Maize Response to Fertilizer and Nitrogen Use Efficiency in Uganda

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ABSTRACT

Maize (*Zea mays* L.) is an important smallholder crop in Uganda. Yields are low because of low soil fertility and little fertilizer use. Yield response to nutrient application and economically optimal rates (EO*x*R, where x = N, P, or K) and N use efficiency (NUE) were evaluated. Twenty-two trials were conducted in four agroecological zones. Yield was consistently increased with N application. Mean maize yield with no N applied (N_0) was 1.79 Mg ha^{-1} and increased by 120% with N application. Mean EONRs were 45 to 24 kg ha^{-1} N with fertilizer use cost to grain price ratios (CPs) of 10 to 30. With N applied, the mean increase in yield due to P application was 0.28 Mg ha^{-1} and mean EOPRs were 9 to 1 kg ha^{-1} P with CPs of 10 to 50. Yield was not increased with K application. Profitability was greater for N than P application. Mean aboveground biomass N with 0 and 150 kg ha^{-1} N applied was 46.3 and 94.3 kg ha^{-1}, respectively. Mean N concentration and N harvest index at the EONR were 1.60 and 63.8%, respectively, and higher than for N_0. Mean recovery efficiency, partial factor productivity, and agronomic efficiency declined with increasing N rate and were 66%, 86 kg kg^{-1}, and 41 kg kg^{-1}, respectively, at the EONR. Fertilizer N use can be very profitable, with high NUE, for smallholder maize production in Uganda, and the financial capacity of smallholders to use fertilizer will increase with reduced CP.

MAIZE IS AN important crop for the smallholder farmers in sub-Saharan Africa, but yield has not increased significantly and per capita food production has declined since the 1980s (Greenland et al., 1994; Sanchez et al., 1996; Muchena et al., 2005). The main contributing factors are poor inherent soil fertility, particularly N and P deficiencies (Bekunda et al., 1997), exacerbated by soil fertility depletion (Vlek, 1993; Sanchez et al., 1996; Lynam et al., 1998) and other biophysical factors. Declining soil fertility and land degradation have particularly affected the land on which the poor depend and threatened food security for the smallholder farmers (Sanchez, 2002). Uganda is among the countries with the most severe soil nutrient depletion in Africa, with mean N, P, and K depletion estimated to be 21, 8, and 43 kg ha^{-1} yr^{-1}, respectively (Stoorvogel and Smaling, 1990; Smaling et al., 1997; Wortmann and Kaizzi, 1998; Nkonya et al., 2005). Unfortunately, only 2% of smallholder farmers in Uganda use inorganic fertilizer (Uganda Bureau of Statistics, 2006).

Social and economic factors often do not favor the use of inorganic fertilizers by smallholder farmers. Inorganic fertilizer use in sub-Saharan Africa costs two to six times as much as in Europe (Sanchez, 2002), mainly due to transport costs, marketing inefficiencies, and other charges. The profitability of fertilizer use is highly variable and dependent on agro-climatic and economic conditions at the local and regional levels (Vlek, 1990), made worse by a lack of credit and agricultural subsidies (Heisey and Mwangi, 1996). These factors contribute to a high CP and an unfavorable net return or benefit/cost ratio (BC). Resource-poor farmers need large returns on the small investments that they are able to make, often requiring a BC >1 within a 6- to 12-mo period (CIMMYT, 1988; Wortmann and Ssali, 2001). As a result, even though maize yield is commonly increased with N and P fertilizer use, the returns on investment are often unattractive to resource-poor farmers.

In western Kenya, the mean sole crop maize response to the application of 25 and 11 kg ha^{-1} N and P, respectively, had a BC >0.75, and the BC was higher for maize–dry bean (*Phaseolus vulgaris* L.) intercropping (Kenya National Agriculture Laboratories, 1987). The mean BC of maize response to N and P was >0.75 in only four of 12 on-farm trials conducted in Uganda in the late 1960s and early 1970s (Foster, 1976). The mean BC for on-farm trials conducted in Uganda during the 1980s with 90 and 40 kg ha^{-1} of N and P applied, respectively, was <0.25, but it was between 0.25 and 0.50 in trials conducted in the 1990s with 84 and 16 kg ha^{-1} of N and P applied, respectively (unpublished results). In another set of 25 on-farm trials conducted in Uganda in the 1990s, the BCs were 0.85, 0.91, and 0.44 for 23 kg N ha^{-1},

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Abbreviations: AE, agronomic efficiency of nitrogen use; BC, benefit/cost ratio; CP, fertilizer use cost to grain price ratio; EONR, economically optimal nitrogen rate; EOPR, economically optimal phosphorus rate; EOR, economically optimal rate; HI, harvest index; IE, internal efficiency; NHI, nitrogen harvest index; NUE, nitrogen use efficiency; N_0, no N applied; PE, physiological efficiency; PFP, partial factor productivity; RE, recovery efficiency; SOM, soil organic matter; UN, aboveground plant nitrogen uptake.

46 kg N ha^{-1}, and 46 kg N + 10 kg P ha^{-1}, respectively, but still below the BC >1 desired for resource-poor farmers (Wortmann and Ssali, 2001).

Nitrogen use efficiency, or grain production per unit of available N in the soil, is important to profitability and environmental sustainability. Cereal NUE is composed of the efficiency of N uptake and the conversion of total crop N uptake to grain (Moll et al., 1982). Application of excess N is often a major cause of low NUE (Meisinger et al., 2008), with recovery, on average, of about 38% of applied N for cereal production. Crop NUE may be low, even with low N application rates, because of limited plant growth due to biotic or abiotic constraints, possibly including deficiencies of P and other essential nutrients (Bekunda et al., 2007). Low fertilizer use efficiency can result from inappropriate fertilizer recommendations that need to account for the cash constraints and risks affecting resource-poor farmers. A challenge in Uganda is to provide fertilizer use guidelines for maize that are appropriate for smallholder farmers considering the diversity of agroecosystems, soils, and socioeconomic factors.

The objectives of this research were to: quantify the yield response of maize to N, P, and K in Uganda; determine economically optimal nutrient rates for N, P, and K and the BC at different CPs; relate soil properties to yield and yield response; and evaluate the NUE of maize in Uganda.

MATERIALS AND METHODS

Site Characteristics and Experimental Design

Nitrogen, P, and K response trials were conducted at 15 site-seasons representing the main maize production areas of Uganda from 2009 to 2010 (Table 1). The sites were Kawanda and Tororo, Ngetta, Bulindi, and Kapchorwa located in the Lake Victoria Crescent, Northern Moist Farmlands, Western Mid-Altitude Farmlands, and Mt. Elgon Farmlands agroecological zones, respectively (Wortmann and Eledu, 1999). All sites had bimodal rainfall with two annual crop seasons, designated as Season a for March to April planting and Season b for August to September planting. Kapchorwa was relatively dry in the 2009b season but wet in 2010a (Fig. 1). There was little precipitation during grain fill at Kawanda in the 2010 seasons and at Ngetta in the 2010b season. Otherwise, rainfall was well distributed for the site-seasons.

The soils varied with site and included Nitisols, Petric Plinthsols, and Acric Ferralsols. The soils at all site-seasons had rooting depths >1.0 m (Table 1). Surface soil samples for the 0- to 20-cm depth, consisting of 10 cores per site-season, were collected with hand probes before planting and fertilizer application to determine the soil pH, soil organic matter (SOM) (Walkley and Black, 1934), and available P and exchangeable K measured in a single Mehlich-3 extract and buffered at pH 2.5 (Mehlich, 1984). Soil texture was determined by the hydrometer method (Bouyoucos, 1936). Soil texture classes included sandy clay loam, sandy loam, and clay. Sand content ranged from 154 to 760 g kg^{-1} soil. The SOM range was 21 to 64 g kg^{-1}. The soil pH at the Tororo site, and at Kawanda in Seasons 2009a and 2010a, was below the critical value of 5.5 (Foster, 1971). Mehlich-3 P was consistently below the critical level of 10 mg kg^{-1} soil at all sites except for Tororo. The sites differed in soil fertility levels, with Ngetta and Tororo having relatively lower fertility, Kawanda and Ngetta having average fertility, and Kapchorwa with relatively better soils (Foster, 1981; Ssali,

Table 1. Characteristics for research sites at five research stations for determination of maize response to applied N, P, and K in Uganda.

	Soil properties									
Location†	Texture‡	Sand	Clay	Organic matter	pH	P	K	Previous crop§	Sowing date	Harvest date
		g kg^{-1}				mg kg^{-1}				
					Season 2009b¶					
Bulindi	C	154	506	46	5.9	4.9	418	FL‡	9 Sept.	9 Feb.
Kapchorwa	C	304	435	64	5.9	8.4	663	CR	15 Sept.	20 Feb.
Kawanda	C	413	476	26	5.4	6.7	286	FL	20 Sept.	30 Jan.
Ngetta	SL	657	224	33	6.1	3.1	258	SM	13 Sept.	5 Feb.
Tororo	SL	729	149	21	5.3	6.2	161	FL	20 Sept.	29Jan.
					Season 2010a					
Bulindi	C	326	505	44	5.9	4.6	235	CR	18 Mar.	21 Aug.
Kapchorwa	C	284	460	53	6.0	9.9	391	CR	15 Apr.	9 Sept.
Kawanda	C	431	452	26	5.6	4.3	286	CR	5 Mar.	7 Aug.
Ngetta	SL	678	187	27	5.9	2.7	252	SF	31 Apr.	29 Aug.
Tororo	SL	760	142	25	5.3	11.2	155	Cr	24 Mar.	15 Aug.
					Season 2110b					
Bulindi	C	168	550	49	6.1	7.9	385	CR	27 Aug.	29 Jan.
Kapchorwa	C	247	473	52	5.8	7.1	467	CR	20 Sept.	25 Feb.
Kawanda	C	431	486	26	5.4	5.3	385	CR	17 Sept.	13 Feb.
Ngetta	SCL	657	244	28	6.1	2.8	281	FL	10 Sept.	13 Feb.
Tororo	SL	729	156	24	5.1	12	183	CR	17 Sept.	6 Feb.

† The latitude, longitude, elevation, and soil classification of the research locations were: Bulindi, 1°30′ N, 31°29′ E, 1021 m, Acric Ferralsol; Kapchorwa, 1°24′ N, 34°37′ E, 1877 m, Nitisol; Kawanda, 0°45′ N, 32°32′ E, 1172 m, Petric Plinthsol; Ngetta, 2°17′ N, 32°56′ E, 1079 m, Petric Plinthsol; Tororo, 0°45′ N, 34°14′ E, 1207 m, Petric Plinthsol.

‡ C, clay; SCL, sandy clay loam; SL, sandy loam.

§ CR, cereal; FL, fallow; SF, sunflower (*Helianthus annuus* L.); SM, simsim (*Sesamum indicum* L.).

¶ The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

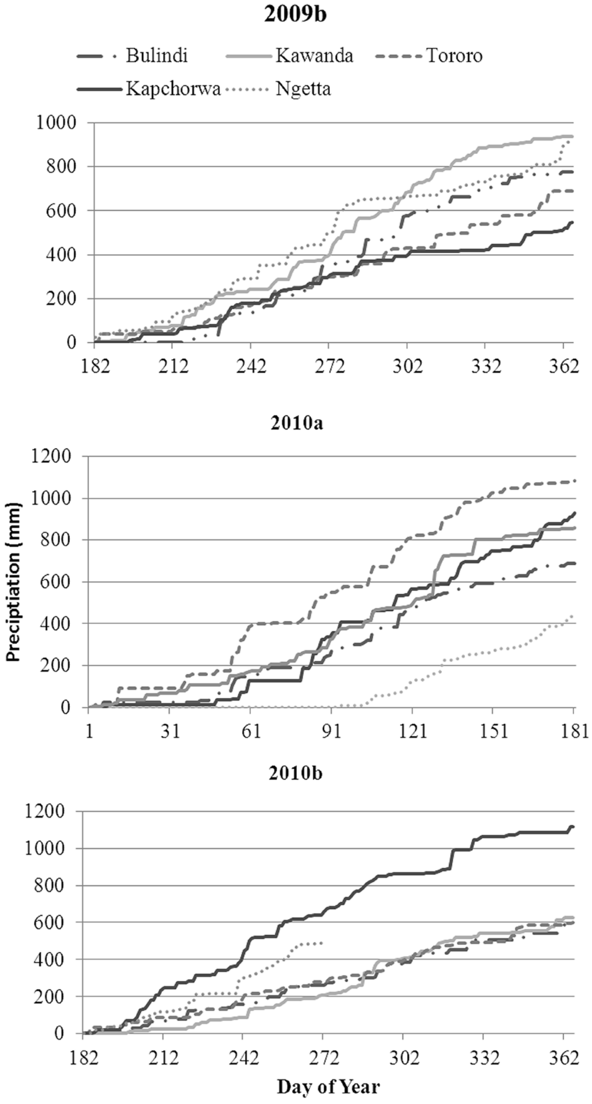

Fig. 1. Cumulative rainfall for five sites across three cropping seasons in Uganda.

2002). The Kapchorwa soils were Nitisols, which are commonly more productive than Acric Ferralsols and Petric Plinthsols.

The nutrient rates evaluated were: 0, 50, 100, and 150 kg N ha^{-1}; 0, 12.5, 25, and 37.5 kg P ha^{-1}; and 0, 30, 60, and 90 kg K ha^{-1}. The treatment arrangement was an incomplete factorial to limit the number of treatments and included N–P–K rates of 0–0–0, 50–0–0, 100–0–0, 150–0–0, 50–12.5–0, 50–25–0, 50–37.5–0, 100–12.5–0, 100–25–0, 100–37.5–0, 150–12.5–0, 150–25–0, 150–37.5–0, 50–12.5–30, 50–25–60, 50–37.5–90, 100–12.5–30, 100–25–60, 100–37.5–90, 150–12.5–30, 150–25–60, and 150–37.5–90. Expecting N to be more limiting to maize growth than P and K, the N_0 treatment occurred only with no P and K applied, and P and K effects were tested only with N applied. Similarly, P was assumed to be more limiting than K and the zero-P treatment had no K applied. There was confounding of P and K treatments; the K effect was determined in the statistical analysis by subtracting the K-minus treatment from the K-plus treatment for the corresponding N and P rates after verifying that the P × K interaction was not significant. The fertilizers applied were urea, triple super phosphate, and muriate of potash. Fertilizer P and 50% of fertilizer N and K were applied shortly before planting; the remaining 50% of N was applied with the K fertilizer 45 to 50 d after planting. The preplant applications were surface broadcast applied and incorporated. The sidedress application of N and K was applied approximately 10 cm to the side of the row and covered.

Cultivars varied by site-season, but each trial had two cultivars including Longe5, Western hybrid, Ssalongo, or IR, all with 115- to 120-d to maturity at 1100-m elevation and all hybrids except Longe5. Each cultivar received the full set of treatments. The treatments were assigned in a randomized complete block design with three replications. The plot size was 4.5 by 6 m. Trial sites were on different land each season.

Crop Management and Data Collection

Residue from the previous crop was removed and vegetative fallow was grazed, generally resulting in net removal of nutrients and reduced biomass returned to the soil. The sites were disk plowed to the 15- to 20-cm depth, followed by disk harrowing once to the 8- to 10-cm depth approximately 2 wk later and shortly before planting. The previous crop varied (Table 1). Seeding was done by hand hoes at approximately the 5- to 8-cm depth at 75- and 30-cm inter- and intrarow spacings, respectively, to have plant populations of 4 to 5 plants m^{-2}. In-season weed control was done with hand hoes twice or thrice depending on the weed intensity. Chlorpyrifos 5% [*O*,*O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] (Dursban, Dow Chemical Co.) was applied in-season to control the stem borer complex, including *Chilo partellus* (Swinhoe).

At harvest, plants were cut at ground level from three inner rows in a 4.2- by 2.25-m area. The ears and stover were separated and air dried for at least 7 d. The water content was then assumed to be similar for grain and stover. The ears were shelled and the harvested grain was weighed. The cobs were added to the stover, which was weighed, and the stover yield was determined. Grain and stover were subsampled, oven dried at 70°C, ground to pass a 0.5-mm sieve, and analyzed for total N in a single digest by a simple wet-ashing technique with colorimetric determination (Okalebo et al., 2002). The oven-dried weight was used to adjust the grain and stover yields to a water content of 140 g kg^{-1}. The harvest index (HI) was calculated. Stover and grain N concentrations, adjusted assuming grain and stover water contents of 140 g kg^{-1}, were used in the calculation of the N uptake in grain and total biomass, the N harvest index (NHI), and other NUE values.

On-Farm Trials

In addition to the researcher-managed trials described above, four and three clusters of on-farm trials were conducted in the 2010a and 2010b seasons, respectively. The generalized characteristics for these clusters were: Abongomola, 2°15′ N, 32°20′ E in the Northern Moist Farmlands with ~1270 mm yr^{-1} precipitation, 1070-m elevation, and 50 to 60% sand content of the soil; Bukanga, 0°41′ N, 33°20′ E in the Lake Victoria Crescent with ~1250 mm yr^{-1} precipitation, ~1160-m elevation, and 35 to 45% sand content of the soil; Kiziranfumbi, 1°21′ N, 31°12′ E in the Western Mid-Altitude Farmlands with ~1320 mm yr^{-1} precipitation, 1160-m elevation, and 40 to 50% sand content of the soil; and Kwera, 2°4′ N, 32°50′ E in the Northern Moist Farmlands with ~1210 mm yr^{-1} precipitation, 1085-m elevation, and 50 to 60% sand content of the soil (Wortmann and Eledu, 1999). The trials had a single set of the same treatments as above per farm.

Farms within clusters were treated as replications, with six to 14 farms (replicates) per cluster. Only grain yield data were collected.

Data Analysis

Statistical analyses were done by site-season, by clusters of on-farm trials, and combined across site-seasons and clusters of on-farm trials using Statistix 9 (Analytical Software, Tallahassee, FL) with site-seasons and replicates as random variables and cultivars and nutrient rates as fixed variables. When significant nutrient rate effects occurred for grain yield, two response functions were fitted for each site-season, including a polynomial quadratic function and an asymptotic quadratic–plateau function, which gave an exponential rise to maximum yield or to a yield plateau. The asymptotic function for N was yield (Mg ha^{-1}) = $a - bc^N$, where a is yield at the plateau or maximum yield, b is the gain in yield due to nutrient application, and c^N determines the shape of the quadratic response, where c is a curvature coefficient, and N is the N or other nutrient rate.

The asymptotic function generally gave the best fit. For some site-seasons, however, there was no yield increase beyond the first increment of applied N. In these cases, the asymptotic function estimated the start of the plateau at unrealistically low nutrient rates and the polynomial function overestimated the yield at N_0. Therefore, the mean of the predicted yields of the polynomial and asymptotic functions were used for nutrient rates intermediate between the treatment levels to determine an adjusted asymptotic function. Specifically for the N rate, predicted values were used for the 10, 20, 40, 60, and 80 kg ha^{-1} N rates to complement the actual means for 0, 50, 100, and 150 kg ha^{-1} for the determination of the adjusted asymptotic function.

Nonlinear regression analysis for N was done across all P levels after confirming a lack of N × P interaction. It was also determined, combined across all trials, for the N rate with no P or K applied. In the combined analysis across all trials, the asymptotic N response regression was done for the site-season N rate means due to failure to converge using the plot data. Differences and relationships were considered significant at $P \leq 0.05$.

The asymptotic function was also applied for the P rate. Phosphorus rate increments were small enough that the asymptotic function alone gave good response functions for site-seasons or clusters of on-farm trials where P rate affected yield. Potassium rate effects were generally not significant and were not significant in the analysis combined across trials. In the combined analysis across all trials, the asymptotic P response regression was done for the site-season P rate means due to failure to converge using the plot data.

The nutrient rate for maximum net return, or the economically optimal rate (EOR) from nutrient application, was calculated for a range of CPs including 10, 15, 20, 25, and 30 for N and K, and 10, 20, 30, 40, and 50 for P. Economic analyses were done with a grain price of US\$0.083 kg^{-1} (2400 Uganda shillings per US\$), and the costs of using fertilizer N, P, and K were a function of grain price and the CP. The mean EORs were determined for each CP of the respective nutrient. Linear and polynomial regression analyses were conducted to account for variations in grain yield, yield response to fertilizer application, and EOR using variations in soil properties, CP, and the previous crop. Equations were developed using nonlinear regression analysis to relate EONR and EOPR to CP. Benefit/cost ratios were calculated and equations were developed to predict the BC from N or P rates and CP.

Nonlinear functions that related aboveground plant N uptake (UN) to the N rate and grain yield were determined. Linear and nonlinear regression analysis, using plot data, were applied as appropriate to relate NUE parameters to the N rate, including grain N concentration and content, NHI, the internal efficiency (IE) of total plant N taken up from the soil and fertilizer, partial factor productivity (PFP), and physiological (PE), recovery (RE), and agronomic (AE) efficiencies of fertilizer N use (Cassman et al., 2002). Values of NUE components were determined using N rate means of site-seasons. The NUE components were calculated as: IE = Y/UN (kg kg^{-1}) where Y is grain yield (kg ha^{-1}); PFP = Y/N rate; NHI = grain N/UN; RE = $(\mathrm{UN}_{+\mathrm{N}} - \mathrm{UN}_{\mathrm{N0}})$/N rate with +N and N_0 the applied or 0 N rate, respectively; PE = $(Y_{+\mathrm{N}} - Y_{\mathrm{N0}})/(\mathrm{UN}_{+\mathrm{N}} - \mathrm{UN}_{\mathrm{N0}})$; and AE = $(Y_{+\mathrm{N}} - Y_{\mathrm{N0}})$/N rate. The units for IE, NHI, PFP, PE, AE, and PFP were kilograms per kilogram.

RESULTS

Yield Response to Nitrogen, Phosphorus, and Potassium

Interactions of N rate with cultivar, P rate and K rate were not significant for site-seasons or accounted for <10% of the treatment effect on grain yield. Therefore, the analyses for N rate were done across P rates and cultivars, and eventually across site-seasons and on-farm trial clusters. Yield with N_0 ranged from 0.96 to 2.93 Mg ha^{-1}, with a mean of 1.60 and 2.20 Mg ha^{-1} for the site-seasons and on-farm trial clusters, respectively (Table 2). There was increased maize yield in response to N application for all site-seasons and clusters. The yield increase due to N application ranged from 0.98 to 2.87 Mg ha^{-1}, corresponding to an increase of 53 to 200%. The overall mean increase was 2.04 and 2.36 Mg ha^{-1} or a 127 and 107% increase for the 15 site-seasons and seven clusters of on-farm trials, respectively. The resulting yield response function was

$$\begin{aligned}\text{Yield} &= 3.92 - 2.14\left(.0948^{N}\right) \qquad [1]\\ &= 3.64 - 2.09\left(0.968^{N}\right) \text{ with no P or K applied}\end{aligned}$$

Yield at the N rate response plateau and mean response to N were not significantly different with no P or K applied (−0.28 and −0.05 Mg ha^{-1}, respectively) compared with the means for all N rate treatments.

Stover yield was increased by N application at seven of 15 site-seasons.

Site-season EONR, determined using all N rate treatments, ranged from 0 to 77 kg ha^{-1}, with CP as a major determinant of the EONR but also with much variation due to site-season effects (Table 3). The overall means of the EONR were 45 to 25 kg N ha^{-1} with CPs of 10 to 30 (Fig. 2). Mean EONRs were 35% higher for maize than for sorghum [*Sorghum bicolor* (L.) Moench] produced under similar conditions (Kaizzi et al., 2012). Accurate determination of the EONR became economically more important as the CP increased. The relationship of the EONR to the CP was

$$\mathrm{EONR} = -9.62 + 68.44\left(0.977^{\mathrm{CP}}\right) \qquad [2]$$

Table 2. Nitrogen application effect at rates of 0, 50, 100, and 150 kg ha^{-1}, determined across all P and K rate levels, on maize grain and stover yield in Uganda at five research stations across three seasons and for seven clusters of on-farm trials in 2010. The results are the means of two cultivars because there was no cultivar × N rate interaction. Interactions of N rate with site-seasons and P rate were not significant.

Location	Grain yield					Stover yield				
	0 kg ha^{-1}	50 kg ha^{-1}	100 kg ha^{-1}	150 kg ha^{-1}	$P > F$	0 kg ha^{-1}	50 kg ha^{-1}	100 kg ha^{-1}	150 kg ha^{-1}	$P > F$
	Mg ha^{-1}					Mg ha^{-1}				
					Season 2009b†					
Bulindi	1.32	2.96	3.43	3.54	***	3.83	4.69	4.86	5.23	NS
Kapchorwa	1.64	4.06	3.97	4.05	***	5.58	7.31	6.67	7.10	NS
Kawanda	1.65	4.06	3.97	4.05	***	5.35	7.31	6.67	7.10	NS
Ngetta	1.25	3.04	3.11	2.89	***	3.75	5.41	5.83	6.00	***
Tororo	0.98	1.96	2.07	2.21	***	8.15	10.21	10.32	11.70	***
					Season 2010a					
Bulindi	1.47	3.66	3.50	3.62	***	4.55	7.25	7.35	7.28	***
Kapchorwa	2.64	4.05	4.39	4.94	***	6.02	9.62	10.19	11.16	***
Kawanda	1.76	3.02	3.06	2.98	***	3.66	5.51	5.68	5.50	***
Ngetta	2.55	5.42	5.45	5.42	***	10.45	12.48	11.58	12.04	NS
Tororo	2.04	4.55	4.25	4.51	***	6.95	7.55	7.39	7.52	NS
					Season 2010b					
Bulindi	2.21	4.65	5.18	5.10	***	5.42	6.61	7.21	7.46	NS
Kapchorwa	1.29	3.05	3.14	3.14	***	3.51	5.39	6.34	6.21	NS
Kawanda	0.96	3.18	3.24	3.21	***	3.22	5.43	5.32	5.32	NS
Ngetta	1.32	2.59	2.83	2.98	***	2.80	3.26	3.72	4.04	***
Tororo	0.95	2.03	2.10	2.03	***	1.99	3.00	3.23	3.41	***
					Combined seasons					
Mean	1.60	3.49	3.58	3.64		5.02	6.74	6.82	7.14	
SE	0.14	0.25	0.25	0.26		0.57	0.66	0.61	0.68	
					Grain yield from on-farm trials‡					
	Season 2010a					Season 2010b				
Bukanga	2.19	4.57	4.62	4.24	***	1.58	2.68	2.74	2.77	***
Kwera	2.32	5.19	5.70	5.27	***	2.19	4.66	5.07	5.07	***
Abongomola	2.93	5.44	5.48	5.76	***	2.48	4.60	4.78	5.09	***
Kiziranfumbi	1.75	3.86	3.86	3.79	***	–	–	–	–	–
Mean	2.20	4.43	4.61	4.57	***					
SE	0.24	0.09	0.10	0.09						
Combined§	1.79	3.79	3.91	3.94	***					

*** Significant effect at $P \leq 0.001$; NS, no significant effect at $P \leq 0.05$.

† The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

‡ The on-farm results are means of six to 14 single replicate trials per cluster-season.

§ Means across all site-seasons and on-farm trials.

The interactions of the P rate with K rates, site-seasons, and cultivars were not significant. Application of P resulted in increased grain yield for three of 15 site-seasons and in three of seven clusters of on-farm trials (Table 4). The increases occurred with the application of 12.5 kg P ha^{-1}. In the analyses combined across site-seasons or clusters, the P rate was significant but P application was profitable for a lower CP only:

$$\text{Yield} = 3.98 - 0.377\left(0.809^{P}\right) \quad [3]$$

where P is the P application rate. Stover yield was increased by P application at only one site-season. The relationship of the EOPR to the CP was

$$\text{EOPR} = -2.84 + 15.75\left(0.972^{\text{CP}}\right) \quad [4]$$

Grain yield was increased by K application at Tororo in 2010a but not at any other site-season or on-farm cluster. The rate of K application was not significant in the combined analysis. Stover yield was increased in five of 15 site-seasons by the application of 30 kg ha^{-1} K.

Soil properties, rainfall, and land use in the previous season did not account for variation across site-seasons in grain yield, yield response to fertilizer application, and the EOR for N and K. The EONRs differed by site-season but the results do not indicate that site properties can be used to improve returns to N application compared with using the overall mean EONR.

Nitrogen Uptake

The mean UN was 46.3 kg ha^{-1} for N_0 (Table 5), which was 48% more than for sorghum under similar conditions (Kaizzi et al., 2012). This is an estimate of the indigenous soil N supply and

Table 3. Asymptotic nonlinear regression coefficients (*a*, *b*, and *c*) for grain yield response to N rate and economically optimal N rates (EONRs) for maize, determined across all P and K levels, with a cost of fertilizer N use (US\$ kg^{-1}) to farm-gate price of grain (US\$ kg^{-1}) ratio (CP) of 10 to 30.

	Coefficients			R^2	EONR at five N/grain price ratios				
Location	***a***	***b***	***c***		**CP = 10**	**CP = 15**	**CP = 20**	**CP = 25**	**CP = 30**
	Mg ha^{-1}				kg ha^{-1}				
				Season 2009b†					
Bulindi	3.76	2.43	0.979	0.10	77	45	26	12	1
Kapchorwa	4.04	2.38	0.926	0.40	38	29	24	20	19
Kawanda	4.02	2.01	0.939	0.41	40	29	23	18	15
Ngetta	3.07	1.81	0.941	0.10	39	28	21	17	13
Tororo	2.39	1.46	0.981	0.43	54	18	0	0	0
				Season 2010a					
Bulindi	3.65	2.22	0.934	0.39	40	30	24	20	16
Kapchorwa	4.64	2.00	0.978	0.22	67	36	18	5	0
Kawanda	3.02	0.98	0.949	0.24	31	18	10	5	0
Ngetta	5.49	2.94	0.942	0.32	49	36	30	25	21
Tororo	4.39	2.34	0.957	0.12	53	37	28	21	16
				Season 2010b					
Bulindi	5.36	3.13	0.972	0.18	76	52	38	28	21
Kapchorwa	3.18	1.88	0.954	0.08	46	32	23	17	12
Kawanda	3.27	2.28	0.946	0.56	46	33	26	21	17
Ngetta	2.95	1.62	0.972	0.21	61	29	15	5	0
Tororo	2.08	1.12	0.948	0.25	34	21	13	7	2
				On-farm trials, season 2010a					
Bukanga	4.35	2.08	0.948	0.13	45	32	25	20	15
Kwera	5.77	3.41	0.966	0.32	71	52	39	31	25
Abongomola	5.56	2.59	0.899	0.23	31	25	21	18	13
Kiziranfumbi	3.88	2.11	0.953	0.30	48	34	25	19	15
				On-farm trials, season 2010b					
Bukanga	2.79	1.79	0.958	0.44	38	22	13	6	0
Kwera	5.20	2.98	0.968	0.13	70	49	63	27	20
Abongomola	4.91	2.41	0.956	0.11	53	37	28	22	17
				All site-seasons and clusters of on-farm trials					
Combined‡	3.92	2.14	0.948	0.08	45	38	35	28	25

† The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

‡ The response equation across all site-seasons and on-farm trials with no P and K applied was yield = $3.64 - 2.09(0.968^{N})$, where *N* is the N application rate. The EONRs were 59, 47, 37, 31, and 25 kg ha^{-1} at CPs of 10, 15, 20, 25, and 30, respectively.

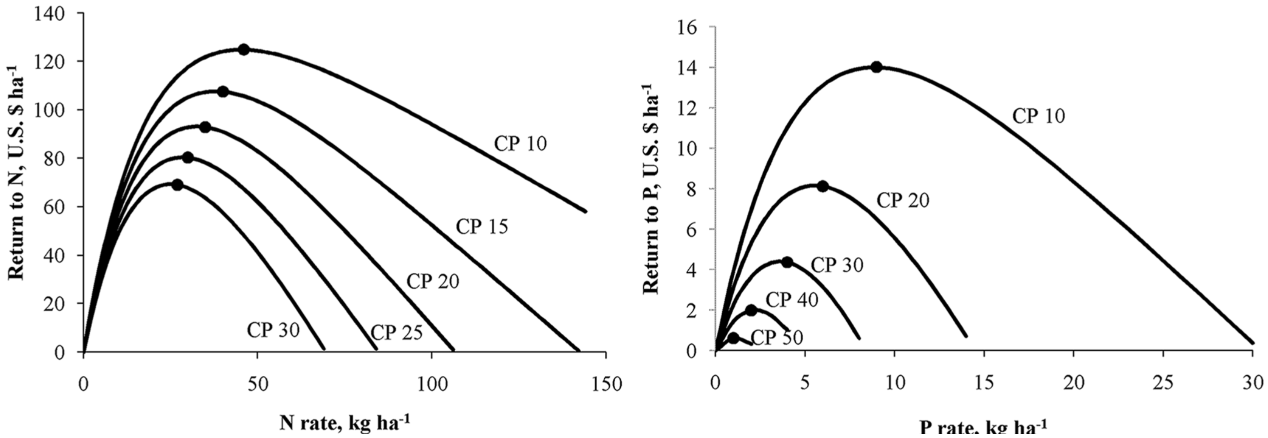

Fig. 2. Economically optimal N and P rates for maize production in Uganda for five ratios of the cost of fertilizer use to the farm-gate grain price (CP).

Table 4. Phosphorus application effect on grain yield at five P application rates and the economically optimal P rate (EOPR) at five P use cost to grain price ratios (CPs), determined with N applied and across K rate treatments, in Uganda at five research stations over three seasons and for seven clusters of on-farm trials in 2010. The results are the means of two cultivars. The interactions of P rate with cultivar and site-season were not significant.

Location	Grain yield					EOPR				
	0 kg ha^{-1}	12.5 kg ha^{-1}	25 kg ha^{-1}	37.5 kg ha^{-1}	$P > F$	CP = 10	CP = 20	CP = 30	CP = 40	CP = 50
	Mg ha^{-1}					kg ha^{-1}				
Kawanda 2010a†	2.72	2.93	3.15	3.17	**	25	0	0	0	0
Tororo 2010a	1.71	2.04	2.11	2.18	***	11	4	0	0	0
Kawanda 2010b	2.59	3.30	3.26	3.46	**	13	9	6	4	2
Combined	3.38	3.58	3.59	3.64	***	2	2	2	2	2
			On-farm trial clusters‡, Season 2010a							
Bukanga	3.05	4.46	4.63	3.90	***	18	15	11	7	4
Kiziranfumbi	3.18	3.84	3.98	3.84	***	13	7	6	4	0
			On-farm trial clusters, Season 2010b							
Abongomola	4.34	4.83	5.16	4.61	**	11	4	0	0	0
Combined§	3.31	3.59	3.64	3.60	***	9	6	4	2	1

** Significant effect at $P \leq 0.01$.

*** Significant effect at $P \leq 0.001$.

† Maize grain yield response to applied P was not significant for 12 of 15 site-years. Stover yield response to applied P was not significant for 14 of 15 site-years.

‡ The on-farm results are for six to 14 single replicate trials per location and season. The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

§ The yield response to applied P across all site-seasons and clusters of on-farm trials was yield = 3.61 – 0.305(0.812^P), where P is the P application rate.

Table 5. Mean effect of N rate (0–150 kg ha^{-1}) on components of N use efficiency by maize, determined across all P and K rate treatments for 15 site-seasons in Uganda.

Component	0 kg ha^{-1}	50 kg ha^{-1}	100 kg ha^{-1}	150 kg ha^{-1}	$P > F$	EONR†
Grain N conc., g kg^{-1}	15.7	16.3	16.8	16.6	***	16.0
Stover N conc., g kg^{-1}	4.44	5.14	5.53	5.87	***	4.90
Grain N content, kg ha^{-1}	25.6	51.2	57.7	57.5	***	45.5
Stover N content, kg ha^{-1}	20.7	30.2	33.1	36.8	***	29.5
Harvest index, kg kg^{-1}	0.236	0.341	0.353	0.334	***	0.311
N harvest index, kg kg^{-1}	0.559	0.640	0.635	0.617	***	0.638
Recovery efficiency, kg kg^{-1}		0.587	0.384	0.271	***	0.666
Agronomic efficiency, kg kg^{-1}		35.1	26.7	21.2	***	41.4
Internal efficiency, kg kg^{-1}	36.7	40.4	38.5	37.9	*	39.7
Partial factor productivity, kg kg^{-1}		67.7	34.6	23.5	***	82.9
Physiological efficiency, kg kg^{-1}		31.3	30.6	29.1	NS	33.7

* Significant effect at $P \leq 0.05$; NS, no significant effect.

*** Significant effect at $P \leq 0.001$.

† Economically optimum N rate was 35 as determined for a N cost/grain price ratio of 20.

ranged from 9 to 126 kg ha^{-1}. The mean UN was 94.3 kg ha^{-1} with 150 kg ha^{-1} N applied (Table 5). Grain yield increased by a mean of 21 kg kg^{-1} of UN for N_0:

$$\text{Grain yield}_{N_0} = 0.114 + 0.0216\,\text{UN} \qquad [5]$$

This compares with approximately 50 kg kg^{-1} increase in UN for no N application under irrigated production in the United States (Wortmann et al., 2011).

Nitrogen Use Efficiency

The mean RE was estimated to be 0.666 kg kg^{-1} at an EONR of 35 kg ha^{-1} compared with 0.271 kg kg^{-1} for the 150 kg ha^{-1} N rate (Table 5). The efficiency of converting UN to grain yield (IE) is a function of the NHI and grain N concentration. Grain N concentration, NHI, and IE at the EONR were 0.0160, 0.638, and 39.7 kg kg^{-1}, respectively, which were higher than for N_0. The mean IE did not increase with higher N rates. The mean NHI was high in comparison with the HI, but stover N and grain N concentrations were lower and higher, respectively, compared with other studies (Wortmann et al., 2011). The mean PFP declined with increasing N rate and was 82.9 kg kg^{-1} at the EONR. The mean AE decreased with increased N rate and was estimated to be 41.4 kg kg^{-1} at the EONR. The mean PE of fertilizer N was not affected by the N rate, as would be expected when grain yield is linearly related to UN.

The following equations, determined from plot data from 15 site-seasons, represent the N rate effect on the various components of NUE:

$$\mathrm{UN}\left(\mathrm{kg\ ha^{-1}}\right)= 51.90+0.722N-0.00293N^2 \quad [6]$$

$$\text{Grain N concentration}\left(\mathrm{g\ kg^{-1}}\right)= 15.8+0.00589N \quad [7]$$

$$\text{Grain N}\left(\mathrm{kg\ ha^{-1}}\right)= 29.75+0.571N-0.00251N^2 \quad [8]$$

$$\mathrm{NHI}\left(\mathrm{kg\ kg^{-1}}\right)= 0.577+0.00184N-0.0000099N^2 \quad [9]$$

$$\mathrm{RE}\left(\mathrm{kg\ kg^{-1}}\right)=0.771-0.00342N \quad [10]$$

$$\mathrm{IE}\left(\mathrm{kg\ kg^{-1}}\right)=49.37-0.199N \quad [11]$$

$$\mathrm{AE}\left(\mathrm{kg\ kg^{-1}}\right)=49.40-0.199N \quad [12]$$

$$\mathrm{PFP}\left(\mathrm{kg\ kg^{-1}}\right)=123-1.32N+0.00441N^2 \quad [13]$$

DISCUSSION

There was much variation in soil properties across trial sites (Table 1). The soils at the Bulindi and Kapchorwa sites were relatively more fertile, based on the observed soil properties and the soil fertility criteria defined by Foster (1981), than those of Kawanda, Ngetta, and Tororo. The soils are predominantly Acric Ferralsols, Nitisols, and Petric Plinthsols whose fertility (available N and P) is closely related to their SOM content and to the presence or absence of fallow periods (Jones, 1972; Foster, 1981).

Grain yield was low compared with many parts of the world but high compared with commonly observed maize yields in Uganda. Biotic and abiotic constraints to yield are many in such tropical, low-input systems, often having unobserved effects on yield individually but with a major cumulative effect. Photosynthetically active radiation, for example, is often inadequate for high maize yield due to tropical daylengths and often cloudy conditions.

Yield Response to Nitrogen, Phosphorus, and Potassium

There was a significant increase in the maize grain yield in response to the application of 50 kg ha^{-1} N with no P or K applied across site-seasons and on-farm clusters (Table 2). The results demonstrated that N was more limiting than P or K for maize yield. The overall mean increase with N application across the 15 site-seasons was 2.04 Mg ha^{-1} compared with 2.44 Mg ha^{-1} for the seven on-farm clusters, with responses ranging from 0.98 to 3.41 Mg ha^{-1}.

The observed differences in yield and response to applied N between site-seasons could not be explained by variations in soil properties despite differences in SOM and sand contents. Soil organic matter is an indicator of sustainability in a soil management system because of the central role of SOM in maintaining soil fertility (Greenland, 1994). The SOM at the trial sites appears to be very stable, however, with slow N mineralization because the mean N in the aboveground biomass was 46.3 kg ha^{-1} for N_0. In comparison, a mean of 150 kg N ha^{-1} was taken up by irrigated maize in the U.S. Midwest with no N (Wortmann et al., 2011). Low N uptake for N_0 could also be attributed to the lack of vigorous crop and root growth, because of various biotic and abiotic constraints, with low recovery of NO_3–N in the profile. The nature of SOM and the proportion that is recalcitrant is also important to the mineralization of organic N.

Only a small fraction of soil organic C and N is associated with microbial decomposer activity, and most N mineralization is from recent organic matter inputs. This small fraction of SOM may contain significant quantities of recently deposited organic material, including fine roots and fungal hyphae, and is often referred to as *particulate* or *light fraction* SOM (Tisdall and Oades, 1982). The light SOM fraction was important to seasonal N cycling in maize-based rotations in Nebraska (Legorreta-Padilla, 2005) and continuous rice (*Oryza sativa* L.) fields in California (Bird et al., 2002). The stability, size, and N contribution are influenced by the nature of the residue quantity and quality, anthropogenic inputs of N, and the physical environment. At the Uganda sites, crop residues from the previous crop had been removed and vegetative fallow was grazed with little replenishment of the active and labile SOM pools.

There was a significant increase in grain yield in the range of 0.20 to 0.66 Mg ha^{-1} in response to the application of P fertilizers for three of 15 site-seasons at Kawanda and Tororo and for three of seven on-farm trial clusters. The effect of P on yield was significant in the combined analysis. Potassium did not increase yield. These results are in agreement with the findings of earlier investigators, who reported N and P as most limiting to cereal production in Uganda (Foster, 1980a,b; Kaizzi, 2002; Kaizzi et al., 2004, 2006, 2007). Farmers will have the greatest return on their investment by applying N at the EONR, but low rates of P application can also be profitable. The response to applied P observed at Tororo may be due to the low soil pH and P adsorption capacity of the soil (Mamo and Wortmann, 2009). The results confirm the potential of inorganic fertilizers to increase maize yield in Uganda to $\geq$4 Mg ha^{-1} (National Agriculture Research Organization, 2001).

Economically Optimal Nitrogen, Phosphorus, and Potassium Rates

The CP affects the EONR and EOPR. The EONR decreased from 45 to 25 kg N ha^{-1} as the CP increased from 10 to 30. The CP is high in Uganda compared with the United States, where the CP for N and P is commonly <10 and 15, respectively (Dobermann et al., 2011), because of the relatively high cost of fertilizer and low grain prices in Uganda. The cost of fertilizers in sub-Saharan Africa is commonly two to six times as much as in Europe (Sanchez, 2002). The opportunity costs of money for resource-poor farmers is very high, which adds to fertilizer use cost (Wortmann and Ssali, 2001). The productivity of rainfed maize production in Uganda is highly variable. and grain prices can fluctuate greatly within and across years. Grain prices are commonly low when harvests are good and farmers have a great surplus above subsistence needs that can be marketed. Buffering of grain prices might be provided by a good grain storage infrastructure. Farmers usually sell much of their surplus immediately after harvest, when the price is relatively low, to meet immediate financial needs. The price is often considerably higher 1 or 2 mo after harvest and profitability is considerably increased when farmers can store their grain and sell at the higher prices.

The profitability of fertilizer use by smallholder farmers is therefore highly variable and dependent on agro-climatic and economic conditions at the local and regional levels (Vlek, 1990). It is worsened by the lack of credit and agricultural subsidies and by low and variable returns on grain sales (Heisey and Mwangi, 1996). Smallholder farmers often require a BC >1 within a 6- to 12-mo period (Wortmann and Ssali, 2001) to justify an investment. Variation in the profitability of fertilizer use due to variable CPs require that farmers adjust the EONR based on current information. Given their constrained access to investment funds, smallholder farmers need to consider the BCs of N and P use, which are affected by both application rates and the CP:

$$\begin{aligned}\mathrm{BC}_{\mathrm{N};\leq 50\ \mathrm{kg\ ha^{-1}}} = {} & 16.17 - 0.237N - 0.790\mathrm{CP} \\ & + 0.00128N^2 + 0.0115\mathrm{CP}^2 \\ & + 0.00452N\,\mathrm{CP}\end{aligned} \quad [14]$$

$$\begin{aligned}\mathrm{BC}_{\mathrm{P};< 30\ \mathrm{kg\ ha^{-1}}} = {} & 5.27 - 0.239N - 0.183\mathrm{CP} \\ & + 0.00313N^2 + 0.00166\mathrm{CP}^2 \\ & + 0.00259N\,\mathrm{CP}\end{aligned} \quad [15]$$

The BC for N is ~300% higher than for P at the EOR. For the same application rate and CP, $\mathrm{BC_N}$ was ~36% higher and $\mathrm{BC_P}$ was 10% lower for maize than for sorghum, with the difference increasing with increased application rates (Kaizzi et al., 2012).

Policy interventions that reduce the cost of fertilizers through subsidies, improved input supply, improved markets, and enabling farmers to get credit on stored produce and thus enabling delayed sales at more favorable grain prices would improve the profitability of fertilizer use. Such interventions would also increase smallholder funds available for fertilizer purchase and the ability to apply fertilizer to more land. Setting a minimum price of grain at the beginning of the season would enable better determination of the EOR and reduce the financial risk of fertilizer use. Current practices of little or no fertilizer use are not sustainable because of soil nutrient and active SOM fraction depletion (Stoorvogel and Smaling, 1990; Wortmann and Kaizzi, 1998; Nkonya et al., 2005).

Alternative practices may improve the economics of fertilizer use. Placement of the preplant fertilizer application in pockets or a band near the seed, compared with broadcast application, may have improved early plant growth and fertilizer recovery. The available information is mixed. Christianson et al. (1990) found it better to broadcast P rather than to place it close to pearl millet [*Pennisetum glaucum* (L.) R. Br.] seed on a sandy soil because root growth depleted the soil water near the plant, which inhibited P uptake. Muehlig-Versen et al. (2003), however, reported 72 to 88% more yield with 3 to 7 kg ha^{-1} P placed near pearl millet seed compared with broadcast application of 13 kg ha^{-1} P.

Nitrogen Use Efficiency

The relationship between crop yield and UN is tightly conserved, achieving higher yields with greater UN (Cassman et al., 2002). A crop subjected to diverse constraints may be inefficient in nutrient use because of low RE but also IE. Most components of NUE were estimated to be higher at the EONR compared with higher N rates, confirming the findings of Meisinger et al. (2008). Grain N concentration, an important component of IE, was relatively high compared with irrigated corn in Nebraska (Wortmann et al., 2011). Comparing other NUE components at the EONR to the Nebraska study with irrigated high-yield maize following maize: RE, NHI, and PFP were similar; IE and PE were low; and AE was high. Both RE and AE in this study were high compared with the values reported for irrigated maize and rainfed sorghum (Binder et al., 2002). The low IE and PE occurred because of low HI and high grain N concentration compared with the Nebraska study. The high AE occurred because of the relatively low EONR, where much yield increase is required to pay for the high cost of N use for smallholder farmers in Uganda. In comparison with sorghum produced under similar conditions, grain and stover N concentration, RE, IE, PE, and AE were lower and NHI and PFP were higher for maize (Kaizzi et al., 2012).

CONCLUSIONS

Maize grain yield increased by 53 to 213% with application of 50 kg N ha^{-1}, verifying that fertilizer N use, and P together with N use, is effective for increasing maize grain yield in Uganda. This has implications for food security and farm profitability. Economic analysis shows that investment in fertilizers will more than pay for itself. At current prices for fertilizers and produce, however, the EOR is low and not sufficient to prevent soil nutrient depletion, especially if crop residues are removed. Reversal of soil degradation due to nutrient mining for system sustainability may require policy interventions to improve the CP. These interventions may be fertilizer subsidies, improved market and input supply efficiency, or increased access to information and credit.

Most important is to reduce the fertilizer cost to enable farmers with little investment capital to apply fertilizer to more of their land. Seasonal variation in the profitability of fertilizer use requires ready access to current information on fertilizer prices and grain market prices to better determine the EONR for the season.

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