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Corn Yield and Grain Nutrient Uptake from 50 Years of Nitrogen and Phosphorus Fertilization

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ABSTRACT

Long-term agricultural field experiments provide valuable information regarding the effects of nutrient inputs on crop productivity. The objectives of this study were to quantify the effects of 50 yr of annual N and P application on irrigated continuous corn *(Zea mays* L.) grain yield, grain nutrient uptake, and economic optimum N rates. Six N (0, 45, 90, 134, 179, and 224 kg N ha^{-1}) and three P rates (0, 20, and 40 kg P ha^{-1}) in a factorial arrangement were applied annually from 1992 to 2010 to a Ulysses silt loam near Tribune, KS. From 1961 to 1991, only two P rates (0 and 20 kg P ha^{-1}) were applied with the six N rates. During the last 19 yr, grain yield increased 20% with P alone and 103% with N alone; however, N and P applied together increased grain yields up to 225% compared to the unfertilized control. The N rate required for maximum profit at 20 and 40 kg P ha^{-1} averaged 172 and 180 kg N ha^{-1}, respectively. At the economic optimum N rate of 172 kg N ha^{-1}, apparent fertilizer nitrogen recovery in grain ($AFNR_g$) was 44% and apparent fertilizer phosphorus recovery ($AFPR_g$) was 63 and 44% with 20 and 40 kg P ha^{-1}, respectively. Fifty years of irrigated corn response to N and P fertilization demonstrated a strong positive interaction between N and P on grain yield, apparent N and P recovery, and profitability.

Core Ideas

- Initiated in 1961, a 50-yr field study quantified continuous irrigated corn response to annual N and P rates.
- Positive N–P interactions on grain yield and grain N/P concentrations were documented.
- Economic optimum N rate varied greatly over years, but averaged ~175 kg N ha^{-1} (1992-2010).
- Significantly greater apparent fertilizer N recovery in grain (~45%) occurred with P fertilization compared to no P (~20%).
- Long-term field studies can be used to improve nutrient effects on productivity.

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The importance of sustaining the productive capacity of agriculture to meet future global demands for food, feed, fiber, and fuel has been well established (CAST, 2013). Most technical advances in agricultural management have resulted from more than a century of short-term field research experiments conducted over diverse conditions (Army and Kemper, 1991). Long-term agricultural field experiments provide an invaluable source of data to assess treatment–environment interactions on crop growth and soil properties critical to sustaining agro-ecosystem function (Brown, 1991; Robertson et al., 2008; Poulton, 1996; Jenkinson, 1991).

In North America, there are 12 long-term field experiments that have been in continuous production for 75 yr or longer (Mitchell et al., 1991). The majority of these experiments evaluate crop rotations and effects of fertilizer and manure applications; however, treatments are replicated in only five of these studies. Since 1942, 13 long-term replicated studies were initiated with a broad range of soil and crop management treatments. In addition to the development of practical crop productivity information, these long-term studies provided a resource for scientists from diverse disciplines evaluating treatment effects on numerous soil properties and processes including soil erosion (Gantzer et al., 1991), soil biology and organic matter (Miles and Brown, 2011; Paustian et al., 1998; Dick, 1992), soil fertility (Girma et al., 2007; Davis et al., 2003; Overman and Scholtz, 2002), soil physical properties (Blanco-Canqui and Schlegel, 2013), and environmental quality (Haberle and Kaš, 2012; Hansen and Djurhuus, 1996).

Although numerous management factors influence crop response to applied N, identifying the quantity of N required for optimum yield is critical to maximizing net return and crop recovery of applied N (Dobermann et al., 2011). Ferguson et al. (1991) reported optimum irrigated corn yields averaged 9.6 Mg ha^{-1} at N rates that varied between 112 and 250 kg N ha^{-1}, depending on location and year. As management practices improved in the western Corn Belt region, optimum grain yield potential has increased to 12 to16 Mg ha^{-1} (Grassini et al., 2009). In 12 irrigated continuous corn trails over 3 yr, Dobermann et al. (2011) reported an economic optimum N rate of 171 kg N ha^{-1} with 14.8 Mg ha^{-1} optimum grain yield.

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Abbreviations: $AFNR_g$, apparent fertilizer nitrogen recovery in grain; $AFPR_g$, apparent fertilizer phosphorus recovery in grain.

Crop recovery of fertilizer N commonly ranges between 30 and 70% (Legg and Meisinger, 1982). A recent review of nutrient use efficiency in cereal crops documented fertilizer N recoveries as high as 65% for corn (Ladha et al., 2005). Although many climate and management factors influence nutrient recovery, $AFNR_g$ decreases with increasing N rate (Oberle and Keeney, 1990). It is well understood that any factor limiting yield potential will reduce applied nutrient recovery and profit (Havlin et al., 2014). For example, in P deficient soils, adequate P fertilization increases yield response to applied N and $AFNR_g$ (Halvorson and Havlin, 1992; Campbell et al., 2005; Selles et al., 2011; Zhang et al., 2009; Dai et al., 2013)

A long-term field experiment was established in western Kansas in 1961 to evaluate irrigated corn response to annual applications of N and P. Yield results were published after 20 yr (Hooker et al., 1983) and 30 yr (Schlegel and Havlin, 1995). As with many long-term field studies, the data were used by other researchers to evaluate additional objectives (Meisinger et al., 2008; Overman and Scholtz, 2002; Nkonya and Featherstone, 2000), by industry and extension educators to advise growers (Polizotto, 2008; Dhuyvetter et al., 2000), and to support agricultural policy (Ribaudo et al., 2011). Schlegel et al. (1996) reported important relationships between economic optimum N rates and N loading in the soil profile, where nitrate leaching potential was increased when N was applied in excess of the economic optimum N rate.

Table 1. Selected soil chemical properties (0–15 cm) of the unfertilized plots from a long-term irrigated continuous corn study at Tribune, KS.

Soil property	Year 1961	1991	2010
CEC, cmol kg^{-1}	–	24	27
pH (1:1)	7.9	8.1	7.8
OM, %	1.4	2.0	2.1
Bray 1-P, mg kg^{-1}	17	6	7
NH_4OAc-K, mg kg^{-1}	500	560	527
DTPA Zn, mg kg^{-1}		1.1	0.7
DTPA-Fe, mg kg^{-1}		5.6	5.4
Nitrate-N (0–15 cm), mg kg^{-1}		0.8	3.0
Nitrate-N (15–30 cm), mg kg^{-1}		0.5	1.0
Nitrate-N (30–60 cm), mg kg^{-1}		0.3	1.8
Nitrate-N (60–90 cm), mg kg^{-1}		0.5	1.7
Nitrate-N (90–120 cm), mg kg^{-1}		0.4	1.7

The objectives of this study were to quantify the effects of 50 yr (with emphasis on the last 19 yr) of annual N and P application on grain yield, grain uptake of N and P fertilizer, and economic optimum N rates for irrigated continuous corn. Our hypothesis was that a higher P rate than included in the initial experimental design may increase grain yield and economic optimum N rate.

MATERIALS AND METHODS

A long-term N and P fertilization experiment was established in 1961 in irrigated continuous corn on a Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustoll) with <1% slope at the Tribune Unit, Southwest Research-Extension Center located in west-central Kansas. The soils are deep, well drained, and were formed in calcareous loess. Selected chemical properties of the surface soil in the control plots are shown in Table 1. Annual yield data and cultural practices through 1991 were reported previously (Hooker et al., 1983; Schlegel and Havlin, 1995). Similar cultural practices were continued through 2010. Since 1992, the experiment is a complete factorial with six N rates (0, 45, 90, 134, 179, and 224 kg N ha^{-1}) and three P rates (0, 20, and 40 kg P ha^{-1}) in a randomized complete block design with five replications. Between 1961 and 1991, the experiment included three combinations of P and K; 0 P with 0 K, 20 kg P ha^{-1} with 0 K, and 20 kg P ha^{-1} with 37 kg K ha^{-1}. In 1992, the P plus K treatment was changed to 40 kg ha^{-1} of P without K. This was done because of lack of yield response to K and potential yield response from a higher P rate. Nitrogen was applied as ammonium nitrate (34–0–0) and P as triple superphosphate (0–20–0). All treatments were broadcast by hand to the same plot each year in the spring and incorporated into the soil prior to planting. The plot size was 3.7 by 18.3 m.

Furrow irrigation was used until 2000 and sprinkler irrigation has been used since 2001 to minimize water stress. The quality of the irrigation water was excellent containing about 2 mg kg^{-1} of nitrate N. Mean annual precipitation and air temperature for the site is 443 mm and 11.2°C, respectively. The experiment is in conventional tillage, which, in the initial years, utilized a moldboard plow. Since the mid-1980s, plots have been annually disked to 10- to 15-cm depth, and occasionally chisel plowed to 15- to 20-cm depth. Commercial hybrids adapted for the area were planted in late April or early May at about 76,000 seeds ha^{-1} in 76 cm rows.

Table 2. The ANOVA (degrees of freedom [df], sums of squares [SS], and probabilities of *F* values [*P* > *F*]) for grain yield, grain N and P concentrations, and apparent fertilizer nitrogen in grain ($AFNR_g$) and phosphorus recovery ($AFPR_g$) for irrigated continuous corn at six N and three P fertility rates grown from 1992 to 2010 (except 1999 because of hail damage) near Tribune, KS.

Fixed effects	df†	Grain yield		Grain N		Grain P		$AFNR_g$		$AFPR_g$	
		SS	*P* > *F*	SS	*P* > *F*	SS	*P* > *F*	SS	*P* > *F*	SS	*P* > *F*
Nitrogen (N)	5	6395	<0.001	892,316	<0.001	18,187	<0.001	13.5	<0.001	26.9	<0.001
Phosphorus (P)	2	4512	<0.001	300,250	<0.001	47,471	<0.001	23.5	<0.001	12.5	<0.001
N x P	10	854	<0.001	78,816	<0.001	5,350	<0.001	1.4	0.001	1.1	0.001
Year (Y)	17	6593	<0.001	446,742	<0.001	17,731	<0.001	11.7	<0.001	10.8	<0.001
Y x N	85	702	<0.001	77,679	<0.001	2,875	<0.001	3.6	<0.001	4.6	<0.001
Y x P	34	277	<0.001	28,670	<0.001	2,946	<0.001	3.1	<0.001	0.6	<0.001
Y x N x P	170	229	<0.001	28,782	<0.001	1,767	<0.001	2.6	0.002	0.9	0.461

† For grain yield only, df's were less for grain N and P (no grain samples in 1995) and for $AFNR_g$ (removal of 0 N treatments) and $AFPR_g$ (removal of 0 P treatments).

Table 3. Grain yield response of irrigated continuous corn to six N and three P fertility rates grown from 1992 to 2010 near Tribune, KS.

N	P	1992	1993	1994	1995	1996	1997	1998	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	1992–2010	1961–2010‡
		Year†																			
kg ha^{-1}		Mg ha^{-1}																			
0	0	4.6	2.7	2.9	1.4	3.6	4.2	3.1	8.2	3.4	2.4	4.9	4.2	3.0	2.6	3.1	2.3	5.3	1.2	3.5	4.1
45	0	5.7	3.9	4.1	2.1	5.5	5.4	4.8	9.4	4.5	2.9	6.7	5.8	4.0	3.5	4.8	3.9	6.8	1.4	4.7	6.0
90	0	5.7	4.3	4.1	2.1	5.9	8.1	6.0	9.3	4.7	3.3	7.7	7.4	4.7	4.9	6.7	4.9	7.7	2.1	5.5	6.9
134	0	6.2	4.5	4.4	2.5	6.1	6.6	5.8	9.0	3.5	3.1	7.6	6.5	4.1	4.3	6.6	4.1	7.3	1.8	5.2	6.8
179	0	7.2	5.5	4.9	2.8	6.5	6.8	6.3	9.7	4.8	3.1	8.0	8.6	5.2	5.3	8.3	5.3	8.7	3.1	6.1	7.5
224	0	6.9	5.1	5.0	3.9	6.9	6.9	8.2	10.3	8.2	4.2	8.8	10.2	6.9	7.2	10.0	6.2	9.7	4.1	7.1	7.9
0	20	5.5	3.1	2.7	1.7	4.0	5.0	3.5	9.6	2.7	2.7	5.9	6.1	3.8	4.3	3.1	3.6	6.9	1.3	4.2	4.4
45	20	8.0	6.5	6.5	4.3	7.0	7.0	6.7	12.2	8.0	4.3	9.2	9.7	6.3	8.1	7.0	6.6	9.3	4.2	7.3	7.4
90	20	9.9	8.6	8.1	5.9	10.3	9.6	9.7	12.8	10.6	5.1	11.8	13.1	8.9	10.1	10.2	8.1	11.2	5.3	9.4	9.2
134	20	10.2	9.5	9.2	6.2	11.6	10.9	11.3	12.8	11.1	4.9	12.1	14.3	10.2	11.0	12.2	8.6	12.7	5.6	10.2	10.1
179	20	10.6	11.0	10.2	6.4	11.6	10.6	11.7	12.7	11.7	5.0	11.9	14.5	10.6	11.3	13.8	9.4	13.2	6.0	10.7	10.6
224	20	11.7	10.6	10.7	6.7	11.3	11.6	11.8	13.0	11.1	5.0	12.4	14.7	10.6	11.3	14.0	9.5	13.0	6.1	10.8	10.6
0	40	5.0	3.3	3.0	1.6	4.6	5.2	3.4	9.6	3.0	2.8	5.9	6.2	3.2	4.5	3.2	3.2	6.7	1.8	4.2	–
45	40	8.0	6.5	6.6	4.1	6.7	7.1	6.0	12.7	8.1	4.8	9.4	9.3	6.3	7.7	7.3	6.5	10.0	3.8	7.3	–
90	40	8.8	9.0	8.0	5.9	10.0	9.7	9.4	13.2	11.4	5.3	11.6	12.9	9.2	10.7	10.4	8.7	11.4	5.6	9.5	–
134	40	9.8	9.6	9.6	7.0	11.5	10.2	11.2	14.0	12.0	5.4	12.5	14.7	10.6	12.7	13.4	9.5	13.5	6.6	10.8	–
179	40	11.2	10.9	10.5	6.3	12.2	11.7	11.6	13.4	11.8	5.3	12.4	15.1	10.8	12.5	14.3	9.2	14.0	6.0	11.1	–
224	40	10.3	11.3	10.9	6.8	11.9	12.1	12.4	13.7	12.1	5.9	12.6	15.0	12.0	12.8	14.5	9.8	14.8	6.5	11.4	–
		ANOVA ($P > F$)																			
N		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
N linear		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
N quadratic		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
P		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
P linear		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	–
P quadratic		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.007	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	–
N × P		0.013	0.001	0.001	0.001	0.001	0.001	0.001	0.008	0.001	0.133	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

† No yield in 1999 reported because of severe hail damage. Hail damage also occurred in 1995, 2002, 2008, and 2010.

‡ For 1961 to 1981 yields, see Hooker et al. (1983) and for 1982 to 1991 yields, see Schlegel and Havlin (1995).

After corn reached physiological maturity, the center two rows of each plot were machine harvested, usually in late September or early October (no harvest in 1999 because of severe hail damage). Grain yield was adjusted to 155 g kg^{-1} moisture. Grain samples were dried, ground, and analyzed for N and P (grain samples not collected in 1995). The total amount of N removed by grain (grain N uptake) was calculated by multiplying grain yield by grain N concentration. The apparent fertilizer N recovery in grain ($AFNR_g$) was calculated by subtracting grain N uptake in the control treatment from the total amount of grain N in the treatment receiving N and dividing the difference by the N rate. The same approach was used for calculating $AFPR_g$.

Analysis of variance was performed to evaluate treatment effects (considering N rate, P rate, and year as fixed effects) on dependent variables using the General Linear Models routine of SAS 9.3 (SAS Institute, 2010). The main effects of N and P rates on grain yield were partitioned into single degree of freedom orthogonal polynomial contrasts with linear and quadratic relationships reported. Linear regression (Proc Reg) was used to determine yield trends across years for specific treatments. Quadratic yield production functions by P rate were calculated using treatment means by year (functions not shown) and across years. The average N rate for maximum yield at each P rate was calculated by equating the first derivative of the quadratic yield function (Fig. 1) to zero and solving for N. The economic optimal N rates were calculated using the same approach except the first derivative was set equal to the fertilizer N cost (US\$ kg^{-1})/corn price (\$ Mg^{-1}) ratio (1:180). Quadratic functions for average grain N and P concentration, $AFNR_g$, and $AFPR_g$ were calculated using N rate means across years (1992–2010).

RESULTS AND DISCUSSION

Grain yields were affected by climatic factors, especially hail. In 1999, no yields were obtained because of severe hail damage, while hail also caused damage to the corn crop in 1995, 2002, 2008, and 2010 resulting in substantial yield losses and great variability in yields across years (Tables 2 and 3). This resulted in year being the largest contributor to yield variability (34% of total sums of squares) but only slightly greater than N (33%), while year interactions with N, P, and N × P contributed only 4, 1, 1% of yield variability, respectively. The remainder of yield variability was attributed mostly to P (23%) with N × P interaction at 4%. Irrigation water was not a significant source of N, because it supplied only about 10 kg N ha^{-1} annually (data not shown). This is in contrast to research in other areas where nitrate N in the irrigation water strongly influenced corn response to fertilizer N (Ferguson et al., 1991; Shapiro, 1999; Hu et al., 2010).

Irrigated corn grain yield increased significantly with N and P applications in each year from 1992 to 2010 (Table 3). These results are consistent with those recorded in earlier years of this experiment (Hooker et al., 1983; Schlegel and Havlin, 1995). During the last 19 yr, grain yield increased 20% (0.7 Mg ha^{-1}) with P alone and 103% (3.6 Mg ha^{-1}) with N alone; however, when N and P were applied together at the highest rates, grain yield was increased by 225% (7.9 Mg ha^{-1}) over the unfertilized treatment. The positive N–P interaction underscores the importance of balanced fertilization (Dai et al., 2013; Zaghloul et al., 2014). Although year was a significant factor (Table 2), the high variability in yields between years as shown in Table 3 resulted in nonsignificant yield trends across years. For example, grain yield of the treatment receiving the highest N and P rate increased 69 kg ha^{-1} yr^{-1} while grain yield of the control treatment decreased 22 kg ha^{-1} yr^{-1}; however, in both cases, the R^2 values were <0.02.

Average grain yield response to N in 1992 to 2010 compared to average grain yield response in 1961 to 2010 showed little difference at 20 kg P ha^{-1}, but lower yields in 1992 to 2010 were recorded compared to 1961 to 2010 with 0 kg P ha^{-1} (Fig. 1, Table 3). This would indicate an increased P deficiency with decreasing soil test P (as would be expected). Soil test P in the unfertilized check from 1992 to 2010 was about 6 to 7 mg kg^{-1} Bray 1-P, which was much less than soil test P in 1961 (Table 1). The higher P rate (40 kg ha^{-1}) initiated in 1992 did not affect long-term yields when N rates were 90 kg ha^{-1} or less but tended to increase grain yields with N rates of 134 kg N ha^{-1} or greater, although the increase was less than

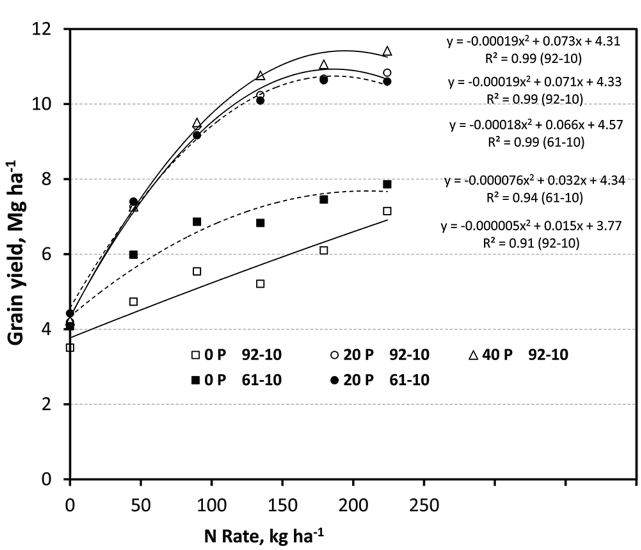

Fig. 1. Average grain yield response to N and P fertilization for irrigated continuous corn grown from 1992 to 2010 and 1961 to 2010 near Tribune, KS.

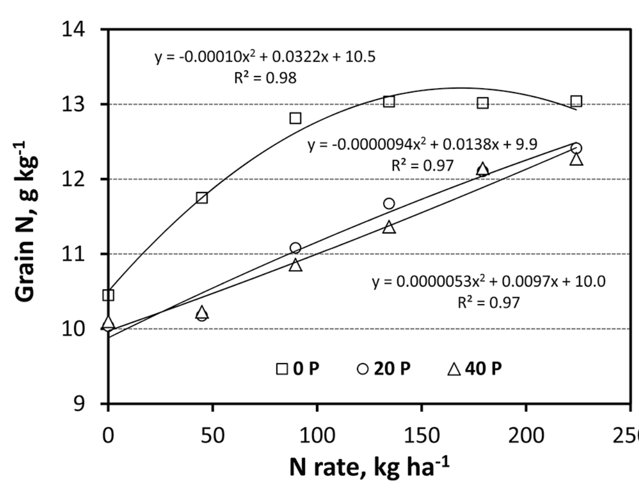

Fig. 2. Average fertilizer N and P effects on grain N concentration of irrigated continuous corn grown from 1992 to 2010 near Tribune, KS.

6%. In contrast, the first increment of P (20 kg ha^{-1}) increased yields 52–96% with N rates at 134 kg ha^{-1} or greater. This would suggest that 20 kg P ha^{-1} is near the required P rate for this environment and crop rotation.

Between 1992 and 2010, the N rate required for maximum grain yield at 20 and 40 kg P ha^{-1} was 187 and 195 kg N ha^{-1}, respectively (Table 4). At 179 kg N ha^{-1} (closest N rate to that required for maximum yield), the average grain yield increase was 0.4 Mg ha^{-1} or <4% indicating a relatively small increase between the 20 and 40 kg P ha^{-1} rates. The wide variation between years (1992–2010) is related to variable growing season conditions, which is commonly reported (Meisinger et al., 2008).

Using a quadratic yield response function averaged across years from 1992 to 2010 (Fig. 1) and \$1.10 kg^{-1} N cost and \$198 Mg^{-1} corn price, the N rate for maximum profit at 20 and 40 kg P ha^{-1} was 172 and 180 kg N ha^{-1}, respectively (Table 4). In comparison, the N rate for maximum profit (1961–1991) at 20 kg P ha^{-1} was 178 kg N ha^{-1} (Schlegel et al., 1996). Although the N cost/corn price ratio was 1:275 (1961–1991) compared to 1:180 (1992–2010), the difference in economic optimum N rate was relatively small within this range of N cost/corn price ratios, although it would result in a slightly higher economic optimum N rate (Havlin and Benson, 2006).

Grain N concentration increased substantially with increasing N rates (Fig. 2). Similar to grain yield, grain N concentration was significantly affected by year, N, and P and all interactions (Table 2) but all interactions combined accounted for only ~12% of grain N variability with N rate accounting for 48% of the variability. Grain N concentration was similar regardless of whether 20 or 40 kg P ha^{-1} was applied across all N rates, but was always less than grain N concentration at 0 kg P ha^{-1}. The lower grain N concentration with added P fertilizer was likely due to dilution of grain N associated with increased grain yield response to P fertilization (Jarrell and Beverly, 1981; Riedell, 2010). Grain N concentration increased linearly with increasing N rates with added P, but the increase was nonlinear without P. With no P applied, grain N concentration did not increase above 90 kg N ha^{-1}, which is due to N dilution associated with continued grain yield increases (135 to 224 kg N ha^{-1}) compared to the P fertilized treatments.

Similar to grain N dilution with increasing P rates, grain P concentration decreased with increasing N rates at all P rates (Fig. 3). Similar to grain N concentration, grain P concentration was significantly affected by year, N, and P and all interactions (Table 2), but all interactions combined accounted for only ~14% of grain P variability with P rate alone accounting for 49% of the variability and 19% with N alone. Grain P concentration was similar with ≥45 kg N ha^{-1} without P fertilizer and for ≥134 kg N ha^{-1} with 20 kg P ha^{-1}.

With no P added, $AFNR_g$ decreased from ~36 to 21% with increasing N rate (Fig. 4) similar to other N response studies (Attia et al., 2015; Hatfield and Prueger, 2001). In contrast with 20 kg P ha^{-1}, $AFNR_g$ was 64% at 45 kg N ha^{-1}, linearly decreasing to 35% as N rate increased to 224 kg N ha^{-1}. At all N rates, there were no differences in $AFNR_g$ between 20 and 40 kg P ha^{-1}. At the economic optimum N rate (with 20 kg ha^{-1} of P fertilizer) of 172 kg N ha^{-1}, $AFNR_g$ was 44%, which was similar to that reported for 1988 to 1991 (Schlegel and Havlin, 1995). Thus, an additional 40 kg ha^{-1} of applied N was recovered in the P fertilized grain compared to no P applied, potentially reducing residual fertilizer N in the soil profile (data not shown). Although not measured in this study, including surface crop residue N better reflects total N recovered by the crop. Assuming 40% of the aboveground biomass

Table 4. Optimum N rate by year for maximum yield and profit at two P rates for irrigated continuous corn grown from 1992 to 2010 near Tribune, KS. Bold numbers represent the lowest and highest values.

Year	N rate for maximum yield		N rate for maximum profit†	
	20 kg P ha^{-1}	40 kg P ha^{-1}	20 kg P ha^{-1}	40 kg P ha^{-1}
	kg N ha^{-1}			
1992	223	190	198	172
1993	199	214	185	197
1994	211	219	195	202
1995	178	174	159	158
1996	174	200	164	186
1997	211	**259**	192	**232**
1998	191	220	179	205
2000	157	**156**	136	**139**
2001	164	167	155	163
2002	**156**	181	**126**	147
2003	169	172	157	160
2004	181	191	171	180
2005	193	216	179	200
2006	175	188	163	177
2007	**224**	214	**211**	203
2008	193	176	175	162
2009	197	235	180	215
2010	174	176	156	158
1992–2010‡	187	195	172	180

† Corn price of \$198 Mg^{-1} and N cost of \$1.10 kg^{-1}.

‡ All values based on average yield (1992–2010) yield functions from Fig. 1.

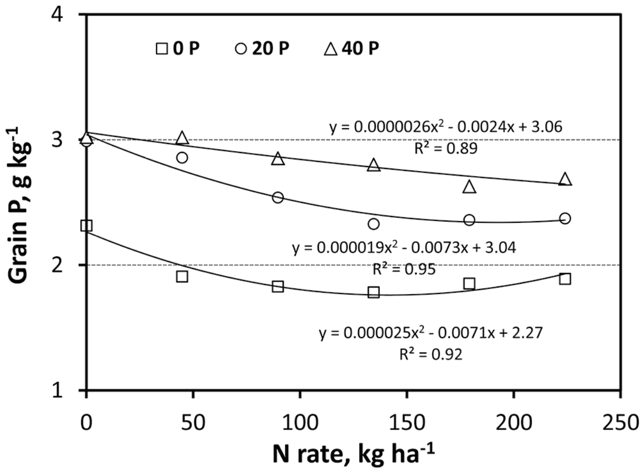

Fig. 3. Average fertilizer N and P effects on grain P concentration of irrigated continuous corn grown from 1992 to 2010 near Tribune, KS.

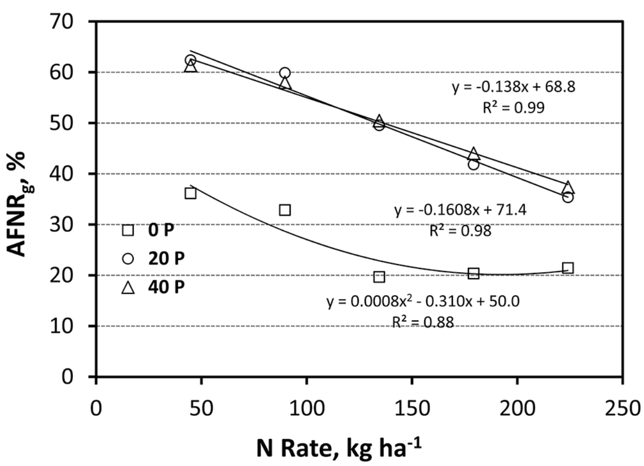

Fig. 4. Influence of N and P fertilizer rates on average apparent fertilizer N recovery in grain ($AFNR_g$) in irrigated continuous corn grain grown from 1992 to 2010 near Tribune, KS.

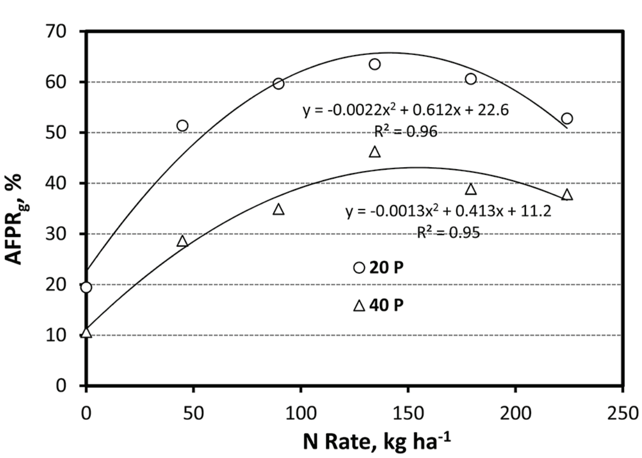

Fig. 5. Influence of N and P rate on average apparent fertilizer P recovery in grain ($AFPR_g$) in irrigated continuous corn grain grown from 1992 to 2010 near Tribune, KS.

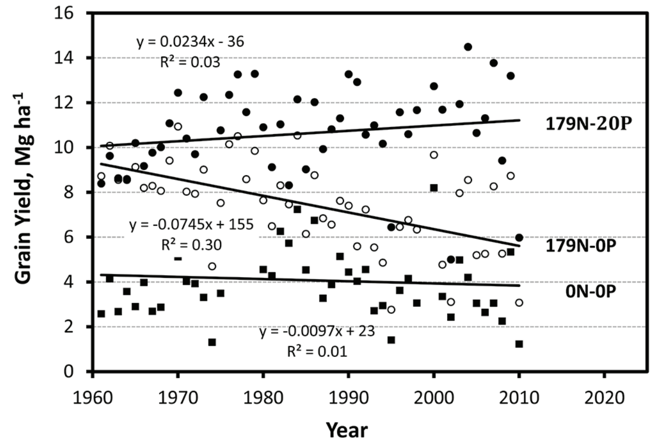

Fig. 6. Annual grain yields from 1961 to 2010 for the unfertilized control treatment along with the N treatment nearest the economic optimal N rate with and without P for irrigated continuous corn grown near Tribune, KS.

is crop residue (Schlegel and Havlin, 1995), total N recovery at 172 kg N ha^{-1} would be 35% without P compared with 73% with 20 kg P ha^{-1}, which is similar to that reported earlier for this study and is consistent with other studies (Roberts, 2008; Cassman et al., 2002; Oberle and Keeney, 1990).

Over the entire range of N rates, $AFPR_g$ was greater with 20 kg P ha^{-1} compared to 40 kg P ha^{-1} (Fig. 5). With no N applied, $AFPR_g$ was only 20 and 11% with 20 and 40 kg P ha^{-1}, respectively. In addition, with both P rates, $AFPR_g$ increased with increasing N rate to a maximum of 139 and 158 kg N ha^{-1} with 20 and 40 kg P ha^{-1}, respectively. At these maximum N rates, $AFPR_g$ was 65 and 44% at 20 and 40 kg P ha^{-1}, respectively. Similarly, at the economic optimum N rate (172 kg N ha^{-1}), $AFPR_g$ was 63 and 44% at the 20 and 40 kg P ha^{-1}, respectively.

No significant differences in unfertilized corn grain yield were detected over the 50 yr (Fig. 6). Similar results have been reported by Stanger and Lauer (2008) and Cook and Trlica (2016). In contrast, corn grain yield significantly decreased over time by applying 179 kg N ha^{-1} without P compared to the same N rate applied with 20 kg P ha^{-1}. In 1961 the average grain response to 20 kg P ha^{-1} was approximately 1 Mg ha^{-1} increasing to 5 Mg ha^{-1} in 2010 (Fig. 6). Dai et al. (2013) and Cook and Trlica (2016) reported a 4 Mg ha^{-1} grain yield increase for continuous dryland corn with P fertilization (20 kg P ha^{-1}) over 18 and 45 yr, respectively.

CONCLUSION

Results from long-term field experiments provide an invaluable resource to scientists and practitioners in developing and communicating improved agricultural management practices. Fifty years of irrigated continuous corn response to N and P fertilization demonstrated a strong positive interaction between N and P. While the economic optimal N rate varied greatly from year to year, the average economic optimal N rate (~170–180 kg N ha^{-1}) did not change from 1961 to 1991 to 1992 to 2010. However, the yield response to P substantially increased over the 50 yr. At the economic optimum N rate (with 20 kg P ha^{-1}), the average (1992–2010) $AFNR_g$ (44%) and $AFPR_g$ (63%) did not change from earlier years of the study. Doubling the P rate (from 20 to 40 kg ha^{-1}) resulted in only a minimal increase of ~4% in grain yield and ~5% in economic optimal N rate.

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