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ABSTRACT

Corn (*Zea mays* L.) N use is of continued interest due to agronomic performance and environmental issues. This 2-yr study evaluated era hybrid response to fertilizer nitrogen (FN) rate in a factorial arrangement of one popular hybrid per five decades (1960–2000 eras) and five N rates (0–224 kg N ha^{-1}). An additional hybrid per era was grown at 168 kg N ha^{-1}. Hybrid productivity and nitrogen use efficiency (NUE) increased across the eras, but not between the 1980 and 1990 eras. Grain yield (GY) increased 65% and total plant biomass 43%, however, total plant nitrogen uptake (PNU) increased only 19% and across N rates was only higher for the 2000 era. At the agronomic optimum nitrogen rate (AONR), there was a linear GY increase of 0.13 Mg ha^{-1} yr^{-1} and GY N response of 0.091 Mg ha^{-1} yr^{-1}, indicating considerable genetic gain. There was no trend in AONR across eras. For plant N status measures, SPAD readings decreased and canopy index values increased across eras. All NUE measures indicated significant improvement in NUE. The apparent nitrogen recovery efficiency (NRE) at N rates near the AONR of each era, however, was not highest for the most recent eras. Harvest index (HI), grain nitrogen harvest index (GNHI), and fraction of total PNU accumulated by R1 were the same among eras. The grain nitrogen concentration (GNC), however, was 24% lower for the 2000 compared to the 1960 era. Corn hybrid development across the 50-yr period improved productivity and NUE, but not the AONR.

Corn GY in the United States has increased from 1.5 Mg ha^{-1} in the early 1900s to 8.5 Mg ha^{-1} in the 2000s (USDA-NASS, 2012). The initial increase in GY occurred during the early 1930s when double-cross hybrids replaced open-pollinated varieties (Russell, 1974), with increases continued because cultural methods improved, such as N use, weed and pest control, timeliness of planting, and increased efficiency of harvest equipment (Cardwell, 1982; Edmeades and Tollenaar, 1990). Additionally, climate changes also contributed to yield increases in the past through increased total rainfall (Assefa et al., 2012). Double-cross hybrids, cultivated during the 1930s to 1960s, resulted in annual gains of 0.065 Mg ha^{-1} (Troyer, 1995), while single-cross hybrids in the 1960s (Russell, 1974) resulted in an annual gain of 0.011 Mg ha^{-1} (Duvick, 1997) and in eras from 1970 to 2000 an annual gain of 0.086 Mg ha^{-1} (Haegele et al., 2013).

Genetic yield improvement of corn hybrids from the 1930s to the 1990s is associated with improved stress tolerance; as newer corn hybrids appeared more tolerant of high plant population densities (Tollenaar and Lee, 2002). Genetic improvement of corn has also been accompanied by a decrease in plant-to-plant variability (Tollenaar and Wu, 1999). In general, 60% of the increase in GY has been attributed to genetic improvement and 40% being attributed to improved agronomic practices (Cardwell, 1982; Edmeades and Tollenaar, 1990; Duvick, 1992; Osteen, 2003). Realistically, the total increase in GY across time is due to the combined effect and interaction between genetics and improved agronomic practices (Tollenaar and Lee, 2002). Increased plant N use accompanied early gains in GY of single-cross maize hybrids (Duvick and Cassman, 1999). However, average N rates applied as fertilizer in the United States have remained relatively static during the past 30 yr (USDA-ERS, 2013), therefore GY gains would be more attributed mainly to genetic improvements

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Abbreviations: AE, agronomic efficiency; AONR, agronomic optimum nitrogen rate; Chl, chlorophyll index; DM, dry matter; FN, fertilizer nitrogen; GNC, grain nitrogen concentration; GNHI, grain nitrogen harvest index; GNU, grain nitrogen use; GY, grain yield; HI, harvest index; IE, internal efficiency; NDVI, normalized difference vegetation index; NRE, nitrogen recovery efficiency; NUE, nitrogen use efficiency; PFP, partial factor productivity; PNU, plant nitrogen uptake; SYE, system efficiency; TPE, total production efficiency; YAONR, yield at agronomic optimum nitrogen rate.

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and other management changes during that period, such as increased seeding rates and narrower rows among other factors.

Improved efficient use of applied nutrients for crop production is a desirable agronomic, economic, and environmental goal (Liang and Mackenzie, 1994). Improving corn fertilizer NUE is important to reduce negative environmental impacts associated with N and manure use such as NO_3 losses to surface and ground water as well as improving N input costs per unit of GY produced (Cassman et al., 2003). Some reasons for low corn NUE include poor alignment of soil/fertilizer N supply with crop demand and uniform N application rates used across spatially variable landscapes (Shanahan et al., 2008).

Corn plant N status can be discerned by tools such as the SPAD chlorophyll meter as readings are highly correlated with leaf N concentration (Markwell et al., 1995) and related to plant N status (Piekielek and Fox, 1992; Wood et al., 1992; Blackmer and Schepers, 1994; Piekielek et al., 1995; Fox et al., 2001; Woli et al., 2013, 2014). Active canopy sensors can also discern corn N status and canopy biomass through indices such as chlorophyll index (Chl) and normalized difference vegetation index (NDVI; Gitelson et al., 2003; Dellinger et al., 2008; Solari et al., 2008; Sripada et al., 2008; Barker and Sawyer, 2010, 2013). Application of sensors to examine N response across different eras of hybrids has not been conducted before and may enhance understanding of hybrid N use and relation to NUE measures.

It would be instructive to examine various NUE measures across hybrid eras to better understand corn N use with hybrid era development. However, there is limited research of NUE with hybrids from different time periods when grown with multiple N rates. Studies have focused on corn GY, response to plant densities, and N response for hybrids representing specific eras (Carlone and Russell, 1987; O'Neill et al., 2004; Assefa et al., 2012; Qian et al., 2012; Ciampitti and Vyn, 2013; Ciampitti et al., 2013; Zhang et al., 2014). In a study conducted with 10-yr eras from 1930 to 1980 with four open-pollinated varieties and four cultivars per era of single-cross hybrids, Carlone and Russell (1987) reported that all cultivars had highly positive linear responses to N rate. In a study of corn hybrid performance trials in Kansas, there was a positive yield trend for the 70-yr period (1939–2009) for both dryland and irrigated corn (Assefa et al., 2012). Corn yield changed from one decade to another, however, were not similar across the seven decades considered. Changes in hybrid technology and crop management factors, such as increased planting density and fertilization rates, also occurred in the same time period (Assefa et al., 2012).

Significant interactions among eras, plant densities, and N rates for GY, partial factor productivity (PFP), and NRE were reported in a study conducted in China with eight corn hybrids released from the 1970s to 2000s (Qian et al., 2012). Generally, total plant biomass and GY of hybrids from more recent decades have been found to be greater than those from older decades across or within environments (Castleberry et al., 1984; Assefa et al., 2012; Zhang et al., 2014). However, specific information for hybrids from multiple eras for corn N rate response, such as determination of optimal N rate, plant and grain N uptake, and NUE, is limited. The objective of this study was to evaluate N response, AONR, and NUE with selected popular hybrids from eras (decades) across the recent 50 yr when grown in the same year/environment.

MATERIALS AND METHODS

Site Description

The study was located near Ames, IA, at the Agricultural Engineering and Agronomy research farms, 42°0′41″ N, 93°44′32″ W in 2007 and 41°59′17″ N, 93°40′46″ W in 2008. Predominant soils were Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll), Harps fine-loamy, mixed, superactive, mesic Typic Calciaquoll), Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll), and Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll) clay loam (Table 1). The previous crop at both sites was soybean [*Glycine max* (L.) Merr.] in a corn–soybean rotation.

Soil test results of samples collected in the spring before tillage in 2007 were in the Very High category for P and K (Table 1), therefore, no P or K fertilizer was applied (Sawyer et al., 2002). In 2008, soil tests were in the Optimum category for K and Low for P, therefore, triple super phosphate was applied on 13 May before tillage based on recommendations for corn (Sawyer et al., 2002). Pre-sidedress soil NO_3–N test (PSNT; Magdoff et al., 1984) soil samples were collected at a 0- to 30-cm depth from no-N control plots across the study area to gain insight into the field history effect on residual NO_3–N and potential for N response. The results (Table 1) indicated the sites would be N responsive (well below the 25 mg kg^{-1} critical value; Blackmer et al., 1989; Fox et al., 1989).

Hybrid Selection and Fertilizer Nitrogen Treatment Applications

The study consisted of 10 DuPont Pioneer (Pioneer Hi-Bred International Inc., Johnston, IA) hybrids, two from each of the 1960, 1970, 1980, 1990, and 2000 era-decades. The hybrids were popular and deemed to be representative of the respective decade, and were recommended by Dr. Don Duvick and Dr. Garren Benson (Pioneer Hi-bred and Iowa State University, respectively; personal communication, 2006 and 2007) for the study. The hybrid corn relative maturity ratings were appropriate for central Iowa (Table 2) and were planted to achieve a final stand appropriate for the respective decade (Table 2) based on advice from Drs. Duvick and Benson. Seeding rates were 5% greater than the desired final stand to compensate for germination and expected seedling mortality.

The experimental design was a split-plot, randomized complete block, using a factorial treatment arrangement and four replications. Treatments for the hybrid by FN rate component were a factorial combination of a single hybrid representing each era from 1960 to 2000 (3206, SX19, 3377, 3394, and 33D11, respectively) and five N rates (0, 56, 112, 168, and 224 kg N ha^{-1}). These hybrids were used for N rate response (plant biomass and GY) and whole plant N analysis. At the 168 kg N ha^{-1} rate, there was an additional hybrid per era (3618, 3529, 3362, 3489, and 34A15 for 1960–2000, respectively), used for plant biomass and whole plant N analysis, with the two 1960 and 2000 era hybrids also used for corn grain N analysis (Table 2). The single N rate of 168 kg N ha^{-1} was chosen for the additional era hybrids as that rate was within the recommended range in Iowa for corn following soybean (Sawyer et al., 2006). The FN was ammonium-nitrate, broadcast after planting on 5 June 2007 and 10 June 2008 at approximately the V4 development stage (Abendroth et al., 2011).

Table 1. Predominant soils and soil test values for the study sites.

Site	Year	Predominant soils			Soil tests				
		Series	Texture†	Classification	pH	STP‡	STK‡	NO_3–N§	OM¶
						mg kg^{-1}			g kg^{-1}
1	2007	Nicollet	L	Aquic Hapludolls	6.5	37 (VH)	197 (VH)	10	42
		Harps	L	Typic Calciaquolls					
		Canisteo	CL	Typic Endoaquolls					
2	2008	Nicollet	L	Aquic Hapludolls	6.7	14 (L)	137 (O)	6	42
		Clarion	L	Typic Hapludolls					
		Canisteo	CL	Typic Endoaquolls					

† L, loam; CL, clay loam.

‡ STP, soil test phosphorus (Bray P_1) and STK, soil test potassium (ammonium acetate) for the 0- to 15-cm depth. Letters in parentheses indicate soil test category interpretation (Sawyer et al., 2002) with L, low; O, optimum; VH, very high.

§ Pre-sidedress soil NO_3–N test values, 0- to 30-cm depth, with no fertilizer N applied.

¶ OM, soil organic matter for the 0- to 15-cm depth.

Each year the study area was field-cultivated for seedbed preparation, with hybrids planted on 15 May each year. Individual hybrid plot size was 6.1 m wide (eight rows, 0.76 m row spacing) by 16.5 m long. Alleys were cut within each large plot to create three subplots with length of 4.7 m. Sets of two rows were randomly selected within these subplots for GY determination and two others for plant sampling. Each plot area for GY or plant sampling was bordered on both sides by rows that were not sampled. The two rows not used for plant sampling were mechanically harvested for GY determination on 4 Oct. 2007 and 31 Oct. 2008, with GY converted to 15.0 g kg^{-1} moisture equivalent.

Corn Plant and Grain Measurements

For the five era hybrids used across N rates, and for the era hybrids used only at the 168 kg N ha^{-1} rate, whole plants were collected at the R1 and R6 development stages. To remain consistent across years and hybrids, the R1 sampling date was based on staging hybrid 33D11, a modern hybrid with a relative maturity of 112 d. All hybrids were close to the R1 stage each year for that sampling. The R6 samples were collected after all hybrids within the trial reached physiological maturity.

Three consecutive plants (at each development stage) located within two adjacent rows (total of six plants) were clipped at the ground level within each plot on 23 July 2007 and 28 July 2008 for R1 and 25 Sept. 2007 and 6 Oct. 2008 for R6. Whole plant samples at R1 were oven dried at 60°C for 7 d and weighed to record DM. The entire dried sample was processed through a modified stationary forage chopper. A subsample of this chopped material was ground with a Wiley mill (Arthur H. Thomas Co., Philadelphia, PA) to pass a 2-mm sieve. Plant parts fractionated for another component of the overall study (1960 and 2000 era hybrids with 168 kg N ha^{-1}, Table 2), were dried individually, weighed, and the entire sample ground to pass a 2-mm sieve with a Wiley mill. Individual fraction weights of each component were summed to obtain whole plant dry matter (DM). Whole plants at R6, including vegetation, cob, and grain (if plant parts were not fractioned), were either dried, weighed, and processed through a wood chipper or allowed to air dry in a ventilated storage building for 7 to 10 d and then processed through a stationary forage chopper. The chopped plant material was dried, weighed, and a subsample ground to pass a 2-mm sieve with a Wiley mill. If R6 plant parts were fractionated, individual vegetative and cob components were dried, weighed, and ground to pass a 2-mm sieve with a Wiley mill; while grain was ground with a flour mill (WonderMill Company, Pocatello, ID). Weighed components were added to obtain whole plant DM.

All ground plant samples were analyzed for total N by modified Kjeldahl digestion with flow-injection analysis. Area-based aboveground plant biomass dry weight, N uptake, and grain N were calculated by determining the average plant spacing and area that the six sampled plants occupied per plot. Only whole plant or grain results are presented here.

Plant Canopy and Nitrogen Status Measurements

Corn plant sensing was performed at the V10–V12 development stage in 2008 (not in 2007) using a Minolta SPAD-502 m (Konica Minolta, Osaka, Japan) and a Crop Circle ACS-210 (Holland Scientific, Lincoln, NE) active canopy sensor to estimate mid-vegetative growth and N status. The SPAD readings from 15 plants were recorded from the uppermost fully developed leaf (leaf with collar fully exposed) at a point one-half the distance from the leaf tip to the leaf base, and halfway between the leaf margin and midrib using the procedure described by Peterson et al. (1993). On the same day, the corn plant canopy

Table 2. Hybrids representing each era and targeted final stand.

Era	Targeted final stand†	Hybrid‡	CRM§
	plants ha^{-1}		d
1960	39.5×10^3	3206	114
		3618	108
1970	54.3×10^3	SX19	113
		3529	108
1980	64.2×10^3	3377	113
		3362	111
1990	74.1×10^3	3394	110
		3489	108
2000	84.0×10^3	33D11	112
		34A15	108

† Common historical plant population respective of each era.

‡ DuPont Pioneer hybrids (Pioneer Hi-Bred International Inc., Johnston, IA) 3206, SX19 (same as B73 × Mo17), 3377, 3394, and 33D11 used with all five N rates and hybrids 3618, 3529, 3362, 3489, and 34A15 used only with 168 kg N ha^{-1}.

§ Corn relative maturity rating (days, d) from Pioneer Hi-bred International.

was measured with the active canopy sensor using the procedure of Barker and Sawyer (2010). The sensor provides visible (VIS) and near-infrared (NIR) reflectance values. The sensor was mounted on a mast, positioned between the center two plot rows, and carried by hand at the 1.5 m s^{-1} speed and 0.60- to 0.90-m height above the crop canopy. Within plots, approximately 22 VIS and NIR values were recorded with a datalogger and averaged to determine a per-plot value. The VIS and NIR plot values were used to calculate Chl index [(NIR/VIS) -1] and normalized difference vegetative index (NDVI) [(NIR – VIS)/(NIR + VIS)].

Nitrogen Use Efficiency Calculations

The NUE concept provides a quantitative measure of the effectiveness of plants to take up and convert available N into plant biomass and harvest components, and recover applied N within a cropping system (Ciampitti and Vyn, 2011). Nitrogen use efficiency measures are relationships of various measured plant parameters or change in parameters; often compared to FN rate applied: GY or plant biomass compared to N rate, total plant N uptake compared to N rate, grain N compared to N rate, GY compared to total plant N, and GY compared to grain N (Novoa and Loomis, 1981). The calculations used here were based on Moll et al. (1982), Snyder and Bruulsema (2007), Ciampitti and Vyn (2011), and Burzaco et al. (2014).

The following NUE measures were calculated for the era hybrids with all N rates. The PFP and total production efficiency (TPE) were also calculated for the two hybrids in each era grown with 168 kg N ha^{-1}.

Agronomic efficiency (AE) indicates the effect of N applied on increase in GY (15.0 g kg^{-1} moisture basis) compared to the control with no FN:

$$\text{AE } (\Delta\text{kg kg}^{-1}) = (\text{GY}_{\text{N}} - \text{GY}_0)/\text{N rate} \quad [1]$$

Nitrogen recovery efficiency indicates the ability of aboveground plant parts at physiological maturity to recover N from N applied compared to the control with no FN:

$$\text{NRE } (\Delta\text{kg kg}^{-1}) = (\text{PNU}_{\text{N}} - \text{PNU}_0)/\text{N rate} \quad [2]$$

Partial factor productivity, the simplest form of crop output efficiency, indicates GY produced (15.0 g kg^{-1} moisture basis) per unit of N applied:

$$\text{PFP (kg kg}^{-1}) = \text{GY/N rate} \quad [3]$$

Total production efficiency is the relationship of total plant biomass including grain (DM basis) produced per unit of N applied:

$$\text{TPE (kg kg}^{-1}) = \text{Plant biomass/N rate} \quad [4]$$

For the two hybrids in each era grown with 168 kg N ha^{-1}, components of grain were calculated such as grain N concentration (GNC), grain nitrogen use (GNU), GNHI, and system efficiency (SYE), HI, GNHI, SYE, and internal efficiency (IE).

Grain N harvest index is the proportion of total plant N uptake in grain:

$$\text{GNHI} = \text{Grain N uptake/PNU} \quad [5]$$

System efficiency is the comparison or relative proportion of grain N to applied N:

$$\text{SYE (\%)} = (\text{Grain N uptake/N rate}) \times 100 \quad [6]$$

Internal efficiency relates the conversion efficiency of accumulated plant N to GY (15.0 g kg^{-1} moisture):

$$\text{IE (kg kg}^{-1}) = \text{GY/PNU} \quad [7]$$

Grain N use is the grain N concentration expressed on a per yield unit basis (15.0 g kg^{-1} moisture):

$$\text{GNU (kg kg}^{-1}) = \text{GY/Grain N uptake} \quad [8]$$

Harvest index is the proportion of total plant biomass in grain (DM basis).

$$\text{HI} = \text{Grain biomass/Total plant biomass (vegetative and grain)} \quad [9]$$

STATISTICAL ANALYSES

Measured parameters and calculated NUE values were analyzed with the GLIMMIX procedure of SAS (SAS Institute, 2012) for the randomized complete block design with a factorial arrangement of era hybrid and N rate; or for era hybrids when only grown at the 168 kg N ha^{-1} rate. Treatments were considered fixed, with year and replication within year random. When significant, differences between effects were determined with the LINES option of the LSMEANS statement ($P \leq 0.10$). When the era hybrid interaction with N rate was significant, linear, linear-plateau, quadratic, and quadratic-plateau regression models were fit using GLM and NLIN procedures of SAS. The N rate response data were visually inspected, and the model selected that was statistically significant ($P \leq 0.10$), with the largest coefficient of determination (R^2), and the smallest error residual. For GY, the regression models were used to determine the AONR and yield at the agronomic optimum nitrogen rate (YAONR).

RESULTS AND DISCUSSION

Climatic Conditions

The 2007 and 2008 growing seasons represented two somewhat different, but not unusual, environments with respect to air temperature and rainfall. In 2007, air temperatures were near average with precipitation above average in April and May, well below average in June and July, and well above average in August (Table 3). The total precipitation for the April to October period was near the 23-yr average. In 2008, temperatures were generally cooler than average during April, May, and June, but near average the rest of the growing season. The below average early season temperatures were accompanied by above average precipitation in May to July, and then below average in August and September. There was a total of 732 mm of precipitation during the growing season in 2008, about 32% greater than the 23-yr average and 58% more compared to 2007.

Table 3. Mean monthly air temperature and precipitation, including long-term averages.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
						Mean monthly temperature, °C							
2007	–6.5	–8.7	5.6	8.3	18.3	21.7	23.6	23.8	18.3	12.8	2.1	–6.2	
2008	–8.7	–8.2	0.3	7.5	14.5	20.9	23.0	21.4	17.7	10.8	3.0	–7.8	
Long-term average†	–6.0	–4.0	2.9	9.7	16.2	21.4	23.3	22.1	17.8	10.8	2.6	–3.9	
						Mean monthly precipitation, mm							
2007	11	54	58	132	146	46	67	169	35	98	0	0	816
2008	0	0	0	110	181	238	201	45	67	81	53	27	1004
Long-term average†	13	19	40	87	122	126	130	99	79	50	43	18	824

† Long-term averages are based on 23-yr (1986–2008) data obtained from Iowa Environmental Mesonet (2014) for a nearby weather station.

Table 4. Aboveground total corn plant biomass, grain yield (GY), and total plant nitrogen uptake (PNU) at R1 (silking) and R6 (physiological maturity) for each era and fertilizer nitrogen (FN) rate. Statistical values for each parameter are $P > F$. Significant era × N rate interaction shown in Fig. 1 and equations in Table 5. Significant N rate main effect responses are given in the footnote when era × N rate interactions are not significant.

	FN, kg N ha^{-1}					
Era	0	56	112	168	224	Mean
			Total plant biomass, Mg ha^{-1}			
1960	12.9	13.8	15.6	15.9	15.0	14.6d†
1970	15.1	16.5	17.6	18.2	18.1	17.1c
1980	15.0	18.7	19.8	19.2	21.2	18.8b
1990	13.8	18.7	19.4	19.1	22.4	18.7b
2000	15.1	19.0	22.8	21.9	21.5	20.0a
Mean	14.4	17.3	19.0	18.8	19.6	
Era			<0.001			
N rate			<0.001			
Era × N rate			0.020			
			GY, Mg ha^{-1}			
1960	6.2	7.4	8.4	8.6	8.6	7.8d
1970	7.8	9.8	10.5	10.5	10.9	9.9c
1980	7.7	10.0	12.1	11.9	12.0	10.7b
1990	8.0	10.4	12.2	12.2	12.2	11.0b
2000	7.9	10.2	12.3	14.3	13.9	11.7a
Mean	7.5	9.6	11.1	11.5	11.5	
Era			<0.001			
N rate			<0.001			
Era × N rate			<0.001			
			Total PNU at R6, kg N ha^{-1}			
1960	89	124	154	191	161	144b
1970	89	113	137	181	179	140b
1980	87	125	159	162	199	146b
1990	75	118	150	156	200	140b
2000	86	127	185	206	199	161a
Mean	85	121	157	179	188	
Era			0.002			
N rate			<0.001			
Era × N rate			0.012			
			Fraction of total R6 PNU at R1, %			
1960	69	73	68	76	76	72a
1970	72	81	85	74	77	78a
1980	69	81	75	75	63	73a
1990	67	73	81	74	65	72a
2000	60	77	68	68	79	70a
Mean	67	77	75	73	72	
Era			0.269			
N rate‡			0.087			
Era × N rate			0.563			

† Means for each measurement followed by the same letter are not significantly different ($P \leq 0.10$).

‡ $y = 67 + 0.148x$ if $x \leq 49$ kg N ha^{-1}, $y = 74\%$ if $x > 49$ kg N ha^{-1}, $R^2 = 0.74$, $P = 0.061$.

Era Hybrid and Nitrogen Rate Response

Corn Plant Biomass

There was an interaction between era and N rate for total plant biomass (Tables 4 and 5, Fig. 1a). The 1960 era hybrid had the lowest total plant biomass across all N rates, and with the smallest increase between no N applied and the highest rate. The 1970 era hybrid had a similar biomass N response as the 1960 era (quadratic response with little to no increase at the highest N rates), but plant biomass was greater with the 1970 era. The 1980 and 1990 eras had similar plant biomass and N response across all N rates (linear increase to the highest N rate). Plant biomass for these two eras was similar to the 1970 era at low N rates, but greater than the 1970 era at the highest rates due to the different response shape. Interestingly, the 2000 era had similar plant biomass with no N applied as for the 1970 to 1990 eras, higher biomass than those eras at intermediate N rates, but the same biomass as the 1980 and 1990 eras at the highest N rate. The smaller plant biomass for the 2000 era at the highest N rate, compared to the 112 and 168 kg N ha^{-1} rates, cannot be explained. A dissimilar plant biomass response of hybrids from 1981 to 2010 was also reported by Zhang et al. (2014). They found that modern hybrids had greater plant biomass and GY than the older hybrids, but there was no clear pattern in plant biomass differences among hybrids of different eras.

The overall trend was an increase in plant biomass across the 1960 to 2000 eras, with 45% greater biomass for the 2000 era compared to the 1960 era at the maximum N rate response. Total plant biomass generally increased with successive older to more recent eras and increasing N rate. Similar results were reported in a recent review of various field studies (Ciampitti and Vyn, 2012). Ma and Dwyer (1998) and Ding et al. (2005) also reported the main difference in N response of older vs. newer corn hybrids was due to less biomass accumulation in older hybrids.

Grain Yield

There was an interaction between era and N rate for GY (Tables 4 and 5, Fig. 1b). The N response trend for eras was similar to total plant biomass, with some notable exceptions. As often found with N rate response in corn, the era GY responses were quadratic with a GY plateau across the highest N rates (Carlone and Russell, 1987; Liang and Mackenzie, 1994). The exception was the 2000 era, which had a GY N response increase to the highest N rate and plateau at 228 kg N ha^{-1}. The GY trends at the YAONR across eras indicated the 1960 era had the lowest YAONR, the 2000 era the highest, the 1970 to 1990 eras intermediate, and with the 1980 and 1990 eras not different (Table 5). Grain yields at the AONR ranged from 8.6 Mg ha^{-1} for the 1960 era to 14.2 Mg ha^{-1} for the 2000 era, with an increase of 0.127 Mg ha^{-1} yr^{-1}. According to the USDA National Agriculture Statistics Service reported GYs for Iowa, corn GY averaged 5.2 Mg ha^{-1} in the 1960 era and 10.4 Mg ha^{-1} in the 2000 era, with an increase of 0.124 Mg ha^{-1} yr^{-1} (USDA-NASS, 2015). Although the slope from our study parallels that from the USDA data, our GYs were considerably higher than the USDA statewide values. The increase in GY across time would

Table 5. Regression parameters for significant interactions (Table 4) of era by fertilizer N rate for total plant biomass, grain yield (GY), and total plant N uptake (PNU) at R6. Regression curves shown in Fig. 1.

Regression parameter†	Era 1960	1970	1980	1990	2000
			Total plant biomass, Mg ha^{-1}		
Regression model‡	Q	Q	L	L	Q
a	12.7	15.1	16.2	15.2	15.0
b	0.037	0.032	0.023	0.031	0.096
c	–0.00012	–0.00008	–	–	–0.00030
R^2	0.91	1.00	0.78	0.81	0.96
$P > F$	0.086	0.002	0.048	0.038	0.036
			GY, Mg ha^{-1}		
Regression model	QP	QP	QP	QP	QP
a	6.14	7.84	7.58	7.99	7.72
b	0.0287	0.0446	0.0586	0.0568	0.0568
c	–0.000084	–0.000176	–0.000194	–0.000189	–0.000125
AONR§, kg N ha^{-1}	171	127	151	150	228
YAONR§, Mg ha^{-1}	8.6	10.7	12.0	12.2	14.2
R^2	1.00	0.98	0.99	0.99	0.98
$P > F$	0.004	0.016	0.015	0.009	0.017
			Total PNU at R6, kg ha^{-1}		
Regression model	Q	Q	Q	Q	Q
a	84	86	89	79	80
b	1.004	0.606	0.634	0.644	1.271
c	–0.00280	–0.00073	–0.00075	–0.00057	–0.00319
R^2	0.92	0.95	0.96	0.97	0.97
$P > F$	0.081	0.049	0.037	0.035	0.032

† a, intercept; b, linear; and c, quadratic coefficients.

‡ Q, quadratic; L, linear; QP, quadratic plateau.

§ AONR, agronomic optimum nitrogen rate; YAONR, grain yield at the agronomic optimum nitrogen rate. For the QP, these are at the model joint point.

be expected as corn GY in general has increased with time; with an average YAONR increase of 65% across the 50-yr period in this study. The N rate response for the 2000 era is interesting as the GY did not reach a plateau within the N rates applied (was close at 228 kg N ha^{-1}). This could indicate that the most recent hybrids had a greater response potential to N application. There were significant era and N rate main effects for grain HI (data not presented, $P = 0.070$ and $P = 0.002$ for era and N rate, respectively). Harvest index was consistent across the 1970 to 2000 eras (mean across N rate of 0.50, with a range 0.49–0.51), but the 1960 era had a lower HI (0.46). The HI N rate main effect means were 0.45, 0.47, 0.50, 0.52, and 0.51 across the 0 to 224 kg N ha^{-1} N rates, respectively, with a linear-plateau N rate response ($y = 0.45 + 0.000446x$ if $x \leq 149$ kg N ha^{-1}, $y = 0.51$ if $x > 149$ kg N ha^{-1}, $R^2 = 0.98$, $P = 0.02$).

The AONR (Table 5) differed across eras, however, the trend was not the same as for YAONR. The lowest AONR was with the 1970 era, the AONR was the same for the 1980 and 1990 eras (as for the YAONR), and the 2000 era had the highest AONR (maximum N applied). The era with the second highest AONR was the 1960 era. The differential in GY levels and N rate responses for the era hybrids indicate potential differences in NUE.

Interestingly, the GY with no N applied was the same for the 1970 to 2000 eras, but lower for the 1960 era (Fig. 2), that is, a linear plateau relationship across decades. The YAONR, however, increased linearly across eras (Fig. 2), with an increase of 0.13 Mg ha^{-1} yr^{-1}. Subtracting the GY with no N applied from the YAONR for each era resulted in a linear increase in N response across eras, with a GY increase of 0.091 Mg ha^{-1} yr^{-1}, which is much higher compared to the increase (0.030 Mg ha^{-1} yr^{-1}) reported by Haegele et al. (2013) with 21 single-cross hybrids released between 1967 and 2006 studied in Illinois field experiments during the 2009 and 2010 growing seasons. In our study, not only has GY increased across

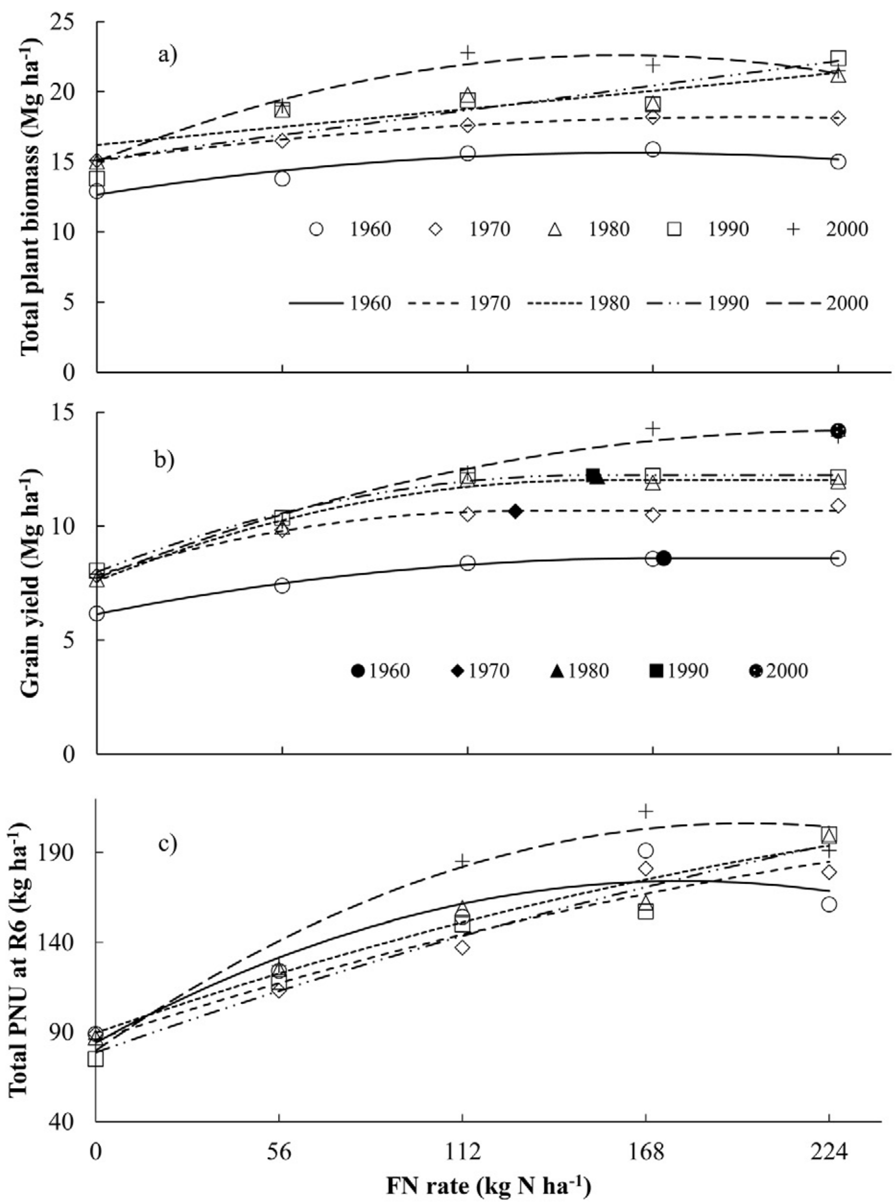

Fig. 1. Interaction of era hybrid by fertilizer nitrogen (FN) rate for (a) aboveground total plant biomass at R6, (b) grain yield (GY), and (c) total plant nitrogen uptake (PNU) at R6. The agronomic optimum nitrogen rate (AONR) for each era hybrid shown for GY (filled symbols). The interaction is based on statistical analysis presented in Table 4 and regression parameters in Table 5.

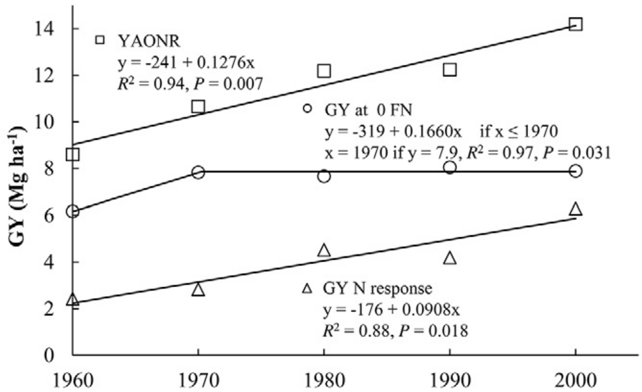

Fig. 2. Grain yield (GY) of each era hybrid at the agronomic optimum nitrogen rate (YAONR; squares), 0 kg N ha^{-1} fertilizer nitrogen rate (FN; circles), and GY N response (YAONR minus GY with 0 kg N ha^{-1} FN; triangles).

time with hybrid development, but also the GY response to optimal N application. This could be considered a genetic gain for hybrid N response. The trend for increasing GY was not present when hybrids were dependent solely on soil derived N (no FN applied). This has potential implications for breeding hybrids in regard to N use, that is, hybrid selection should consider GY response to optimal N application and not just unfertilized GY.

In regard to modern hybrids having a greater potential response to N application, our GY results for the era hybrids are similar to those reported by several studies (Castleberry et al., 1984; Sangoi et al., 2002; Echarte et al., 2008; Ciampitti and Vyn, 2012; Zhang et al., 2014). Carlone and Russell (1987) evaluated the performance of cultivars representing 10-yr eras in treatment combinations of plant density and N level, and reported a significant variation in GY due to cultivars when averaged over years and all density-N treatments. In a review of 100 published and unpublished papers, Ciampitti and Vyn (2012) reported that corn GY was higher for a new era hybrid

Table 6. Leaf SPAD reading, canopy chlorophyll index (Chl), and canopy normalized difference vegetation index (NDVI), corn V10 development stage, for each era and fertilizer nitrogen (FN) rate, 2008 only. Statistical values for each parameter are *P* > *F*. Significant N rate main effect responses are given in the footnote.

	FN, kg N ha^{-1}					
Era	0	56	112	168	224	Mean
			SPAD			
1960	45	53	58	56	56	54b†
1970	47	53	55	61	61	56a
1980	41	52	56	59	56	53bc
1990	45	51	55	57	56	53bc
2000	44	52	55	54	56	52c
Mean	45	52	56	57	57	
Era			0.018			
N rate‡			<0.001			
Era × N rate			0.410			
			Chl			
1960	4.2	5.4	5.3	5.4	5.4	5.2d
1970	4.3	5.3	5.5	5.5	5.6	5.3cd
1980	4.2	5.5	5.8	5.7	5.8	5.4c
1990	4.3	5.6	6.0	6.0	6.0	5.6b
2000	4.4	5.4	6.2	6.2	6.4	5.7a
Mean	4.3	5.4	5.8	5.8	5.9	
Era			<0.001			
N rate§			<0.001			
Era × N rate			0.098			
			NDVI			
1960	0.678	0.730	0.725	0.730	0.730	0.719c
1970	0.683	0.726	0.734	0.734	0.738	0.723bc
1980	0.677	0.731	0.743	0.741	0.744	0.728b
1990	0.681	0.736	0.751	0.750	0.750	0.734a
2000	0.687	0.732	0.757	0.757	0.762	0.739a
Mean	0.681	0.731	0.742	0.743	0.745	
Era			<0.001			
N rate¶			<0.001			
Era × N rate			0.424			

† Means for each measurement followed by the same letter are not significantly different (P ≤ 0.10).
‡ $y = 45 + 0.152x - 0.00048x^2$ if $x \leq 158$ kg N ha^{-1}, $y = 57$ if $x > 158$ kg N ha^{-1}, $R^2 = 1.00$, $P < 0.001$.
§ $y = 4.3 + 0.025x - 0.00010x^2$ if $x \leq 122$ kg N ha^{-1}, $y = 5.8$ if $x > 122$ kg N ha^{-1}, $R^2 = 1.00$, $P = 0.003$.
¶ $y = 0.681 + 0.0012x - 0.000006x^2$ if $x \leq 101$ kg N ha^{-1}, $y = 0.743$ if $x > 101$ kg N ha^{-1}, $R^2 = 0.74$, $P = 0.002$.

grouping (1991–2011) compared to that for an older era hybrid grouping (1940–1990). On the other hand, Ciampitti and Vyn (2011) in a study at two Indiana locations found that both plant density and N rate affected plant growth parameters and GY, but hybrid effects were negligible.

Genetic yield gain for the last 70 yr has been positive and linear (Duvick, 2005). The genetic yield gain for double-cross hybrids cultivated during the period 1930 to 1960 was reported to be 0.065 Mg ha^{-1} yr^{-1} (Troyer, 1995). Appearance of single-cross hybrids introduced in 1990s increased genetic yield gain to 0.011 Mg ha^{-1} yr^{-1} (Duvick, 1997). For the hybrids from the 1960s through 2000s in our study, GY increase (YAONR) was 0.013 Mg ha^{-1} yr^{-1}, and GY N response (YAONR minus GY with no N applied) 0.091 Mg ha^{-1} yr^{-1}. Zhang et al. (2014) evaluated the genetic yield gain for N rates of 0, 120, and 240 kg N ha^{-1} with 12 corn hybrids released from 1981 to 2010. They found the genetic yield gains were 0.046, 0.065, and 0.083 Mg ha^{-1} yr^{-1} for the three N rates, respectively.

Plant Nitrogen Uptake

There was an interaction between era and N rate for total aboveground PNU at maturity (Tables 4 and 5, Fig. 1c). The era PNU amount and interaction, however, was different than found for total plant biomass and GY. For example, the PNU with no N applied and with the lowest N rate was the same for all eras. The 1960 era had greater PNU at the lowest two N rates than the 1970 to 1990 eras, and the 2000 era had the largest PNU at 112 and 168 kg N ha^{-1}. In addition, only the 1960 and 2000 eras had no additional N uptake from the 168 to 224 kg N ha^{-1} rate as compared to the 1970 to 1990 eras that had an increase in PNU to the highest N rate. This difference in PNU response to N rate across eras indicates a change in plant demand and conversion to total biomass or GY. A general increase in PNU with increasing N rate for all eras would be expected and as reported by Halvorson and Bartolo (2014). Ma and Dwyer (1998) reported high PNU with modern hybrids, but that response did not occur consistently across all N rates in our study. In agreement with our findings, Ciampitti and Vyn (2012) reported that total PNU (per-plant basis) at maturity did not change between the old (1940–1990) and new era (1991–2011) groupings.

The fraction of PNU at maturity taken up by R1 was influenced only by the main effect of N rate (Table 4), with a linear-plateau N rate response. The amount of N present at R1 relative to R6 was lowest with no N applied, but the same across all applied N rates (Table 4). There was no difference in the fraction between eras or the interaction of era and N rate. This indicates that the N uptake rate across vegetative and reproductive stages was the same for all eras. This is interesting as there is continual debate concerning change in N uptake patterns of old vs. modern hybrids (Benjamin et al., 1997; Dharmakeerthi et al., 2006; Ciampitti and Vyn, 2012). Ciampitti and Vyn (2012) reported the fraction of PNU at maturity taken up by R1 was as high as 83% for old hybrids while it was only 58% for modern hybrids. Similarly, Dharmakeerthi et al. (2006) reported an average 46% of the total PNU at R1 in a study conducted from 1997 to 2001 in southern Ontario. However, Benjamin et al. (1997) in Colorado reported a range from 60 to 75% PNU taken up at R1 for a modern hybrid. The fraction of total PNU by R1 was high in our study (mean of 73%). At plant maturity the mean total PNU across N rates was 19% higher for the 2000 era compared to the 1960 era (at the maximum N rate response), and across eras was 121% higher at the highest N rate compared to the no N control. Comparatively, there was no similar pattern in the fraction of total PNU taken up by R1.

Plant Canopy Sensing

There were no interactive effects between era and N rate for measurements with the SPAD meter (Table 6). For the Crop Circle canopy sensor, since the interaction P value was almost 0.10, interactive effects are not presented. There was a quadratic-plateau response to the main effect of N rate for SPAD readings, Chl index, and NDVI index. The canopy sensing index values increased with N rate to a maximum response plateau, which reflects the corn canopy response to N application. These results indicate that any of the three sensing measurements could provide an indication of era hybrid N status. However, compared to the GY AONR (Table 5), the SPAD and sensing index maximum values were generally at a lower N rate than the AONR, especially for the canopy sensing Chl and NDVI index values. This lower maximum canopy sensing value response, compared to the GY AONR, at the mid-vegetative stage has been found in other studies (Barker and Sawyer, 2013).

The SPAD readings and sensing values, mean across N rate, for eras did not have the consistent trend as found with N rate (Table 6), and were somewhat different for different eras. The SPAD chlorophyll meter readings were lowest for the 1980 to 2000 eras, and highest for the 1960 to 1970 eras. Comparatively, the Chl and NDVI values increased across eras, that is, lower with the older eras and highest with the recent eras, a trend that matches the increase in aboveground total plant biomass. The differences in SPAD readings and canopy index values among eras indicates that mid-vegetative plant architecture and biomass varied among eras, as well as indication of N status, which would influence interpretation of sensing results in regard to N stress or adequacy determination.

Nitrogen Use Efficiency

The NUE measures AE, PFP, and TPE decreased with increasing N rate (Table 7). There was an era × N rate interaction for PFP and TPE, but only an N rate main effect for AE. Each of these NUE measures uses a ratio of total plant biomass, GY, or change in plant biomass or GY to N rate. The results reflect the typical decrease in NUE with increasing N application rate. The NRE, which uses the ratio of change in total PNU to N rate, also decreased with increasing N rate (Table 7). The decrease with more applied N is consistent with the results reported by Guillard et al. (1995), Shapiro and Wortmann (2006), and Qian et al. (2012), reflecting the related increase in N uptake and GY as N rate increased. However, Halvorson and Bartolo (2014) reported that NRE did not vary with N rate in continuous corn. The influence of N rate on NUE measures using GY or GY response are consistent with other research (Ladha et al., 2005; Ciampitti and Vyn, 2011; Halvorson and Bartolo, 2014; Burzaco et al., 2014; Zhang et al., 2014), and reflects the curvilinear with plateau GY response to N rate, that is, decreasing to no GY response at N rates approach or are above optimum.

Table 7. Corn agronomic efficiency (AE), apparent nitrogen recovery efficiency (NRE), partial factor productivity (PFP), and total production efficiency (TPE) for each era and fertilizer nitrogen (FN) rate. Statistical values for each parameter are $P > F$. Significant era × N rate interactions shown in Fig. 3 and equations in Table 8. Significant N rate main effect responses are given in the footnote when era × N rate interactions are not significant.

Era	FN, kg N ha^{-1}				
	56	112	168	224	Mean
			AE, Δkg kg^{-1}		
1960	19	20	15	11	16c†
1970	38	22	15	14	22c
1980	41	40	23	19	31b
1990	39	36	24	18	30b
2000	43	40	38	28	37a
Mean	36	32	23	18	
Era			<0.001		
N rate‡			<0.001		
Era × N rate			0.695		
			NRE, Δkg kg^{-1}		
1960	0.55	0.59	0.60	0.33	0.52bc
1970	0.39	0.40	0.44	0.39	0.41c
1980	0.63	0.59	0.44	0.51	0.54b
1990	0.78	0.62	0.47	0.56	0.61ab
2000	0.73	0.88	0.74	0.51	0.71a
Mean	0.62	0.62	0.54	0.46	
Era			0.001		
N rate§			0.071		
Era × N rate			0.602		
			PFP, kg kg^{-1}		
1960	134	75	52	38	74d
1970	176	94	63	48	95c
1980	176	108	70	54	102b
1990	186	109	72	54	105ab
2000	184	110	85	62	110a
Mean	171	99	68	51	
Era			<0.001		
N rate			<0.001		
Era × N rate			0.029		
			TPE, kg kg^{-1}		
1960	249	143	94	67	138d
1970	294	158	108	81	160c
1980	319	176	114	96	176b
1990	336	174	114	100	181b
2000	341	203	130	97	193a
Mean	308	171	112	88	
Era			<0.001		
N rate			<0.001		
Era × N rate			0.022		

† Means for each measurement followed by the same letter are not significantly different ($P \leq 0.10$).
‡ $y = 0.70 - 0.001x$, $R^2 = 0.89$, $P = 0.056$.
§ $y = 43 - 0.113x$, $R^2 = 0.98$, $P = 0.011$.

Table 8. Quadratic regression model parameters for the significant interactions (Table 7) of era × fertilizer N rate for partial factor productivity (PFP) and total production efficiency (TPE). Regression curves shown in Fig. 3.

Regression parameter†	Era				
	1960	1970	1980	1990	2000
			PFP, kg kg^{-1}‡		
a	209	283	268	287	272
b	−1.56	−2.24	−1.88	−2.09	−1.84
c	0.00359	0.00534	0.00415	0.00470	0.00407
R^2	0.99	0.99	1.00	1.00	0.99
$P > F$	0.082	0.079	0.019	0.046	0.098
			TPE, kg kg^{-1}§		
a	386	469	515	558	525
b	−2.83	−3.66	−4.10	−4.68	−3.78
c	0.00630	0.00869	0.00996	0.01180	0.00837
R^2	1.00	0.99	1.00	1.00	1.00
$P > F$	0.056	0.086	0.047	0.067	0.030

† a, intercept; b, linear and c, quadratic coefficients.
‡ PFP is change in grain yield (GY) per unit of fertilizer N (Δ kg GY per kg fertilizer N).
§ TPE is total plant biomass DM per unit of fertilizer N (kg plant biomass DM per kg fertilizer N).

The NUE measures increased with advancement from the oldest to the most recent era (Table 7), except that all NUE measures were consistently the same for the 1980 and 1990 eras. Compared to the oldest era studied (1960), there was a large increase in NUE with the most recent era (2000). This indicates a considerable advancement in corn hybrid ability to use applied N to produce plant biomass and grain, which is consistent with results reported by other studies (Moll et al., 1982; McCullough et al., 1994; Coque and Gallais, 2007; Wang et al., 2014). The mean apparent NRE across N rates was 0.71 for the 2000 era, however, NRE was not greatly different and not highest for the most recent eras at the N rate near the AONR for each era (NRE mean 0.48 Δkg kg^{-1} across eras at the NRE nearest the AONR for each era).

There was an interaction of era and N rate for PFP and TPE (Tables 7 and 8, Fig. 3). Most notable was the much lower PFP and TPE for the 1960 era than other eras at all N rates, especially at the lowest two N rates. The 1980 and 1990 eras had the same PFP and TPE N rate response, as found for the mean across N rate results. Except for the 1960 era, the PFP values were the same for all eras with 56 kg N ha^{-1}, but separated as N rate increased. The 2000 era had the highest PFP across N rates. The opposite occurred for TPE where there was separation in TPE values at 56 kg N ha^{-1}. These differences in results for PFP and TPE indicate that the TPE measure (based on plant biomass) would be more discerning of hybrid differences at low N rates than PFP (based on GY), but the opposite at N rates near the optimum.

Nitrogen Response with Two Hybrids per Era

An additional hybrid was grown at the 168 kg N ha^{-1} rate for each era, and grain parameters such as GNHI, SYE, IE, grain N, GNU, and GNC were measured for the 1960 and 2000 era hybrids. The additional hybrid and grain N parameters allowed calculation of additional N uptake and NUE measures (Table 9). Several parameters had increases from the oldest to most recent hybrids, as found for the individual hybrid per era results; total plant biomass, PNU, GY, PFP, and TPE. For IE, values increased with newer hybrids, except the 2000 era which was not different than the 1970 and 1980 eras and lower than the 1990 era. These results confirm the trends found with the single hybrid per era and indicate similarity in popular hybrids within era.

The fraction of total PNU at R1 did not change with era and was at a high percentage (73%) of N taken up by beginning of the reproductive stage. The grain HI was also the same across eras. Several grain measures increased significantly from the 1960 to 2000 era; grain N, SYE, and GNU; each reflecting the increase in GY. For the 1960 compared to the 2000 era, GNC was 24% lower with the 2000 era, and GNHI did not change. The decrease in GNC is noteworthy as many assumed hybrid changes across time that affect NUE calculations, for example GY increase, do not take into account the lower grain N concentration. Ciampitti and Vyn (2013) found that GNC was the main N parameter that changed across time (declined), and that lower GNC for recent era hybrids is consistent with results by Duvick (1997) and Ciampitti and Vyn (2012).

CONCLUSIONS

Corn hybrids changed significantly from the 1960 to 2000 era in most respects, but not all. Grain yield increased by 65% and total plant biomass by 45% with agronomic optimum N input; however, total PNU increased only with the 2000 era (19%). With no FN applied, total plant biomass and PNU

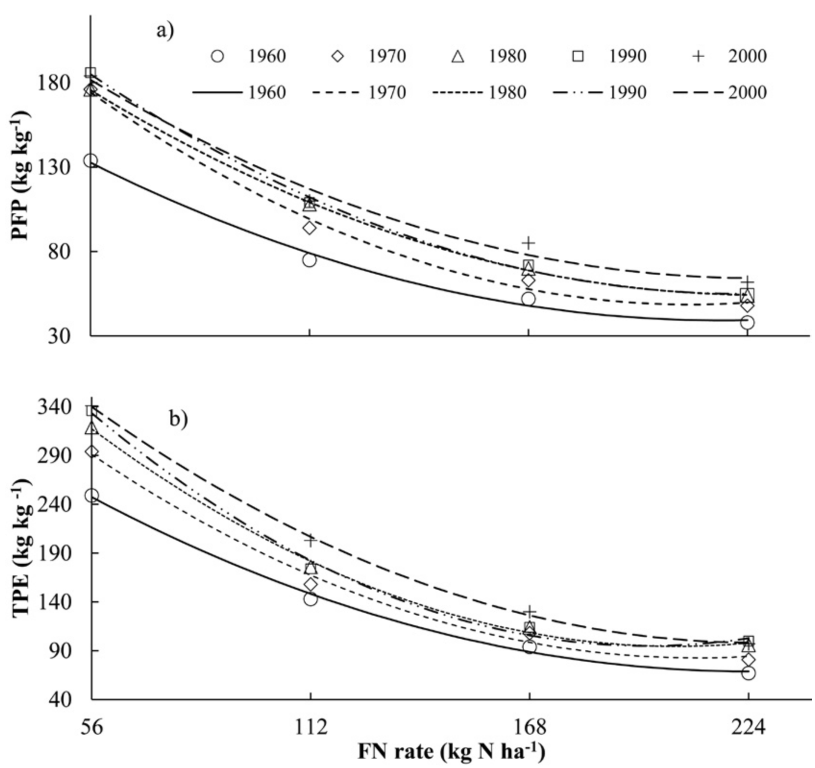

Fig. 3. Interaction of era hybrid by fertilizer nitrogen (FN) rate for (a) partial factor productivity (PFP) and (b) total production efficiency (TPE). The interaction is based on statistical analysis presented in Table 7 and regression parameters in Table 8.

Table 9. Aboveground total corn plant biomass, corn grain yield (GY), total plant nitrogen uptake (PNU), harvest index (HI), partial factor productivity (PFP), total production efficiency (TPE), grain nitrogen harvest index (GNHI), system efficiency (SYE), internal efficiency (IE), grain N, grain nitrogen use (GNU), and grain nitrogen concentration (GNC) for two hybrids in each era at 168 kg N ha^{-1}. Grain components measured only for 1960 and 2000 eras.

	Era					
Parameter	1960	1970	1980	1990	2000	$P > F$
Total plant biomass, Mg ha^{-1}	14.8d†	18.2c	18.5bc	20.2b	22.3a	<0.001
GY, Mg ha^{-1}	8.4e	10.3d	11.2c	12.6b	14.1a	<0.001
Total PNU at R6, kg ha^{-1}	178b	169b	161b	163b	213a	<0.001
Fraction of total R6 PNU at R1, %	77a	74a	77a	71a	68a	0.327
HI	0.49a	0.49a	0.52a	0.53a	0.54a	0.138
PFP, kg kg^{-1} N	50e	62d	67c	75b	84a	<0.001
TPE, kg kg^{-1} N	89d	108c	110c	120b	133a	<0.001
GNHI	0.71a	–	–	–	0.73a	0.314
SYE, %	75b	–	–	–	92a	<0.001
IE, kg kg^{-1} N	48d	63c	72b	79a	66bc	<0.001
Grain N, kg ha^{-1}	127b	–	–	–	155a	<0.001
GNU, kg kg^{-1} N	58b	–	–	–	80a	0.008
GNC, g kg^{-1}‡	1.61a	–	–	–	1.23b	<0.001

† Means in each row (measurement) followed by the same letter are not significantly different ($P \leq 0.10$).
‡ DM basis.

was the same for all eras, but GY was lower for the 1960 era than all other eras, which were not different. Not only did GY increase across time with hybrid development, but also GY response to agronomic optimal N application. Across eras, there was a linear increase in YAONR (0.13 Mg ha^{-1} yr^{-1}) and GY N response (0.09 Mg ha^{-1} yr^{-1}), indicating considerable genetic gain in GY and GY response to applied N across the 50-yr period. There was no consistent trend in AONR across the eras, with the highest AONR for the 2000 era (171, 127, 151, 150, 228 kg N ha^{-1}, respectively, for the 1960, 1970, 1980, 1990, and 2000 eras). The 1960 era hybrid had the second highest AONR despite having the lowest GY and N response. Interestingly, the 1980 and 1990 era hybrids had the same total plant biomass, PNU, response to N, and AONR.

The recently developed techniques to monitor plant N status and canopy response, SPAD meter and active canopy sensing, did not reflect the interactive effect between era and N rate. Sensing index values and SPAD readings had typical increasing values with increasing N rate and plateau values that indicated maximum canopy N response. Among eras, SPAD readings decreased slightly with more recent eras, but canopy sensing Chl and NDVI index values increased from the oldest to most recent eras. The canopy sensing results are likely due to greater plant biomass production from the oldest to most recent era, but could also be due to differences in hybrid leaf architecture, growth rate, and expression of N status.

Nitrogen use efficiency measures related to plant biomass and GY, as typically found, decreased with increasing N rate. All NUE measures increased across the 1960 to 2000 eras, indicating a considerable advancement in corn hybrid ability to use applied N to produce plant biomass and grain. The apparent NRE for N rates nearest the AONR of each era, however, were not highest for the most recent eras. As was found for total plant biomass, PNU, response to N, and AONR, the 1980 and 1990 era hybrids had the same values for all NUE measures. The PFP and TPE efficiency measures were lowest for the 1960 era across all N rates. For TPE, differences in values (1970–2000 eras) were greatest with the low N rates, and little difference with the high N rates, but the opposite for PFP where differences were greatest at the high N rates. Therefore, TPE would be more discerning of hybrid differences at deficient N rates than PFP, but PFP would be more discerning at N rates near optimum.

Hybrid characteristics, such as HI, GNHI, and fraction of total PNU accumulated by R1 were not different between the 1960 and 2000 eras. However, the GNC was 24% lower for the 2000 era compared to the 1960 era. This GNC decrease has important implications for estimation of corn N use and NUE as the decrease in GNC can result in lower than expected grain N removal with harvest despite genetic GY or NUE improvement across time. Although NUE efficiency increased with hybrid development, there was no trend in AONR across eras.

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