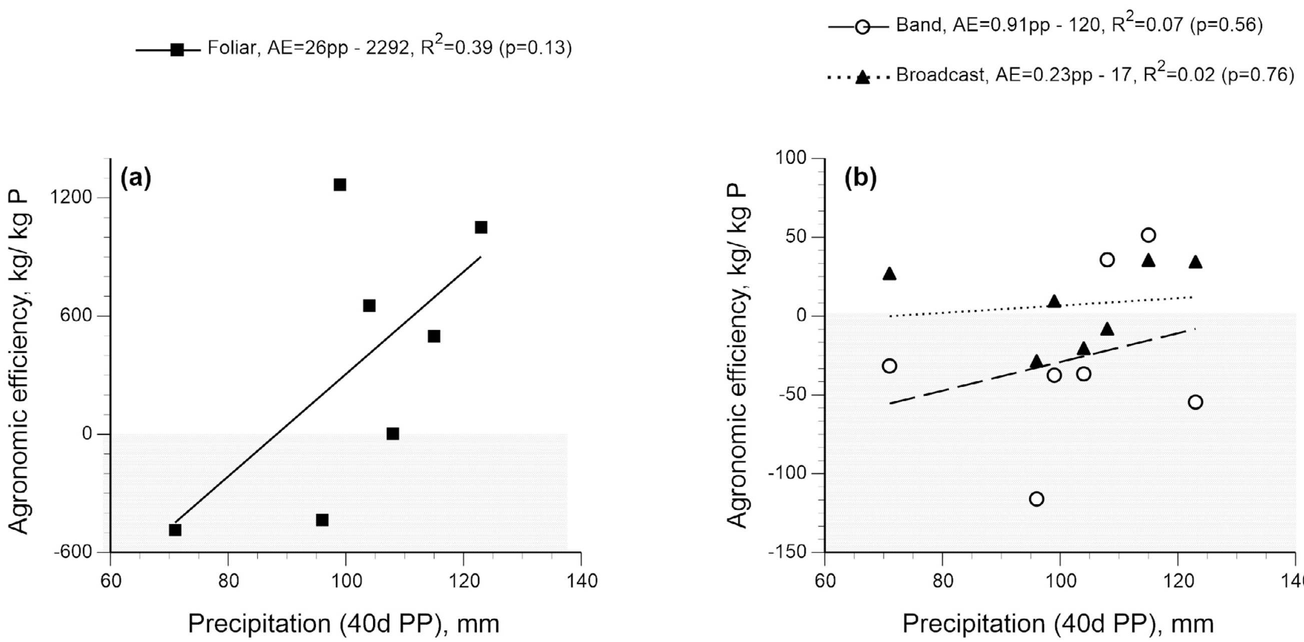

Figure 4. Agronomic efficiency (AE) of maize as affected by accumulated precipitation during the bracketing-silking period (40d PP) for three P fertilizer treatments; foliar (a), band and broadcast (b). The dotted area shows negative AE's.

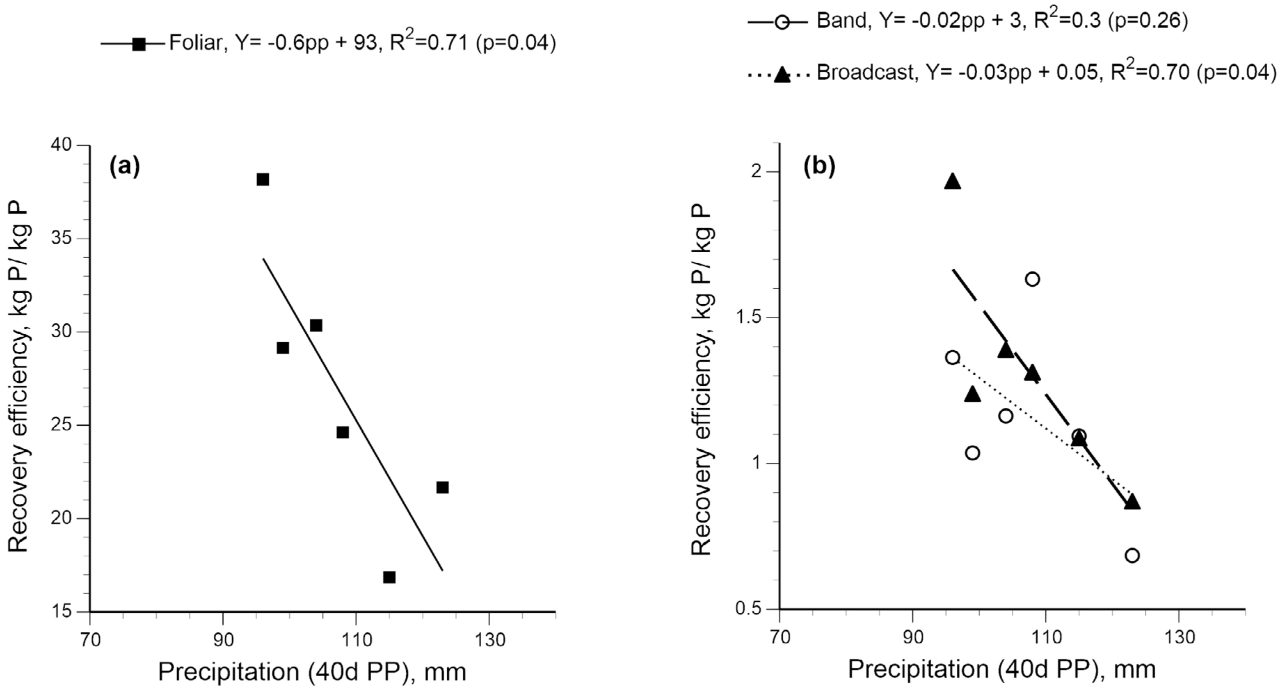

Figure 5. Relationship between grain P recovery efficiency (RE) of maize and accumulated precipitation during bracketing-silking period (40d PP).

Conversely, RE increased as 40d PP approached dry conditions (intercept). This RE improvement was larger for the application to foliage than granular to soil. In any case, grain P removal (16-38 kg P/kg P) due to foliar P application was substantially higher than the P rate applied. On the other hand, regression analysis with GDD showed that heat units did not affect RE variations.

Soil available P

On average, estimating soil available P on each treatment from samples collected to 30 cm depth on the top of the beds showed differential tendencies over the years; broadcast remained about constant, the foliar and control (0P) decreased, and the band-applied treatment increased (Fig. 6). At the inception of the study, soil available P among treatments averaged about 46 mg/kg. After seven crop harvests, according to a non-linear model to estimate P decay over seasons (Eghball et al., 2003), the available P declined by 3%, 24%, and 34% for broadcast, foliar P, and control (0P) plot, respectively. On the contrary, the band-applied application treatment increased by 13%. Notably, even though the P rate for both granular applications was the same, available P content showed opposite results. Soil available P decay estimation, on the other hand, to reach a level of about 15 mg/kg was in the order of control (0P) plot > foliar (years 2031, 2042, respectively).

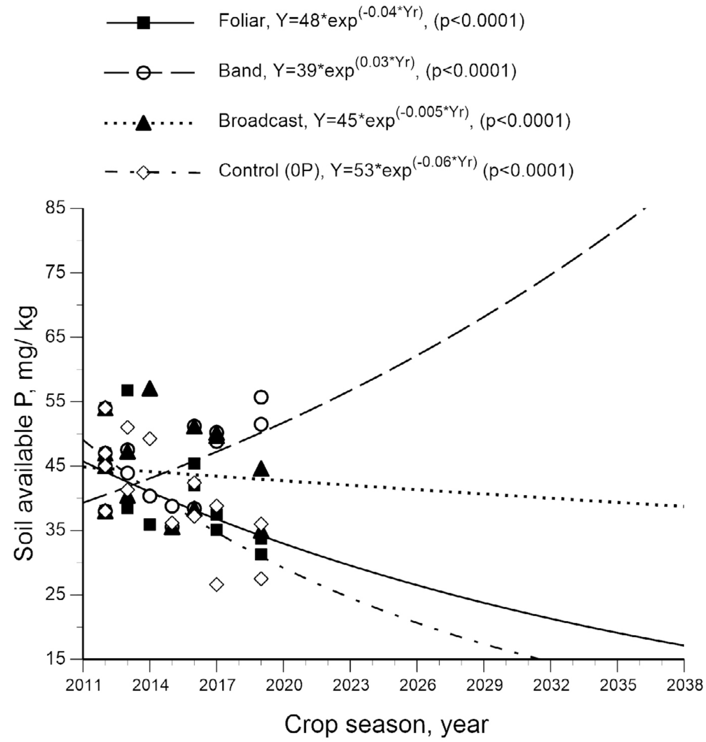

Figure 6. Changes of soil available P content to 30 cm depth over the seasons for three P treatments and a control plot (0P) from 2012 to 2019, except 2018.

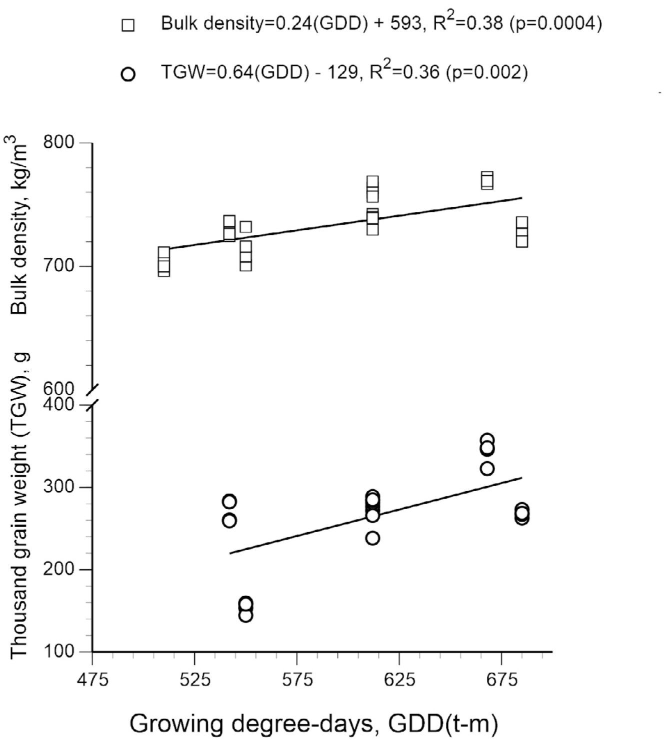

Figure 7. Pooled bulk density and thousand-grain weight (TGW) of rainfed maize as affected by the cumulative growing degree-days [GDD(t-m)] from tasseling to maturity stage of three P treatments and a control plot (0P).

Grain quality

Results from the analysis of variance (Table 1) showed that Year's main effect had a significant influence on grain quality measured as bulk density and TGW. Bulk density varied from a low of 703 kg/m^3 in 2012 to a high of 770 kg/m^3 in 2015, and TGW from 154 g in 2019 to 344 g in 2015 (Table 2). These two measurements averaged 734 kg/m^3 and 282 g, respectively. Pooled data regressed on GDD(t-m) explained the effect of years on bulk density and TGW (Fig. 7); as GDD(t-m) increased from about 500 to 680 units, there was a corresponding increase in these two measurements. According to regression coefficients, TGW was more responsive (slope) to GDD(t-m) changes than bulk density.

Discussion

Maize yield

Even though the soil tests high available P, maize grain yield showed a differential response to P fertilizer application. In general, grain yield was higher for the foliar P fertilizer. This increment agrees with Rafiullah et al. (2021), who reported biomass increments attributed to foliar P spray. Veneklaas et al. (2012), on the other hand, ascribed this effect to leaf senescence, which may be bound to an improved P distribution within the plant. However, a significant drawback in spraying foliage is that an over-application can lead to leaf burn (Bushong et al., 2016). Nevertheless, as this effect was not observed in this study, the foliar rate and growth stage of application is deemed appropriate.

The differential yield response to P treatments, on the other hand, was linked to precipitation (40d PP) and heat units [GDD(t-m)]. The association between yield response and these two weather factors varied among treatments. Even though the effect was remarkably more significant on foliar P spray, results suggest that weather is a principle that governs the optimum use of P fertilizer (Withers et al., 2005). This suggestion is consistent with Ye et al. (2017), who showed a positive response to post-silking precipitation and GDD. Furthermore, research in Mexico by Murray-Tortarolo et al. (2018) found an average correlation coefficient of r=0.45 between rainfed maize yield and precipitation, but this strength of dependency varies from a low of 0.35 to 0.91 suggesting that other factors such as planting date are also involved. The size of yield variation due to weather factors is consistent with the findings in this study. However, if the amount of precipitation continues decreasing and temperatures increase, the potential effect on maize yield and its relationship with fertilizer P is unknown.

The two methods of granular P application also showed differential results; the average maize yield due to broadcast was higher than the band-applied treatment. This result confirms that the broadcast P application is an acceptable practice for no-till systems (Freiling et al., 2022). Then, once crops remove soil P to an acceptable level, it is necessary to maintain it to prevent yield declination (Sonmez & Pierzynski, 2017). On the other hand, the control (0P) plot produced intermediate yield results, although the cessation of P fertilizer application to soil has been underway for over seven crop seasons. This result indicates that soil available P has not reached a sufficiency Bray P-1 level, despite the presumably decreased supply capacity over time (Tang et al., 2011).

Efficiency parameters

Treatments showed positive and negative AE values; in the latter case, untreated-P plots produced more yield than treated-P plots. This result suggests that available P accumulated from previous fertilization is a valuable resource (Zhang et al., 2022) that needs specific management to maintain adequate yields. Contrastingly, AE for granular P applications was negative in most crop seasons, indicating that this source of P fertilizer warrants concerns in terms of yield. Moreover, although the AE of foliar P was strongly negative in two crop seasons, yield response was consistently larger than granular P applied to the soil. This enhancement indicates that foliar P can generally improve efficiency (Girma et al., 2007; Rafiullah et al., 2021). Nevertheless, the effect of P fertilizer sources and soil available P on AE varies due to multiple biophysical and management factors (Zhang et al., 2022). Accordingly, Girma et al. (2007) found that precipitation is a weather factor that affects AE. However, Yu et al. (2021) conjectured that temperature also affects AE but might depend on moisture conditions. Although the effect of these two weather variables was not statistically significant in this study, accumulated precipitation during the bracketing-silking period seemed to affect the AE of foliar P positively.

The average AE for the foliar P treatment was positive, band-applied negative, and broadcast almost nil. The negative AE for the band-applied treatment raises concerns as previous research indicates that this practice improves efficiency (Ridoutt et al., 2013; Dhillon et al., 2017). Then, as the benefit of the band-applied treatment in this study was not evident, the advantages of this application method should occur at sites with different soil P conditions (Freiling et al., 2022) and tillage practices. Thus, the granular broadcast application seems an appropriate practice to fertilize crops grown under permanent beds in soils testing low P.

Generally, grain P recovery was higher than the P dose applied in fertilizers. However, the RE of foliar P fertilizer was much higher than the granular application. This result suggests that foliar spray enhances the access to soil available P through changes in root architecture (Noack et al., 2010); unfortunately, there is limited information on what degree roots can explain variations in P efficiencies (Yu et al., 2021). Even though P recovery from granular treatments was much lower than foliar P, the RE was larger than one unity indicating that the soil has not reached the critical P level (Johnston & Poulton, 2019). Irrespective of the differential results between foliar and granular P application, the size of RE points out that significant amounts of soil available P have accumulated from past fertilizations and still is the most important source of P nutrition for maize (McLaughlin et al., 2011; Roberts & Johnston, 2015) after seven crop seasons.

The maize crop in this study behaved as plants over-fertilized as they appeared to have achieved a level of ‘‘luxury consumption’’, i.e., not all P taken up by the plants turned into grain yield or biomass production (Cadot et al., 2018). However, as the soil has not reached a critical Bray P-1 level, foliar P fertilization should continue as the crop management practice to maintain the high rate of grain P removal. Nevertheless, once the soil reaches a critical level, breeding programs should have developed maize hybrids that translocate minimum amounts of P to grains (Rose et al., 2013). Research has shown the possibility that reducing grain-P concentrations has no adverse effects on seedling vigor or grain yield (Pariasca-Tanaka et al., 2015).

Soil available P and grain quality

Phosphorus application to foliage and the control (0P) plot reduces soil available P over the years. This reduction by foliar P suggests crop uptake exceeds the applied P rate. Soil P reduction due to foliar P, as the sole P fertilization source, indicates that the practice is appropriate to reach an adequate soil P level without harming maize yield. Although the control (0P) plot also mined available soil available P, the strategy may not be appropriate due to the effect on yield. According to the non-linear model applied to foliar P to estimate P decay over time (Eghball et al., 2003), the soil would be testing about 15 mg/kg by 2039 (28 years after the onset of the experiment). Assuming this soil’s available P content is the critical Bray P-1 level, the next step will be to maintain it by replacing the P removed by the harvested maize (Johnston & Poulton, 2019). However, once the soil reaches the critical level, crop P requirement might be minor as plant breeding programs advance in developing genotypes with that trait (Withers et al., 2014), but probably still dependent on in-season rainfall (McBeath et al., 2012).

Although the two granular P fertilizer treatments received the same P rate, the resulting soil available P content over the years differed, the band-applied increased, and the broadcast maintained the initial label. In the former case, the fertilizer supposedly concentrates on top of the bed, complicating the collection of a representative sample (Grant & Flaten, 2019), meanwhile the broadcast treatment deposits most fertilizer granules at the bottom of the furrows, while a tiny portion is on the top of the bed. These application protocols may explain the differential results. However, as the purpose is to diminish the high soil available P content, the granular P applications should be replaced by P spray to foliage. To revert the supposed stratified P due to granular P applications in this no-till system into an enhanced soil available P reduction, one-time tillage (Wortmann et al., 2010) seems an option that should be further studied.

On the other hand, irrespective of soil P decay as related to P fertilizer management, grain quality parameters depend on weather conditions, mainly temperature (Tamagno et al., 2016).

Conclusions

The key objective of the study was to estimate the performance of maize fertilized with foliar P as a management strategy to mine accumulated soil available P. Results indicated that foliar P is an appropriate fertilization management to bring down soil available P as it has no detrimental effects on yield and efficiency parameters of maize. According to estimations, the soil available P content will reach a critical level (~15 mg/kg) after 28 years of continuous foliar P as sole P fertilization input and retaining crop residues on the top of the soil. However, it is unknown if the foliar P fertilizer will continue as the appropriate P source to feed the crop plants as the soil available P mining continues. Meanwhile, serious consideration must be given to temporarily replacing the granular P in soils testing high as foliar P produces a greater yield of maize planted in permanent beds. This planting system marks the inception of a process of reducing excessive P applications that make the agricultural practice a more sustainable activity. On the other hand, the future feasibility of this input depends mainly on the crop breeding programs that need to develop new hybrids that translocate low P rates to grain.

Data availability: The data used to support the findings of this study are available from the first author upon request.

Acknowledgments: Authors acknowledge the support of INIFAP-CEVAMEX to conduct this long term-trial.

Competing interests: The authors have declared that no competing interests exist.

Authors' contributions: **Agustin Limon-Ortega:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Aurelio Baez-Perez:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing.

Funding: The authors received no specific funding for this work.

References

Bai Z, Haigang L, Xueyun Y, Baoku Z, Xiaojun S, Boren W, et al., 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. Plant Soil 372: 27-37. https://doi.org/10.1007/s11104-013-1696-y

Bushong JT, Miller EC, Mullock JL, Arnall DB, Raun WR, 2016. Irrigated and rain-fed maize response to different nitrogen fertilizer application methods. J Plant Nutrition 13: 1874-1890. https://doi.org/10.1080/01904167.2016.1187747

Cadot S, Bèlanger G, Ziadi N, Morel C, Sinaj S, 2018. Critical plant and soil phosphorus for wheat, maize, and rapeseed after 44 years of P fertilization. Nutr Cycl Agroecosyst 112: 417-433. https://doi.org/10.1007/s10705-018-9956-0

Chien SH, Prochnow LI, Tu S, Snyder CS, 2011. Agronomic and environmental aspects of phosphate fertilizers varying in source and solubility: and update review. Nutr Cycl Agroecosyst 89: 229-255. https://doi.org/10.1007/s10705-010-9390-4

Dhillon J, Torres G, Driver E, Figueiredo B, Raun WR, 2017. World phosphorus use efficiency in cereal crops. Agr J 109: 1670-1677. https://doi.org/10.2134/agronj2016.08.0483

Eghball B, Shanahan JF, Varvel GE, Gilley JE, 2003. Reduction of high soil test phosphorus by corn and soybean varieties. Agr J 95: 1233-1239. https://doi.org/10.2134/agronj2003.1233

Freiling M, Tucher S, Schmidhalter U, 2022. Factors influencing phosphorus placement and effects on yield and yield parameters: A meta-analysis. Soil Till Res 216: 105257. https://doi.org/10.1016/j.still.2021.105257

Girma K, Martin KL, Freeman KW, Mosali J, Teal RK, Raun WR, et al., 2007. Determination of the optimum rate and growth stage for foliar applied phosphorus in corn and winter wheat. Comm Soil Sci Plant Analysis 38: 1137-1154. https://doi.org/10.1080/00103620701328016

Govaerts B, Barrera-Franco MG, Limon-Ortega A, Muñoz-Jimenez P, Sayre KD, Deckers J, 2008. Clasificación y evaluación edafológica de tres sitios experimentales del altiplano central de México. Tropicultura 26: 2-9.

Grant CA, Flaten DN, 2019. 4R Management of phosphorus fertilizer in the Northern Great Plains. J Environ Qual 48: 1356-1369. https://doi.org/10.2134/jeq2019.02.0061

Johnston AE, Poulton PR, 2018. The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. Eur J Soil Sci 69: 113-125. https://doi.org/10.1111/ejss.12521

Johnston AE, Poulton PR, 2019. Phosphorus in agriculture: A review of results from 175 years of research at Rothamsted, UK. J Environ Qual 48: 1133-1144. https://doi.org/10.2134/jeq2019.02.0078

Maharjan B, Das S, Nielsen R, Hergert GW, 2021. Maize yields from manure and mineral fertilizers in the 100-year-old Knorr-Holden Plot. Agr J 113: 5383-5397. https://doi.org/10.1002/agj2.20713

McBeath TM, McLaughlin MJ, Noack SR, 2011. Wheat grain yield response to and translocation of foliar-applied phosphorus. Crop Pasture Sci 62: 58-65. https://doi.org/10.1071/CP10237

McBeath TM, McLaughlin MJ, Kirby J, Armstrong RD, 2012. The effect of soil water status on fertiliser, topsoil and subsoil phosphorus utilisation by wheat. Plant Soil 358: 337-348. https://doi.org/10.1007/s11104-012-1177-8

McLaughlin MJ, McBeath TM, Smernik R, Stacey SP, Ajiboye B, Guppy C, 2011. The chemical nature of P accumulation in agricultural soils-implications for fertiliser management and design: an Australian perspective. Plant Soil 349: 69-87. https://doi.org/10.1007/s11104-011-0907-7

Murray-Tortarolo GN, Jaramillo VJ, Larsen J, 2018. Food security and climate change: the case of rainfed maize production in Mexico. Agr Forest Meteorology 253-254: 124-131. https://doi.org/10.1016/j.agrformet.2018.02.011

Nielsen DC, Halvorson AD, Vigil MF, 2010. Critical precipitation period for dryland maize production. Field Crops Res 118: 259-263. https://doi.org/10.1016/j.fcr.2010.06.004

Noack SR, McBeath TM, McLaughlin MJ, 2010. Potential for foliar phosphorus fertilization of dryland cereal crops: a review. Crop Pasture Sci 61: 659-669. https://doi.org/10.1071/CP10080

Pariasca-Tanaka J, Vandamme E, Mori A, Segda Z, Saito K, Rose TJ, et al., 2015. Does reducing seed-P concentrations affect seedling vigor and grain yield of rice? Plant Soil 392: 253-266. https://doi.org/10.1007/s11104-015-2460-2

Rafiullah, Khan MJ, Muhammad D, Mussarat M, Huma, Adnan M, et al., 2021. Foliar versus soil phosphorus (P) application for improving P use efficiency in wheat and maize in calcareous soils. J Plant Nutr 44(11): 1598-1610. https://doi.org/10.1080/01904167.2021.1871744

Reid K, Schneider K, Joosse P, 2019. Addressing imbalances in phosphorus accumulation in Canadian agricultural soils. J Environ Qual 48: 1156-1166. https://doi.org/10.2134/jeq2019.05.0205

Ridoutt BG, Wang E, Sanguansri P, Luo Z, 2013. Life cycle assessment of phosphorus use efficient wheat grown in Australia. Agr Syst 120: 2-9. https://doi.org/10.1016/j.agsy.2013.04.007

Roberts TL, Johnston AE, 2015. Phosphorus use efficiency and management in agriculture. Resour Conserv Recycl 105: 275-281. https://doi.org/10.1016/j.resconrec.2015.09.013

Rose T, Liu L, Wissuwa M, 2013. Improving phosphorus efficiency in cereal crops: Is breeding for reduced grain phosphorus concentration part of the solution? Front Plant Sci 4: 1-6. https://doi.org/10.3389/fpls.2013.00444

Sonmez O, Pierzynski GM, 2017. Changes in soil phosphorus fractions resulting from crop residue removal and phosphorus fertilizer. Comm Soil Sci Plant Anal 48: 929-935. https://doi.org/10.1080/00103624.2017.1323094

Syers K, Bekunda M, Cordell D, Corman J, Johnston J, Rosemarin A, et al., 2011. Phosphorus and food production. UNEP Year Book 2011: Emerging Issues in Our Global Environment. United Nations Environment Programme, Nairobi, pp. 35-46.

Tamagno S, Greco IA, Almeida H, Di Paola JC, Marti Ribes F, Borras L, 2016. Crop management options for maximizing maize kernel hardness. Agr J 108: 1561-1570. https://doi.org/10.2134/agronj2015.0590

Tang X, Li J, Ma Y, Hao X, Li X, 2008. Phosphorus efficiency in long-term (15 years) wheat-maize cropping systems with various soil and climate conditions. Field Crops Res 108: 231-237. https://doi.org/10.1016/j.fcr.2008.05.007

Tang X, Shi X, Ma Y, Hao X, 2011. Phosphorus efficiency in a long-term wheat-rice cropping system in China. J Agr Sci 149: 297-304. https://doi.org/10.1017/S002185961000081X

Torres Flores JL, Mendoza García B, Prasanna BM, Alvarado G, San Vicente FM, Crossa J, 2017. Grain yield and stability of white early maize hybrids in the Highland Valleys of Mexico. Crop Sci 57: 3002-3015. https://doi.org/10.2135/cropsci2017.03.0145

van de Wiel CCM, van der Linden CG, Scholten OE, 2016. Improving phosphorus use efficiency in agriculture: opportunities for breeding. Euphytica 207: 1-22. https://doi.org/10.1007/s10681-015-1572-3

Veneklaas EJ, Lambers H, Bragg J, Finnegan PM, Lovelock CE, Plaxton WC, et al., 2012. Opportunities for improving phosphorus-use efficiency in crop plants. New Phytol 195: 306-320. https://doi.org/10.1111/j.1469-8137.2012.04190.x

Withers PJA, Nash D, Laboski CAM, 2005. Environmental management of phosphorus fertilizers. In: Phosphorus: agriculture and the environment; Sims JT, Sharpley AN (eds). Agr Mon 46, ASA-CSSASSSA, pp: 782-827.

Withers PJ, Sylvester-Bradley R, Lones DL, Healey JR, Talboys PJ, 2014. Feed the crop not the soil: rethinking phosphorus management in the food chain. Environ Sci Tech 48: 6523-6530. https://doi.org/10.1021/es501670j

Wortmann CS, Drijber RA, Franti TG, 2010. One-time tillage of no-till crop land five years post-tillage. Agr J 102: 1302-1307. https://doi.org/10.2134/agronj2010.0051

Ye Q, Lin X, Adee E, Min D, Assefa Mulisa Y, O'Brien D, et al., 2017. Evaluation of climatic variables as yield-limiting factors for maize in Kansas. Int J Climatol 37: 464-475. https://doi.org/10.1002/joc.5015

Yu X, Keitel C, Feike A, Dijkstra, 2021. Global analysis of phosphorus fertilizer use efficiency in cereal crops. Global Food Secur 29: 100545. https://doi.org/10.1016/j.gfs.2021.100545

Zhang L, Chen J, Chu G, 2022. Legacy phosphorus in calcareous soil under 33 years of P fertilizer application: Implications for efficient P management in agriculture. Soil Use Manag 38: 1380-1393. https://doi.org/10.1111/sum.12792

Zhou G, Wang Q, 2018. A new nonlinear method for calculating growing degree days. Sci Rep 8: 10149. https://doi.org/10.1038/s41598-018-28392-z