Relationship between Grain Crop Yield Potential and Nitrogen Response

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ABSTRACT

The relationship between yield potential and N response in long-term cereal production is not well known. The objective of this study was to evaluate the relationship between yield potential (yield level) and N responsiveness in long-term winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) field experiments in Stillwater, OK (53 yr), Altus, OK (two trials, 45 yr each), Arlington, WI (49 yr), Shelton, NE (11 yr), Nashua, IA (32 yr), and Kanawha, IA (26 yr). Nitrogen responsiveness or the response index (RI) was determined by dividing the actual grain yield from high N rate plots by the yield from either the 0-N fertilizer check (RI 0-N) or medium N rate plots (RI mid-N). Linear relationships between maximum yield, RI 0-N, RI mid-N, and year were thus examined. For the seven long-term trials comprising 261 yr of site data, yield and N responsiveness were not related whether or not a medium N rate or the check plot (0-N) was used to determine RI. Because yield level and N responsiveness are independent, and both impact N demand, using both should assist in formulating more accurate fertilizer N recommendations.

If a nutrient is deficient, that deficiency should be expressed both as a function of intensity (severity of the deficiency) and capacity (total demand). Liebig's law of the minimum states that the nutrient present in the least relative amount is the limiting nutrient (Bray, 1954). Bray (1954) interpreted Liebig's law of the minimum to mean that yield would be directly proportional to the amount of deficient nutrient present and the crop content of that nutrient. Stanford (1973) reported that optimum use of N included the N requirement of the crop at an expected level of yield, the amount of N mineralized during the season, the amount of residual N present early in the season, and the expected efficiency of the N to be applied. Stanford (1973) concluded that the validity of N fertilizer predictions depend on realistic estimates of yield, efficiency, and residual mineral N supply.

Importance of Grain Yield Potential for Making Nitrogen Recommendations

Unless otherwise indicated, "yield" used in this paper is in reference to grain yield for predominantly maize and wheat data that are included in this paper. Research in the Netherlands by Spiertz and De Vos (1983) indicated that winter wheat N rate recommendations should be based on the amount of residual soil N and the crop requirement in a given environment, where both components were expected to vary considerably due to environmental conditions. They further reported that an accurate assessment of the potential yield for different growing conditions would improve N fertilizer recommendations. Ying et al. (1998) showed that N requirements increased with increasing yield for high-yield rice (*Oryza sativa* L.) in tropical and subtropical environments. Similar work by Mohammed et al. (2013) reported the need to make N recommendations by year since yield levels at the same N rate changed radically over time. Results from Mullen et al. (2003) were consistent noting the importance of first recognizing yield potential, and that ensuing fertilizer N requirements would depend on the likelihood of obtaining a response. Fowler (2003) noted that N fertilization rates increased when grain protein concentration targets increased for high yield potential wheat varieties. Schepers et al. (1992) suggested that SPAD 502 chlorophyll meter readings may provide a better estimate of potential yield than leaf N concentration. They were the first to compare chlorophyll meter readings from well fertilized rows to those from the test area (precursor to using N-rich strips). This method encouraged having an N reference for local growing conditions (Schepers et al., 1992). Findings by Lory and Scharf (2003) showed that fertilizer recommendations that ignore yield entirely are limited to explaining <50% of the variation in the economic optimum N rate for maize.

Work by Raun et al. (2001) focused on predicting actual wheat grain yield using mid-season spectral measurements. They reported that the normalized difference vegetation index (NDVI) collected from winter wheat at the Feekes 5 growth

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Abbreviations: GDD, growing degree days; MRTN, maximum return to nitrogen; NDVI, normalized difference vegetation index; RI, response index; RI 0-N, grain yield from the high nitrogen rate plot divided by the check or 0-N plot; RI mid-N, grain yield from the high N rate plot divided by the yield from the middle nitrogen rate; SI, sufficiency index.

stage (Large, 1954) divided by the cumulative growing degree days (GDD) could be used to predict final grain yield over various sites and years, where wheat had been planted and sensed at different times. Similar work by Teal et al. (2006) showed that yield potential in maize could be accurately predicted in season with NDVI measurements combined with knowledge of GDD's accumulated from planting to sensing. Fox et al. (1994) noted that chlorophyll meter readings alone could not be used to accurately predict fertilizer N rates for economic optimum yield. Work by Tkachuk, (1969), published the known amounts of N in the grain for the different crops. Using this information, N removal (yield goal multiplied by percent grain N) can be predicted by dividing the amount of N in the grain by the expected use efficiency. This discussion is a reminder that fertilizer N rates have historically been based on the expected grain yield, and that yield goals have been a starting point to determine that level. Nonetheless it is important to note that differing N rates at the same level of wheat grain yield have been reported (Arnall et al., 2009).

Importance of Nitrogen Responsiveness for Making Nitrogen Recommendations

Mullen et al. (2003) reported that the in-season RI based on NDVI sensor readings from a non-N limiting reference area (N-rich strip) divided by NDVI readings from the farmer practice presented a viable method for identifying environments where the potential to respond to N fertilizer exist. Similar research by Varvel et al. (2007) computed a sufficiency index (SI) using chlorophyll meter readings from the farmer practice divided by chlorophyll meter readings from a non-N limiting reference strip. Prior work for maize suggested that SI's lower than 95% indicated an N deficiency thus requiring additional N (Varvel et al., 1997). Research conducted over locations and years in Missouri noted that economically optimum fertilizer N rates vary widely from year to year, field to field, and from place to place within a field (Peter Scharf, personal communication, February 2012). Similarly, Mamo et al. (2003) reported that temporal variations must be considered with site-specific N fertilizer management. Scharf et al. (2005) noted that economically optimal N fertilizer rates for maize were very different between fields and highly variable within fields. Related work by Bundy and Andraski (2004) with winter wheat noted that economic optimum N fertilizer rates over 21 site-years varied significantly, ranging from 0 to 170 kg N ha^{-1}. This research showed that yields at the economically optimum N rates ranged from 2.29 to 5.58 Mg ha^{-1}.

Nitrogen Fertilization Theory

Practices for making fertilizer N rate recommendations vary widely. Over the years, recommendations have predominantly been based on a yield goal established before planting. Research by Dahnke et al. (1988) indicated that the yield goal was the "yield per acre you hope to grow." More recently, North Dakota has based pre-plant N rates on relative historic productivity, either low, medium or high, in one of three main regions within the state where different N rate responses are expected (North Dakota State University, 2009). Other yield goals in the Midwest have been determined by averaging yields from the last 5 yr, and adding 20% to that value (Zhang and Raun, 2006). While problematic, the use of 0.033 kg N kg^{-1} wheat, 0.021 kg N kg^{-1} maize (2 lb N bu^{-1} wheat or 1.2 lb N bu^{-1} maize) is an improvement over what farmers often do (same historical rate, year after year). With adequate soil moisture at planting, Rehm and Schmitt (1989) proposed that it would be prudent to target a 10 to 20% increase over the recent average when selecting a grain yield goal. They also suggested that if soil moisture is limiting, the use of past maximums, and an average may not be the best method for setting a grain yield goal for the ensuing crop. In addition, the use of farm or county averages was not recommended for progressive farmers concerned with high farm profitability (Rehm and Schmitt, 1989). Other researchers in midwestern states report N rate recommendations computed using the cropping system [maize following maize and maize following soybean, *Glycine max* (L.) Merr.], selected regions, and price ratios (Sawyer et al., 2006). At prices of \$1.1 kg^{-1} N and \$0.28 kg^{-1} maize grain (\$0.50 lb^{-1} N, and \$7.00 bu maize), the economic N rate recommendation for Iowa is between 215 and 242 kg N ha^{-1} (192–216 lb N acre^{-1}), and generally lower for Minnesota, Michigan, and Ohio. Iowa State agronomists observed that the flat net return surrounding the N rate at MRTN (maximum return to N) reflects small changes near the optimum N rate, and indicate that choosing an exact N rate was not critical to maximize profit (Sawyer et al., 2006). They also noted that because of a poor relationship between yield and economic optimum N, their regional N rate guideline did not incorporate yield level. In Montana, Dinkins and Jones (2007) recommended subtracting soil NO_3–N (0–61 cm) from the amount of fertilizer N required to attain a specific yield potential. Similarly, Schmitt et al. (2008) recommended subtracting late fall or spring pre-plant soil NO_3–N from the recommended N fertilizer rate derived from a realistic yield goal.

Recently, Raun et al. (2010) observed no relationship between N responsiveness and yield level in three long-term experiments in Nebraska and Oklahoma. Because yield and N responsiveness were independent of one another, and because both affect the demand for fertilizer N, they recommended that estimates of both be combined to calculate realistic in-season N fertilizer rates. Therefore, the objectives of this work were to evaluate additional data coming from long-term studies from maize-producing regions to further examine the concept that yield potential and N responsiveness are unrelated.

MATERIALS AND METHODS

Grain yield data from seven long-term field experiments from Oklahoma, Nebraska, Wisconsin, and Iowa were analyzed (Tables 1 and 2). All long-term trials had plots where N was applied annually at different N rates and a zero-N check. Experiments included in this analysis were long-term dryland wheat plots at Stillwater, OK (Magruder Plots) (Girma et al., 2007b), a long-term irrigated maize study near Shelton, NE (Varvel et al., 2007), a long-term dryland maize trial near Arlington, WI (Bundy et al., 2011), two long-term dryland winter wheat trials near Altus, OK (Exp. 406, Exp. 407) (Raun et al., 1998), and two long-term dryland maize experiments in Iowa (Nashua, IA, NERF or Northeast Research Farm, Kanawha, IA, NIRF or North Central Research Farm) (Mallarino and Ortiz-Torres, 2006). Irrigation was provided as needed with a linear-drive

Table 1. Location, long-term experiment, soil type, year initiated, years included, and crop for added analysis.

Location	Soil, management	Year initiated	Years included (total years)	Crop
Stillwater, OK, Magruder†	Kirkland silt loam	1892	1958–2011 (53)	winter wheat
	fine-mixed thermic Udertic Paleustoll,			
	fall disking, conventional tillage			
Arlington, WI‡	Plano silt loam	1958	1958–2007 (49)	maize
	fine-silty, mixed, mesic, Typic Argiudoll,			
	moldboard plowing in the spring (1958–1983)			
	or fall (1984–2007)			
Altus, OK, Exp. 406§	Tillman-Hollister clay loam	1966	1966–2011 (45)	winter wheat
	fine-mixed, thermic Typic Paleustoll,			
	fall disking, conventional tillage			
Altus, OK, Exp. 407§	Tillman-Hollister clay loam	1966	1966–2011 (45)	winter wheat
	fine-mixed, thermic Typic Paleustoll,			
	fall disking, conventional tillage			
Shelton, NE¶	fine-silty, mixed, mesic, Pachic Haplustoll,	1991	1995–2005 (11)	maize
	residues shredded, spring disking			
Nashua, IA#, NERF††	Kenyon loam	1979	1979–2010 (32)	maize
	fine-loamy, mixed, superactive, mesic Typic Hapludoll,			
	chisel plow in the fall, spring disking			
Kanawha, IA#, NIRF	Webster silty clay loam	1954	1985–2010 (26)	maize
	fine-loamy, mixed, superactive mesic, Typic Endoaquolls,			
	moldboard plowing in the fall, spring disking			

† Girma et al. (2007b).
‡ Bundy and Andraski (2004).
§ Raun et al. (1998).
¶ Varvel et al. (2007).
# Mallarino and Ortiz-Torres (2006).
†† NERF–Northeast Research Farm, NIRF–North-Central Research Farm.

sprinkler system at the Shelton, NE, site (Varvel et al., 2007). All of these long-term trials were not included in the analysis reported by Raun et al. (2010). Each long-term experiment, crop, year initiated, actual years included in the analysis, soil type, and tillage are reported in Table 1. Fertilizer N rates, and sources used in each long-term experiment are included in Table 2. At Stillwater, OK, only years from 1958 to present were included due to changes in yield potential as a function of improved genetics (introduction of semidwarf varieties). At Kanawha, IA, only years since 1985 were included due to previous changes in the N fertilization rates. For the long-term maize trial at Arlington, WI, years were divided into two groups, 1958 to 1983 and 1984 to 2007. These two groups were formed to account for differences in yields due to improved hybrids, higher planting populations (79,000–86,000 plants ha^{-1}) and an increase in the N rate applied. Since 1986, 16 different maize hybrids were used at the Arlington, WI, site (Bundy et al., 2011). For both long-term winter wheat trials at Altus, all years (1966–2011) were included in this analysis.

Table 2. Fertilizer N rate treatments included in each long-term experiment evaluated.†

Location	N Fertilizer rates, kg N/ha	Method of application, source	Experimental design, (reps)
Stillwater, OK, Magruder	High rate 37 (1958–1967)	Broadcast pre-plant, UR‡	unreplicated (1)
	High rate 67 (1968-present)		
Arlington, WI§	Mid-rate 56– 140 (1958–1983)	Injected, AA (1963–1984, 1993–2007)	RCBD (4)
	High rate 112–280 (1958–1983)	Broadcast, UR (1984–1992)	
	Mid-rate 140–168 (1984–2007)		
	High rate 252–280 (1984–2007)¶		
Altus, OK, Exp. 406	Mid-rate 45 (1966-present)	Broadcast pre-plant, AN,#	RCBD (6)
	High rate 179 (1966-present)		
Altus, OK, Exp. 407	Mid-rate 45 (1966-present)	Broadcast pre-plant, AN,#	RCBD (6)
	High rate 90 (1966-present)		
Shelton, NE	High rate 200 (1995–2005)	Broadcast, AN	RCBD (4)
	Mid-rate 100 (1995–2005)		
Nashua, IA, NERF	Mid-rate 90 (1979–2010)	Broadcast, UR, incorporated	RCBD (3)
	High rate 269 (1979–2010)		
Kanawha, IA, NIRF	Mid-rate 90 (1985–2010)	Broadcast, UR, incorporated	RCBD (3)
	High rate 269 (1985–2010)		

† All experiments included a 0-N check.
‡ AA–anhydrous ammonia, AN–ammonium nitrate, UR–urea; RCBD-randomized complete block design.
§ N rates ranged between 56 and 168 (mid-rate) and 112 and 280 (High rate) from 1958 to 2007.
¶ 1984–1992, N as UR.
# Source switched to UR in 1995.

Grain yield from the highest observed treatment yield in any year, was regressed on RI, and on year at all sites. The highest yielding plots were not always from the high N rates, but sometimes found in mid-N rate plots. Because the highest yielding

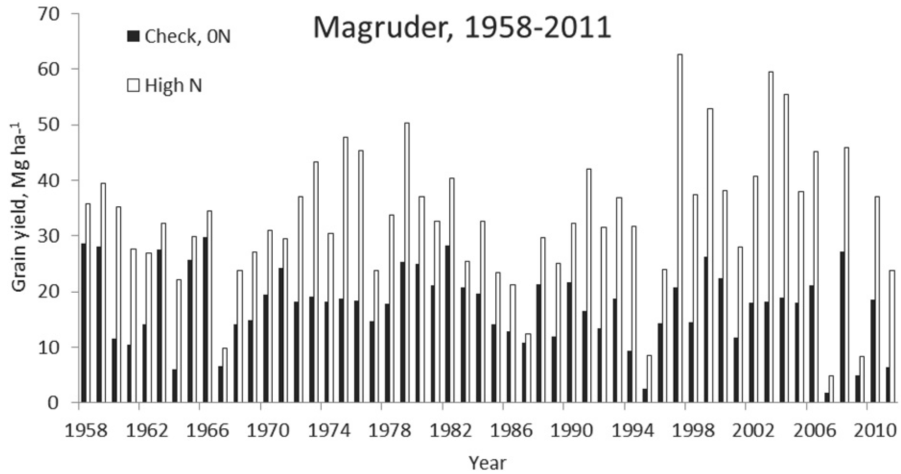

Fig. 1. Winter wheat grain yield response to fertilizer N applied, Stillwater, OK, 1958 to 2011 (Check–no N applied, High–N ranged from 37–67 kg N ha^{-1}).

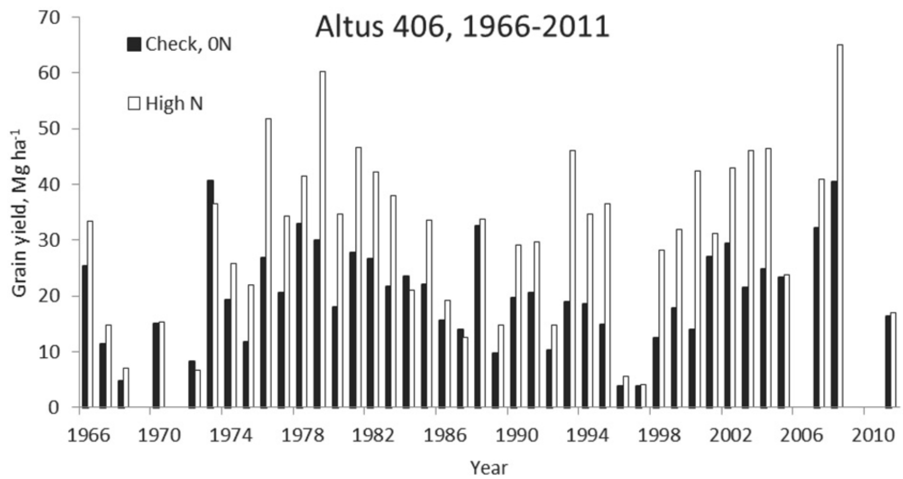

Fig. 2. Winter wheat grain yield response to fertilizer N applied, Exp. 406, Altus, OK, 1966 to 2011 (Check–no N applied, High–N was 179 kg N ha^{-1}).

plot was random in terms of the N, autocorrelation when evaluating yield and N responsiveness was avoided.

The RI was computed using two different methods: grain yield from the high N rate plot divided by the check or 0-N plot (RI 0-N), and grain yield from the high N rate plot divided by the yield from the middle N rate (RI mid-N). The RI 0-N method calculates high values of estimated responsiveness since soil N levels will be continually depleted (check plots receiving no N year after year). Computed N responsiveness using the mid-N rate (RI mid-N) was considered important because it better reflected farmer N fertilizer practices (applying no fertilizer N is not something farmers will do). This second calculation of RI was not included in the Raun et al. (2010) paper. No mid-N rate was included for the non-replicated six treatments from the Stillwater, OK, experiment that was initiated in 1892, thus no computation of RI mid-N was possible. For Altus, OK, Exp. 406; Altus, OK, Exp. 407; Arlington, WI (1958–1983); Arlington, WI (1984–2007); Shelton, NE; Nashua, IA, NERF; and Kanawha, IA, NIRF, the computation of RI mid-N (high N rate, kg ha^{-1}/mid-N rate, kg ha^{-1}) used 180/45, 89/45, (112–280)/(56–140), (252–280)/(140–168), 200/100, 269/90, and 269/90, respectively. Note that the rates were the same at Nashua and Kanawha, IA. For both time periods used for the Arlington, WI, site, the high N rate, or numerator, was always greater than the mid-rate, or denominator for the computation of RI mid-N rate. The linear relationships between grain yield, RI (mid-N and 0-N), and year were evaluated using PROC GLM (SAS Institute, 2008). Linear models with a slope significance of $p > |t| < 0.05$ were considered to be significant.

RESULTS

For all long-term experiments included in this analysis, grain yields over time for the check (0-N) and high N rate plots, are reported for Stillwater, OK, Magruder; Altus, OK, Exp. 406; Altus, OK, Exp. 407; Arlington, WI (1958–1983), Arlington, WI, 1984–2007); Shelton, NE, Nashua, IA, NERF; and Kanawha, IA, NIRF (Fig. 1–8, respectively).

Linear regression models for the relationships between RI (RI mid-N and RI 0-N), grain yield, and year, for Stillwater, OK, Altus, OK, Exp. 406 and Exp. 407; Arlington, WI (1958–1983 and 1984–2007), Shelton, NE; Nashua, IA; and Kanawha, IA, are reported in Table 3. Regression models for grain yield vs. RI mid-N and RI 0-N showed that only 2 of 15 had slope components that were significant ($p > |t| < 0.05$). Coefficients of determination (r^2) values for these same 15 models were all <0.20, and 14 of 15 had r^2 values $\leq$0.09 (Table 3).

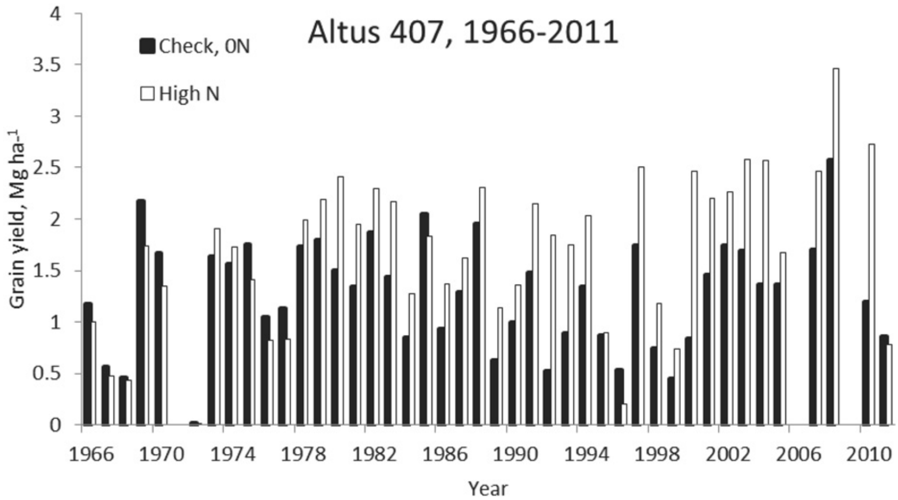

Fig. 3. Winter wheat grain yield response to fertilizer N applied, Exp. 407, Altus, OK, 1966 to 2011 (Check–no N applied, High N was 90 kg N ha^{-1}).

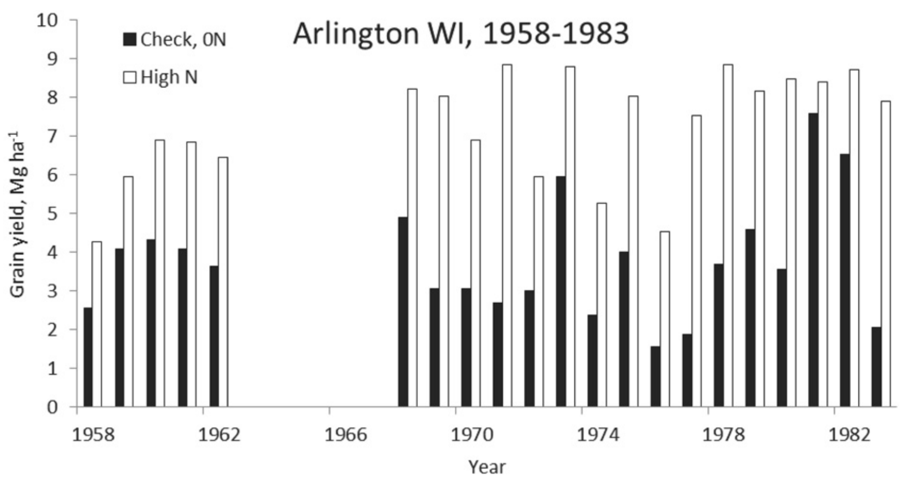

Fig. 4. Maize grain yield response to fertilizer N applied, Arlington, WI, 1958 to 1983 (Check–no N applied, High N ranged from 112–280 kg N ha^{-1}).

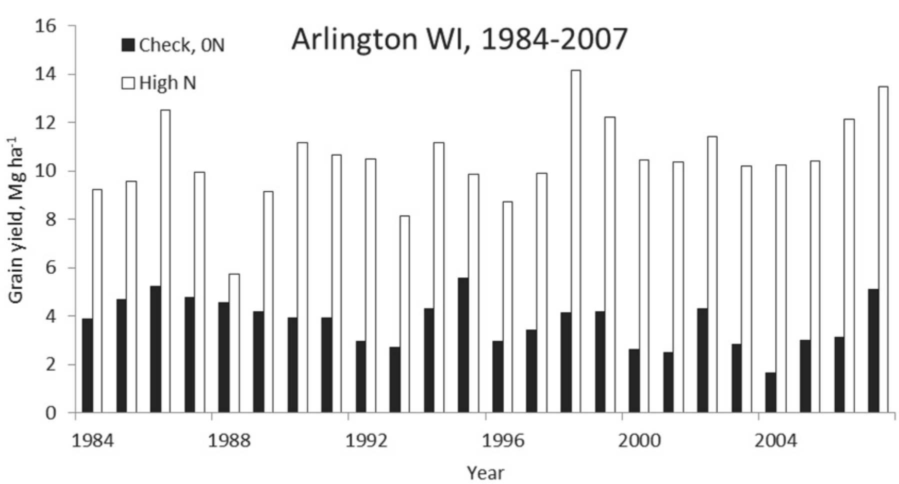

Fig. 5. Maize grain yield response to fertilizer N applied, Arlington, WI, 1984 to 2007 (Check–no N applied, High N ranged from 252–280 kg N ha^{-1}).

Grain yield increased slightly with year in four of the eight data sets ($p > |t| < 0.05$, for slope)(Table 3). Two of these occurred at Arlington, WI, (1958–1983 and 1984–2007) where 16 different improved maize hybrids have been planted since 1986. Similarly, two others occurred in Iowa where improved maize hybrids were periodically introduced. Increased yields with time in the maize trials were expected since genetic yield potentials have increased (Hammer et al., 2009). At the other sites, there was no relationship between grain yield and year (Table 3). With knowledge that improved

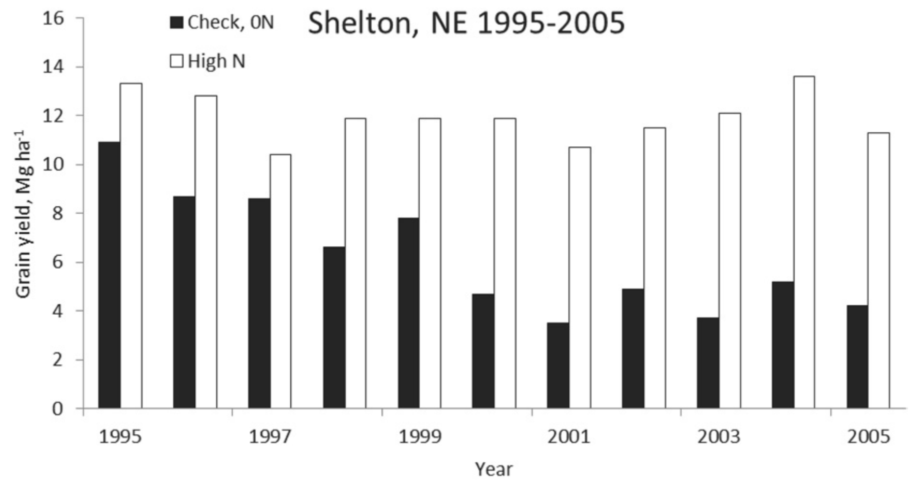

Fig. 6. Maize grain yield response to fertilizer N applied, Shelton, NE, 1995 to 2005 (Check–no N applied, High N was 200 kg N ha^{-1}).

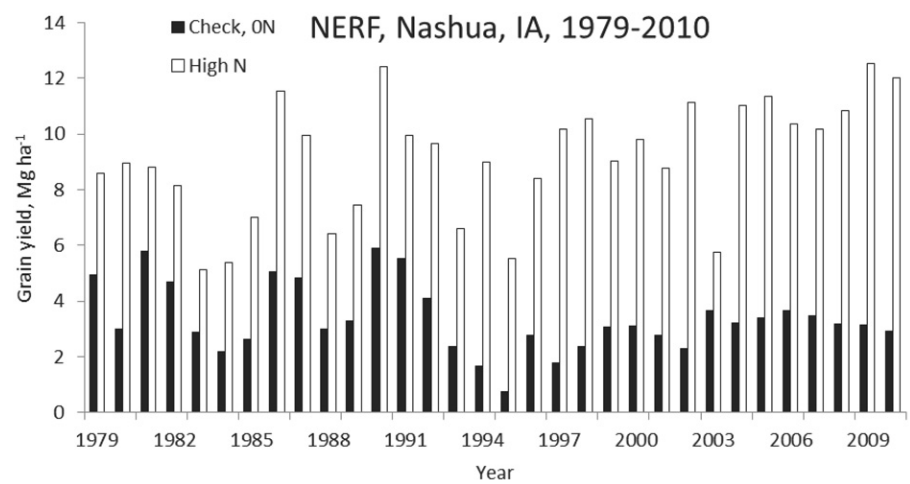

Fig. 7. Maize grain yield response to fertilizer N applied, Nashua, IA, 1979 to 2010 (Check–no N applied, High N was 269 kg N ha^{-1}).

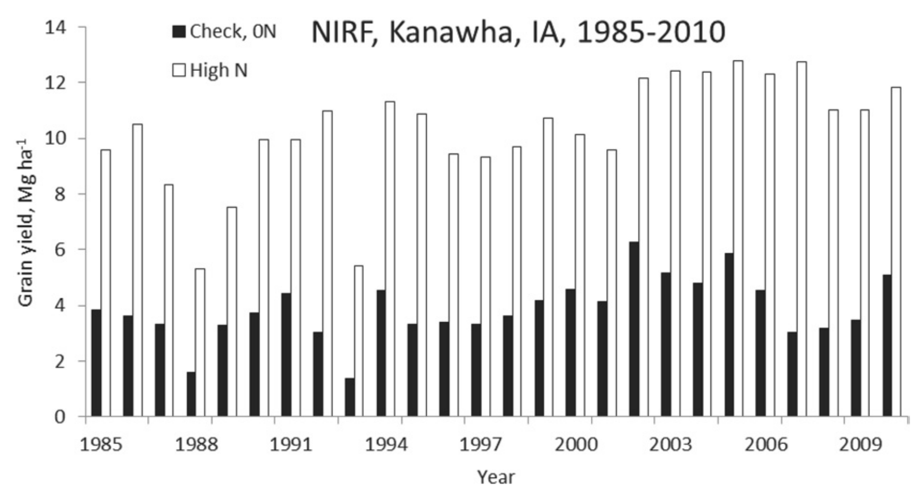

Fig. 8. Maize grain yield response to fertilizer N applied, Kanawha, IA, 1985 to 2010 (Check–no N applied, High N was 269 kg N ha^{-1}).

winter wheat varieties with higher yield potentials were periodically introduced in Exp. 406, Exp. 407, and Stillwater, OK, a positive relationship between year and maximum grain yield was expected. Because this was not observed, it further supports the difficulty in predicting or setting yield goals using data from prior years. It should also be noted that minimum, maximum, and average yields varied widely at all sites (Table 4) and showed no identifiable trend with time.

A significant slope ($p > |t| < 0.05$) between year and RI (RI 0-N and RI mid-N) was observed for 7 of the 15 relationships evaluated (six positive, one negative Table 3). Considering all sites evaluated, no consistent relationship between N responsiveness and year was found. Also, no consistent relationship

Table 3. Linear regression results including r^2, slope and slope significance for the relationships between N response index (RI, determined two different ways), grain yield, and year, for Magruder (winter wheat), Exp. 406 (winter wheat), Exp. 407 (winter wheat), Arlington, WI (maize); Shelton, NE (maize); Nashua, IA (maize); and Kanawha, IA (maize).

	Variables			Slope significance	
Experiment	Independent	Dependent	Slope	$p > \|t\|$†	Model r^2
Stillwater, OK, Magruder	$RI_{0\text{-}N}$‡	grain yield	0.23	0.16	0.04
Altus, OK, Exp. 406	$RI_{0\text{-}N}$	grain yield	0.79	0.08	0.08
Altus, OK, Exp. 407	$RI_{0\text{-}N}$	grain yield	0.59	0.05	0.09
Arlington WI (1958–1983)	$RI_{0\text{-}N}$	grain yield	0.12	0.78	0.01
Arlington WI (1984–2007)	$RI_{0\text{-}N}$	grain yield	1.11	0.03	0.2
Shelton, NE	$RI_{0\text{-}N}$	grain yield	–0.22	0.61	0.03
Nashua, IA, NERF§	$RI_{0\text{-}N}$	grain yield	0.17	0.52	0.01
Kanawha, IA, NIRF	$RI_{0\text{-}N}$	grain yield	–0.72	0.3	0.04
Stillwater, OK, Magruder	$RI_{mid\text{-}N}$¶	grain yield	–#	–	–
Altus, OK, Exp. 406	$RI_{mid\text{-}N}$	grain yield	1.01	0.37	0.02
Altus, OK, Exp. 407	$RI_{mid\text{-}N}$	grain yield	1.57	0.09	0.07
Arlington WI (1958–1983)	$RI_{mid\text{-}N}$	grain yield	–5.5	0.18	0.09
Arlington WI (1984–2007)	$RI_{mid\text{-}N}$	grain yield	–0.51	0.94	0.01
Shelton, NE	$RI_{mid\text{-}N}$	grain yield	–1.19	0.77	0.01
Nashua, IA, NERF	$RI_{mid\text{-}N}$	grain yield	2.79	0.07	0.11
Kanawha, IA, NIRF	$RI_{mid\text{-}N}$	grain yield	–2.72	0.24	0.06
Stillwater, OK, Magruder	Year	grain yield	0.01	0.13	0.04
Altus, OK, Exp. 406	Year	grain yield	0.01	0.32	0.03
Altus, OK, Exp. 407	Year	grain yield	0.01	0.12	0.06
Arlington WI (1958–1983)	Year	grain yield	0.10	0.01	0.30
Arlington WI (1984–2007)	Year	grain yield	0.13	0.01	0.26
Shelton, NE	Year	grain yield	–0.04	0.66	0.02
Nashua, IA, NERF	Year	grain yield	0.11	0.01	0.23
Kanawha, IA, NIRF	Year	grain yield	0.17	0.01	0.41
Stillwater, OK, Magruder	Year	$RI_{0\text{-}N}$	0.01	0.10	0.05
Altus, OK, Exp. 406	Year	$RI_{0\text{-}N}$	0.01	0.18	0.05
Altus, OK, Exp. 407	Year	$RI_{0\text{-}N}$	0.01	0.01	0.24
Arlington WI (1958–1983)	Year	$RI_{0\text{-}N}$	0.03	0.12	0.12
Arlington WI (1984–2007)	Year	$RI_{0\text{-}N}$	0.07	0.01	0.41
Shelton, NE	Year	$RI_{0\text{-}N}$	0.19	0.01	0.71
Nashua, IA, NERF	Year	$RI_{0\text{-}N}$	0.05	0.04	0.14
Kanawha, IA, NIRF	Year	$RI_{0\text{-}N}$	0.01	0.92	0.01
Stillwater, OK, Magruder	Year	$RI_{mid\text{-}N}$	–	–	–
Altus, OK, Exp. 406	Year	$RI_{mid\text{-}N}$	0.01	0.35	0.02
Altus, OK, Exp. 407	Year	$RI_{mid\text{-}N}$	–0.01	0.62	0.01
Arlington WI (1958–1983)	Year	$RI_{mid\text{-}N}$	–0.01	0.46	0.03
Arlington WI (1984–2007)	Year	$RI_{mid\text{-}N}$	–0.01	0.04	0.18
Shelton, NE	Year	$RI_{mid\text{-}N}$	0.02	0.01	0.76
Nashua, IA, NERF	Year	$RI_{mid\text{-}N}$	0.01	0.03	0.15
Kanawha, IA, NIRF	Year	$RI_{mid\text{-}N}$	–0.01	0.92	0.01

† $p > |t|$- probability of obtaining a greater absolute value of t.
‡ $RI_{0\text{-}N}$ determined by using the check plot (0-N) as the denominator.
§ NERF–Northeast Research Farm, NIRF–North-Central Research Farm.
¶ $RI_{mid\text{-}N}$ determined using a low or moderate N rate treatment as the denominator.
# No mid-N rate available for Magruder.

between N responsiveness and grain yield could be established when wheat (143 yr) and maize (118 yr) were evaluated separately (Fig. 9 and 10).

DISCUSSION

Raun et al. (2010) demonstrated that grain yield levels (yield potential) for maize and wheat were independent of N responsiveness or RI. This was the product from analysis of two long-term winter wheat experiments and one long-term maize experiment in Oklahoma and Nebraska, respectively. They concluded that, because yield potential and N responsiveness were not related, both should be used to calculate mid-season fertilizer N rate recommendations. Earlier research by Raun et al. (2002) showed that mid-season N rates based on estimated yields and N responsiveness increased NUE by more than 15%. Also, Tubana et al. (2008) showed that estimated maize

Table 4. Range, mean, standard deviation, and CV for grain yield and N response index (RI, determined two different ways), for the Magruder plots (winter wheat), Exp. 406 (winter wheat), Exp. 407 (winter wheat), Arlington, WI (maize); Shelton, NE (maize); Nashua, IA (maize); and Kanawha, IA (maize).

Experiment	Variable	Range Min.	Range Max.	Mean	SD	CV
				— Mg ha^{-1} —		%
Stillwater, OK, Magruder	RI $_{0\text{-N}}$†	0.94	3.58	1.79	0.65	36
Altus, OK, Exp. 406	RI $_{0\text{-N}}$	0.8	2.56	1.47	0.35	24
Altus, OK, Exp. 407	RI $_{0\text{-N}}$	0.77	2.48	1.3	0.38	29
Arlington WI (1958–1983)	RI $_{0\text{-N}}$	1.11	4	2.16	0.79	37
Arlington WI (1984–2007)	RI $_{0\text{-N}}$	1.26	4.12	2.84	0.73	25
Shelton, NE	RI $_{0\text{-N}}$	1.21	3.27	2.15	0.74	34
Nashua, IA, NERF‡	RI $_{0\text{-N}}$	1.06	7.34	3	1.38	46
Kanawha, IA, NIRF	RI $_{0\text{-N}}$	1.93	4.18	2.77	0.56	20
Stillwater, OK, Magruder	RI $_{\text{mid-N}}$§	–	–	–	–	–
Altus, OK, Exp. 406	RI $_{\text{mid-N}}$	0.62	1.45	1.01	0.14	14
Altus, OK, Exp. 407	RI $_{\text{mid-N}}$	0.8	1.4	1.05	0.12	12
Arlington WI (1958–1983)	RI $_{\text{mid-N}}$	0.93	1.25	1.07	0.08	7
Arlington WI (1984–2007)	RI $_{\text{mid-N}}$	0.92	1.1	1	0.05	5
Shelton, NE	RI $_{\text{mid-N}}$	1	1.23	1.1	0.08	7
Nashua, IA, NERF	RI $_{\text{mid-N}}$	0.95	2.05	1.32	0.24	18
Kanawha, IA, NIRF	RI $_{\text{mid-N}}$	1.09	1.73	1.35	0.17	13
Stillwater, OK, Magruder	Yield	0.62	4.38	2.54	0.78	31
Altus, OK, Exp. 406	Yield	0.34	4.62	2.36	1.02	43
Altus, OK, Exp. 407	Yield	0.57	3.8	2.12	0.76	36
Arlington WI (1958–1983)	Yield	4.26	8.97	7.34	1.47	20
Arlington WI (1984–2007)	Yield	6.13	14.14	10.68	1.82	17
Shelton, NE	Yield	10.6	13.6	11.98	0.98	8
Nashua, IA, NERF	Yield	5.11	12.53	9.14	2.11	23
Kanawha, IA, NIRF	Yield	5.3	12.78	10.28	1.98	19

† RI $_{0\text{-N}}$ determined by using the check plot (0-N) as the denominator.
‡ NERF–Northeast Research Farm, NIRF–North-Central Research Farm.
§ RI $_{\text{mid-N}}$ determined using a low or moderate N rate treatment as the denominator. No mid-rate available for Magruder.

yield potential and N responsiveness were needed to arrive at accurate mid-season fertilizer N rates. A modified algorithm for spring wheat using both predicted yield and N responsiveness were also used in Sonora, Mexico, to determine in-season N rates for 13 on-farm trials (Ortiz-Monasterio and Raun, 2007). Using this approach, they increased farmer profits by US$56 ha^{-1} when averaged over all sites.

The biological reasons that would explain why yield potential and N responsiveness are independent of one another include knowing that there are wetter than normal years when yield levels are high, but where limited N response to fertilizer has been reported (Raun et al., 2009; Raun and Johnson, 1999). Similarly, finding large increases in yield from applied N in mild/dry years is not unusual (Girma et al., 2007a). The unpredictable nature of the environment was evident at Arlington, WI, where the check plot yielded 5.6 Mg ha^{-1} in 1995. Considering that no N had been applied for 37 yr, it was somewhat surprising to find a yield level almost 60% of the highest yield observed in 1995 (9.5 Mg ha^{-1}) (Fig. 5). Without exception, near maximum yields were randomly observed in check plots having received no fertilizer N for many years, at all sites (Fig. 1–8).

The influence of environment on N demand is variable and unpredictable. A consequence of unpredictable weather effects on crop requirements has been to use reference plots (high N rates) and crop sensing before in-season N application (Tremblay and Belec, 2006). This is then bound to the understanding that weather (particularly rainfall in dryland crop producing areas) is the primary driver of both plant growth and soil nutrient availability, and that weather changes dramatically year to year. This was in turn reflected in unusually high check plot yields that were randomly observed over time in all seven long-term trials evaluated. Specifically for this work, this was further expressed in the random nature of N response (estimated using RI) over time and that was observed in each long-term experiment (Fig. 1–8).

We believe that yield potential and N responsiveness are important as has been argued by several agronomic researchers and that both should thus be considered when making fertilizer N rate recommendations. Use of either alone would likely lead to less accurate estimates. Numerous research articles have shown that yield potential impacts N demand (Cassman et al., 2002; Tilman et al., 2002). If increased grain yields are expected at higher N rates, demand at some point must be proportional to rate (if deficient). Weather clearly influences the demand for fertilizer N from year to year, and optimum N rates change from year to year, at the same yield level. Ample research shows that optimum N rates for cereal production do indeed change year to year, and by amounts that are highly significant (Scharf et al., 2005; Bundy and Andraski, 2004), and this is fundamental to our understanding of why N demand is temporally dependent.

Some have argued that determining N responsiveness using the high N plot yield divided by the 0-N check plot yield could result in overestimating N responsiveness that might be encountered in producer fields. This argument is specious. In fact, the zero N rate is specific to each field, year, and farmer fertilizer practice. Even in a 0-N check plot, all fields will possess some level of N fertility. The RI is the ratio of grain yield for that level of fertility (0-N or mid-N) and the yield where N is non-limiting. Optimum N rates would then be a function of the RI and potential yield for that specific field, year, fertilizer practice, and all the other agronomic factors affecting yield. To better reflect what changing N responsiveness would be encountered by a producer, the mid-N rate was also analyzed as the denominator for the computation of RI. As noted earlier, farmers would not have a 0-N reference plot since they will always apply N unless in a legume–cereal rotation. Nonetheless, even using a mid-N rate to compute RI, no relationship between grain yield and RI mid-N was found at any site (Table 3) or when analyzed by crop (over sites, Fig. 9 and 10). In fact, the relationship between yield level and N responsiveness was worse using the mid-N rate as the divisor when computing RI (Fig. 9 and 10).

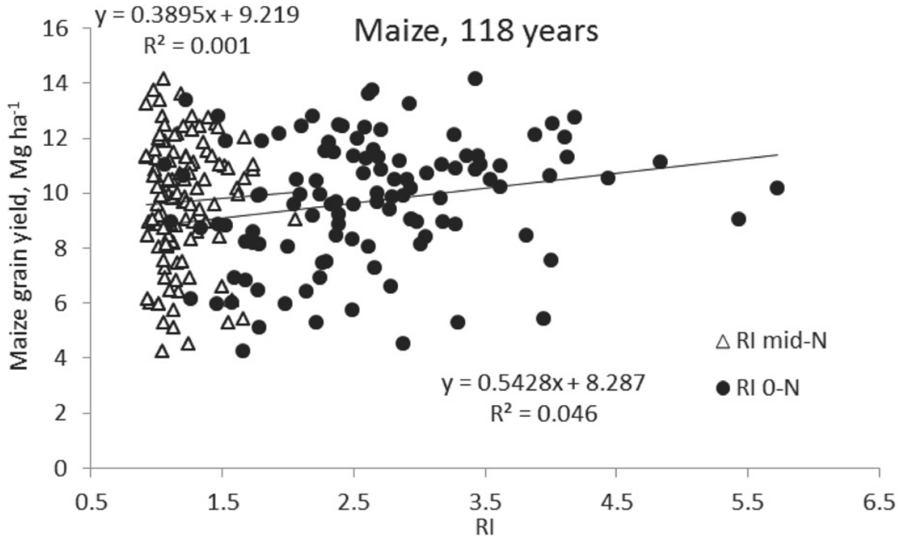

Fig. 9. Relationship between maize grain yield and N response index (RI) for 118 yr of site data from Wisconsin, Nebraska, and Iowa.

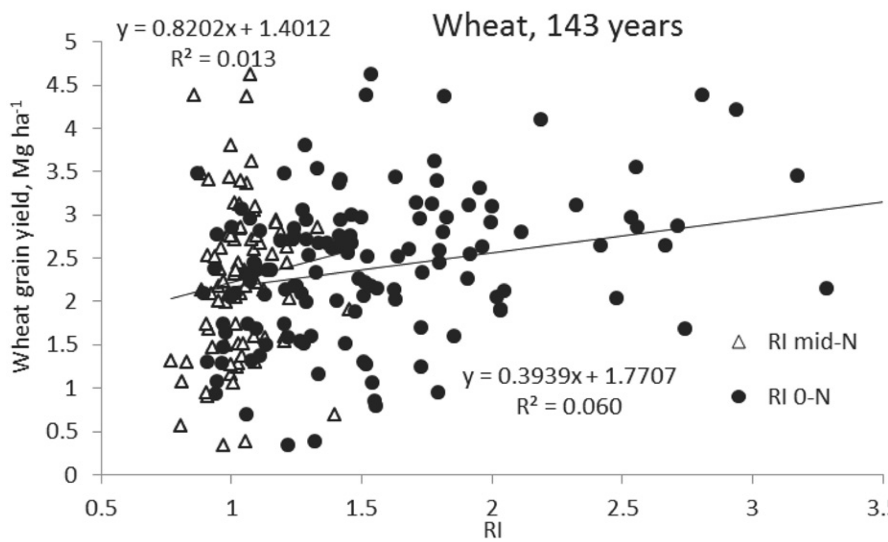

Fig. 10. Relationship between wheat grain yield and N response index (RI) for 143 yr of site data in Oklahoma.

CONCLUSIONS

Nitrogen responsiveness or RI was determined by dividing the grain yield from high N rate plots by the yield from either the 0-N fertilizer check (RI 0-N) or medium N rate plots (RI mid-N). For the seven long-term trials evaluated in this study, yield and N responsiveness were not related whether or not the medium N rate or check plot (0-N) was used to determine N responsiveness. Many research articles reported here show that both N responsiveness and yield potential influence the final demand for fertilizer N. Results from the seven long-term experiments reported in this paper document that N responsiveness and yield potential are independent of one another. These results imply that algorithms for accurate mid-season fertilizer N rates may thus require the inclusion of both potential yield and the RI as independent variables.

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