LONG-TERM (16-YEAR) COMPARISON OF PHOSPHORUS FERTILIZATION STRATEGIES: TARGETED SOIL TEST VALUES VS. CROP REMOVAL IN CORN PRODUCTION

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ABSTRACT

Developing effective phosphorus (P) fertilization strategies to optimize corn (Zea mays L.) yields across varying environmental conditions is essential. This 16-year study, conducted on Nora silt loam soil in Concord, NE (initial Bray-1 P of 16±3 mg kg^{-1}), evaluated different P fertilization strategies under dry, normal, and wet years. The treatments included: no P or N (NPNN), no P (NP), phosphorus applied at crop removal (CRP), and maintaining soil P at 15 (B15), 30 (B30), and 45 (B45) mg kg^{-1} Bray-1 P, with equivalent nitrogen rates across all treatments except NPNN. Results indicated a 25% and 33% reduction in soil test phosphorus (STP) for the NPNN and NP treatments, respectively. Maintaining soil P at B30 and B45 required 1.8 times more P than CRP and B15. Although the B30 and B45 treatments increased corn grain P concentration by 6-12% compared to B15 and CRP, they did not lead to yield improvements during normal and dry years. The NP treatment reduced yields by 9% in normal years and 12% in wet years. In contrast, CRP outperformed B15 during wet years, yielding 8% more. Economic analysis revealed that B45 generated a 56% higher net return in normal years, while CRP delivered the highest return on investment (ROI) at 4.8. This study emphasizes the challenges of managing soil P under varying environmental conditions, showing that while higher STP levels (B30 and B45) may enhance grain P concentration, they do not consistently boost yields or ROI compared to CRP and B15.

INTRODUCTION

Phosphorus (P) is a critical nutrient in corn (Zea mays L.) production, second only to nitrogen (N) in both agronomic importance and cost (Olson et al., 1987; Beegle, 2005). Effective P management is essential, though recommendations vary widely due to differing soil properties and environmental conditions. Corn production typically relies on two main P management strategies: maintaining soil test P (STP) at a critical level (CL) or applying P based on crop removal (CRP). The CL approach keeps STP above a deficiency threshold, while CRP replaces only the P removed during harvest, allowing gradual STP increases over time (Fulford & Culman, 2018). Climate variability further complicates P management, as crop yields and STP levels may respond differently under dry, normal, or wet conditions.

The debate continues about whether maintaining STP above the CL could enhance yield resilience under stress or if CRP and CL applications can yield similar or better returns on investment (ROI) with lower input costs (Penn et al., 2023; Fixen & Grove, 1990). This 16-year study in eastern Nebraska assessed the long-term impacts of maintaining STP levels at 15, 30, and 45 ppm Bray-1 P, compared with CRP, on corn yield, STP dynamics, and economic returns. The study's objectives included evaluating whether higher STP levels boost yields and economic outcomes and whether CRP would be more cost-effective than CL.

MATERIALS AND METHODS

A long-term (2000–2015) study was conducted on Nora silt loam soil at the Haskell Agricultural Laboratory in Concord, NE, where continuous corn had been grown since 1974. The soil, depleted of P due to nitrogen-only applications since 1986, had a baseline STP of 16 ppm Bray-1 P, pH of 5.4, and 280 lb/ac K. Six treatments in a randomized block design with four replications were applied: no P or N (NPNN), no P (NP), CRP, and targeted STP levels of 15 (B15), 30 (B30), and 45 (B45) ppm Bray-1 P. Except for NPNN, equivalent amount of nitrogen was applied to all treatments annually. Phosphorus was applied preplant, initially as monoammonium phosphate (MAP) or diammonium phosphate (DAP) and later as triple superphosphate from 2002 onward.

The targeted STP levels were achieved using initial P applications calculated from baseline STP values, with an estimated requirement of 8.6 lb P/ac to raise STP by 1 ppm (Fernández & Hoeft, 2009). CRP applications were adjusted annually based on the previous year's crop removal. Soil samples were taken post-harvest from an 8-inch depth and analyzed for STP to inform P applications, adjusted if STP deviated more than 5 ppm from target levels. Standard crop management practices were used, and yields were measured with a plot combine. Precipitation and evapotranspiration data helped categorize growing conditions as dry, normal, or wet years (Shekhar & Shapiro, 2019). Economic analysis included net profit and ROI, calculated from yield increases, corn prices, and P fertilizer costs.

RESULTS AND DISCUSSION

Phosphorus Application Mass and Changes in STP Levels

This study required varying amounts of P application across treatments to maintain target STP levels. To reach their respective target STP level, the B30 and B45 treatments received substantial P in the early years, based on the estimate of 8.6 lb P ac^{-1} to raise STP by 1 ppm Bray-1 P (Fernández & Hoeft, 2009). During the first two years, B15, B30, and B45 received 23%, 44%, and 63% of their total P, respectively. By 2004, B30 achieved its target, while B45 maintained STP above the target until 2009. This suggests a multi-year build program could be more practical for producers, as it spreads costs and prevents excessive initial applications. Over the 16-year study, total P applied was highest for B45 (569 lb P ac^{-1}), followed by B30 (390 lb P ac^{-1}), B15 (234 lb P ac^{-1}), and CRP (290 lb P ac^{-1}). Statistically, B45 received more P than B30, with both surpassing B15 and CRP, which were similar.

Without P application (NP and NPNN), STP levels declined from 16 ppm to 7 ppm (NP) and 11 ppm (NPNN) over 16 years, consistent with soil P depletion due to crop uptake. This gradual decrease aligns with findings that soil P levels decline more slowly than they increase, due to P's limited availability from less labile pools (Randall et al., 1997; Rehm & Schmitt, 1993). Conversely, the targeted P treatments initially exceeded their respective targets: two years after the first application, STP levels

Table 1. Effect of phosphorus application strategies on phosphorus application rates and quantity by year and across years (2000-2015) at Concord, NE.

Treatments†	CRP	B15	B30	B45	SE‡
Year applied	-------------------- lb P ac^{-1} --------------------				
2000	8c§	11c	124b	259a	9.8
2001	21b	43ab	46ab	100a	20.9
2002	20a	6a	12a	0a	6.5
2003	17a	0b	0b	0b	0.2
2004	13a	10a	10a	8a	4.7
2005	16a	8a	25a	11a	9.2
2006	22a	0b	0b	0b	0.4
2007	32a	29a	29a	4a	8.9
2008	20a	21a	14a	22a	9.9
2009	19a	21a	19a	14a	4.4
2010	20a	22a	66a	52a	14.6
2011	26a	21a	12a	12a	5.4
2012	15ab	13ab	7b	3a	6.2
2013	8a	6a	7a	12a	4.5
2014	7a	8a	8a	18a	4.1
2015	25a	15ab	9b	28a	4.9
Total (2000 – 2015)	290c	234c	390b	569a	26.9

†CRP indicates P applied at crop removal, and B15, B30, B45 indicate treatments to maintain STP levels at 15, 30, and 45 ppm (Bray-1P), respectively.
‡Indicates weighted standard error (SE) for all variables.
§Different letters in the same row indicate means are significantly different at $P < 0.05$

Table 2 Effect of phosphorus application strategies on soil phosphorus levels by year (2000-2015) at Concord, NE.

	Soil test P levels						
Treatments†	NPNN	NP	CRP	B15	B30	B45	SE‡
Year	------------------------------ Bray-1P ppm ------------------------------						
2000	14b§	16b	18b	16b	35a	37a	4.4
2001	14c	11c	25bc	21bc	47b	102a	9.7
2002	16c	15c	36c	34c	72b	133a	12.8
2003	13b	13b	23b	22b	36b	90a	10.4
2004	13c	13c	23bc	22bc	31b	68a	5.2
2005	17c	15c	37c	36c	73b	133a	12.3
2006	9c	8c	23bc	18c	35b	77a	5.3
2007	9d	10d	24c	18cd	36b	55a	3.4
2008	11de	8e	25c	16d	33b	51a	2.4
2009	9c	7c	19b	12c	25b	42a	2.5
2010	20cd	7d	22c	21c	43b	60a	4.8
2011	10cd	7d	21b	17bc	38a	44a	2.3
2012	11d	8d	25bc	18cd	34b	52a	3.8
2013	10d	8d	24c	19c	34b	44a	2.2
2014	13c	9c	26b	21b	40a	46a	2.8
2015	12cd	8d	32b	21c	37b	55a	3.7

†NP and NPNN indicate treatments with no added P and neither P nor N applied, respectively, CRP indicates P applied at crop removal, and B15, B30, B45 indicate treatments to maintain STP levels at 15, 30, and 45 ppm (Bray-1P equivalents), respectively.
‡Indicates weighted standard error (SE) for all variables.
§Different letters in the same row indicate significant mean differences at $P < 0.05$

reached 19, 42, and 91 ppm for B15, B30, and B45, respectively, reflecting an initial overshoot. These levels peaked in 2002, then gradually declined to near target levels, suggesting that high initial applications have prolonged residual effects. Splitting initial applications over time may better align with target attainment and prevent overshoot (McCallister et al., 1987; Richards et al., 1995).

In later years, P applications for B30 and B45 decreased to maintenance levels, similar to or even lower than CRP, indicating a stabilizing effect after target STP was achieved. The CRP and B15 treatments maintained similar STP levels across most years, with CRP gradually increasing STP from 16 ppm in 1998 to 28 ppm by 2015, without falling below the initial level. These results support that CRP applications can gradually raise STP over time (Sims et al., 2023; Wortmann et al., 2018).

Grain Yield and Grain P Concentration

In the early years, yield differences from phosphorus (P) application were minimal due to soil test P (STP) levels near the critical threshold of 16 ppm. Over the 16-year study, however, P application significantly increased average corn grain yield compared to no P, while nitrogen absence reduced yield by 38%. Average yields across P treatments (CRP, B15, B30, and B45) were similar, at 123, 120, 121, and 126 bu ac^{-1}, respectively, with B45 showing a 5% higher trend than B15 but without statistical significance. This aligns with findings that yield gains diminish when STP exceeds critical levels (Penn et al., 2023; Iqbal et al., 2019). In dry years, yields across treatments were 28-44% lower than in normal or wet years, indicating moisture limitations on yield. Yields in the absence of P (NP) were reduced by 9% and 12% in normal and wet years, respectively, while CRP showed an 8% higher yield than B15 in

Table 3 Effect of P fertilizer application strategies on corn grain yield during dry (SPEI > -1.13 < -2.17), normal (SPEI > -0.69 < 0.51), wet (SPEI > 1.16 < 1.59), and across all study years (2000-2015) at Concord, NE.

	Corn yield			
	Dry years (3 years)	Normal years (10 years)	Wet Years (3 years)	All years (2000-2015 years)
Treatments‡	----------------bu ac^{-1}----------------			
NPNN	72	73	83	75
NP	78	112	142	112
CRP	84	123	166	123
B15	84	121	153	120
B30	84	121	161	121
B45	80	127	167	126
SE§	17.5	8.0	6.4	8.0
Contrasts †		*P* > F		
NPNN vs (NP + CRP + B15 + B30 + B45)	**	***	***	***
NP vs (CRP + B15 + B30 + B45)	NS	***	***	***
CRP vs B15	NS	NS	*	NS
B30 vs B45	NS	NS	NS	NS
(CRP + B15) vs (B30 +B45)	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.
†Orthogonal treatment comparisons.
‡NP and NPNN indicate treatments with no added P and neither P nor N applied, respectively; CRP indicates P applied at crop removal, and B15, B30, B45 indicate treatments to maintain STP levels at 15, 30, and 45 ppm (Bray-1P equivalents), respectively.
§Indicates weighted standard error (SE) for all variables.
Corn grain yields expressed at 15.5 % moisture.

wet conditions, suggesting potential yield losses when STP is only maintained near the critical level under high-yield potential.

Absence of P fertilization (NP treatment) showed a 16% decrease in grain P concentration compared to P-applied treatments, with CRP and B15 averaging 0.32% grain P concentration. Higher STP levels in B30 and B45 increased grain P concentration by 9% compared to B15 and CRP, demonstrating "luxury consumption" where excess P uptake does not enhance yield (Cadot et al., 2018; Penn et al., 2023). In dry years, grain P concentration increased by 6-10% due to limited carbohydrate production from moisture stress, causing less P dilution. Overall, maintaining soil at higher STP levels (B30 and B45) raised grain P concentration by 11% and 6% in dry and normal years, respectively, compared to CRP and B15, reflecting increased P uptake without a significant yield benefit.

Table 4 Effect of phosphorus application strategies on grain P concentration during dry (SPEI > -1.13 < -2.17), normal (SPEI > -0.69 < 0.51), wet (SPEI > 1.16 < 1.59), and across all study years (2000-2015) at Concord, NE.

	Grain P concentration			
	Dry years (3 years)	Normal years (10 years)	Wet Years (3 years)	All years (2000-2015)
Treatments‡	------------------------------------ % ------------------------------------			
NPNN	0.34	0.32	0.33	0.32
NP	0.29	0.28	0.27	0.28
CRP	0.33	0.32	0.3	0.32
B15	0.34	0.32	0.31	0.32
B30	0.37	0.34	0.32	0.34
B45	0.38	0.34	0.34	0.35
SE§	0.02	0.02	0.05	0.02
Contrasts †	*P* > F			
NPNN vs (NP + CRP + B15 + B30 + B45)	NS	NS	NS	NS
NP vs (CRP + B15 + B30 + B45)	***	***	**	***
CRP vs B15	NS	NS	NS	NS
B30 vs B45	NS	NS	NS	NS
(CRP + B15) vs (B30 + B45)	*	***	NS	***

*, **, ***: Significant at *P* < 0.05, 0.01, and 0.001, respectively.
†Orthogonal treatment comparisons.
‡NP and NPNN indicate treatments with no added P and neither P nor N applied, respectively, CRP indicates P applied at crop removal, and B15, B30, B45 indicate treatments to maintain STP levels at 15, 30, and 45 ppm (Bray-1P equivalents), respectively.
§Indicates weighted standard error (SE) for all variables.

Economic Analysis of Fertilization Strategies

The economic analysis of P fertilization strategies revealed that the highest yield increase and net income were observed with the B45 treatment, though not significantly different from crop removal-based P application (CRP). The B45 and CRP treatments generated additional revenue of $14 and $24 per acre, respectively, over the B15 treatment. However, B45 incurred the highest annual P costs at $18 per acre, while CRP costs were similar to B15 and lower than B30 and B45. Despite higher marginal income, the B45 and B30 treatments had the lowest return on investment (ROI) at 3.0, whereas CRP yielded the highest ROI at 4.9, making it the most economical approach for maximizing net profit. Under dry conditions, applying P should be minimized when soil test P is near or above the critical level (CL), as higher application rates increase financial risk without yield benefits. In contrast, normal growing conditions supported B45's profitability due to yield gains, emphasizing that high STP levels could be beneficial if soil P loss risk and budget constraints are manageable.

Table 5. Annual net profit and return on investment (ROI) of P fertilization strategies during dry (SPEI > -1.13 < -2.17), normal (SPEI > -0.69 < 0.51), wet (SPEI > 1.16 < 1.59), and across all study years (2000-2015) at Concord, NE.

	Average across year (2000 – 2015)						Dry year		Normal year		Wet year	
	Δ Yield[a]	Net income[b]	P applied	Cost[c]	Net return	ROI[e]	Δ Yield	Net return	Δ Yield	Net return	Δ Yield	Net return
Treatment[†]	bu ac^{-1}	\$ ac^{-1}	lb P ac^{-1} yr^{-1}	\$ ac^{-1}	\$ ac^{-1}		bu ac^{-1}	\$ ac^{-1}	bu ac^{-1}	\$ ac^{-1}	bu ac^{-1}	\$ ac^{-1}
CRP	12ab	43ab	18c	9c	34	4.9	-27	-104	11b	31b	54	185
B15	8c	30c	14c	7c	22	3.6	-27	-106	9b	25b	41	140
B30	11bc	38bc	24b	12b	25	3.1	-27	-108	10b	24b	49	163
B45	15a	53a	36a	18a	36	3	-32	-132	17a	42a	56	182
SE[‡]	4.1	15	1.7	1	15	1.3	4.6	17	1.4	6	4.5	16
						P > F						
	*	*	***	***	NS	NS	NS	NS	***	*	NS	NS

ΔYield [a] = Increase in yield over average no P (NP) yield across all years (112 bu ac^{-1}).
[b]Net income = Income calculated from increase in yield (Δ Yield) and corn price.
[c]Cost = Cost of P application calculated using price of P fertilizer and average P applied each year.
[e]ROI = Return on investment from P application calculated as ratio of income and cost.
[†]Treatments are P applied at crop removal (CRP), and B15, B30, B45 are treatments to maintain STP levels at 15, 30, and 45 ppm (Bray-1P equivalents), respectively.
SE[‡] = Indicates weighted standard error.

SUMMARY

This study compared crop removal (CRP) and critical level (CL) approaches to phosphorus (P) fertilization, investigating whether raising the CL from 15 ppm Bray-1 P would improve yield and economic returns. Results showed that maintaining soil test P (STP) above the CL, especially at very high levels (B45), tended to enhance yield by 5%, particularly in normal and wet years, though benefits were less evident in dry conditions due to moisture constraints. While B45 generated additional revenue, it required twice the P application of CRP, leading to lower return on investment (ROI). CRP emerged as the most cost-effective strategy, achieving the highest ROI (4.9) by increasing yield moderately (1–8%) without the high costs associated with maintaining elevated STP levels. This approach also reduces soil testing frequency, supporting sustained productivity without excessive P inputs. These findings highlight the importance of adjusting P management based on weather and crop demands and suggest a potential need to revisit Nebraska's P recommendations for dryland corn. Further regional research is recommended to validate these outcomes for broader applicability.

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