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REVIEW & INTERPRETATION

Variability in Optimum Nitrogen Rates for Maize

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ABSTRACT

Maize (*Zea mays* L.) grain yield levels and the response to fertilizer nitrogen (N) are expected to change from year to year and from location to location. Because yield level and N response have been documented to be independent and are known to influence N demand, optimum N rates at the same location vary each year due to unpredictable changes in the environment. The objective of this study was to further analyze maize grain yield levels and optimum fertilizer N rates from published data in maize growing regions of the United States. Optimum N rates were determined by calculating the difference in N uptake between the highest-yielding plot and the check plot (no N applied [0-N]). The difference in grain N uptake between the fertilized plot and the 0-N check plot was then divided by 0.33 (the assumed average N use efficiency) to estimate optimum N rate by site and year. For the 213 site-years of data included in this study, grain yields in both the high N rate and check (0-N) plots were highly variable. Optimum N rates fluctuated from year to year at all locations. Optimum N rates were not highly correlated with the high–N rate yield (R^2 = 0.20) or 0-N check yield (R^2 = 0.16). The wide range in optimum N rates observed in all maize experiments suggests the need to adjust N rates by year and location. A potential solution is to use midseason sensor-based technologies that can accurately predict yield potential and simultaneously encumber N responsiveness known to be independent of yield.

Core Ideas

- Optimum fertilizer nitrogen rates for maize are highly variable.
- Demand for fertilizer nitrogen changes year to year.
- Yield level and nitrogen responsiveness are independent.
- Nitrogen use efficiency can improve by changing N rates every year.
- In-season sensor based N management can optimize fertilizer nitrogen rates.

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Nitrogen (N) fertilizer is an expensive input and is often needed to maximize grain crop yields. The increased area under maize production has led to increased prices and accelerated use of N fertilizer. Bundy et al. (1999) reported that 3.6 million t of N fertilizer were applied annually for maize production in 12 states within the northcentral United States, at a cost of 600 to 800 million USD. This estimate excluded N from manure and legumes used in crop rotations. The total N fertilizer used by 15 US States for maize in 2014 rose to 5 million t of fertilizer at an estimated cost of \$500 Mg^{-1} or 2.5 billion USD for 36.6 million ha (USDA–NASS, 2015a). Snyder (2012) documented that US maize consumes 37 to 51% of the total annual fertilizer N. Over the last 100 yr, maize yield levels have increased nearly eightfold in the United States (Kraatz et al., 2008); this increase is attributed in part to increased fertilizer N use. In 2012, US farmers planted 39.3 million ha of maize (USDA–NASS, 2015b) and produced almost 273 million t of maize grain. Maize production increased to 361 million t in 2014 on a total of 36.6 million ha (USDA–NASS, 2015b). Iowa is the leading US state for maize production, with a total of 5.5 million ha in 2013. In 2010, Iowa accounted for almost 14% of the total maize planted in the United States (Dale et al., 2010).

Keeney and Muller (2000) reported that the US Grain Belt have a large amount of artificially drained soils, a high percentage of total land in agriculture, and the highest N fertilizer rates. More than 30% of the cropland in the Midwest is in need of subsurface drainage to maintain the productivity of poorly drained soils (Kanwar et al., 2005). However, drainage systems serve as a pathway through which nitrate nitrogen (NO_3–N) can be transported to streams and rivers (Cooper, 1993). Nitrate-contaminated drainage water from artificial subsurface drainage systems (tiles) is a primary source of NO_3–N loading to surface water within the midwestern United States grain belt (David et al., 1997). In research conducted near central Iowa, Jaynes et al. (2001) documented NO_3–N loss in tile drainage water totaling 48, 35, and 29 kg N ha^{-1} for high (172–202 kg ha^{-1}), medium (114–135 kg ha^{-1}), and low (57–67 kg ha^{-1}) N fertilizer rates, respectively. Rabalais et al. (1999) suggested that excessive nutrient runoff derived mainly from agricultural land had increased the spread and severity of the hypoxic zone within the Gulf of Mexico. Dale et al. (2010) noted that Illinois,

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Abbreviations: NDVI, normalized difference vegetation index; NUE, nitrogen use efficiency; RI, response index.

Iowa, and Indiana alone produce 15% of the world's maize and soybeans, and these regions have the highest N and P loading, which has led to the hypoxic or "dead zone" in the Gulf of Mexico. Nutrient flow from the Mississippi-Atchafalaya river basin into the Gulf of Mexico determines the size of the seasonal hypoxia zone (Alexander et al., 2008). Further, David et al. (2010) reported the highly productive, tile-drained maize belt from southwestern Minnesota, Indiana, Iowa, Illinois, and Ohio is the greatest contributor of nitrate yield to the Mississippi river. Application of N in excess of that taken up by maize also leads to potential NO_3–N loss to ground water through leaching. Overfertilization may not always result in additional grain yield; instead, it can increase N losses (Raun and Johnson, 1995). Alternatively, lower N rates can lead to decreased economic returns (Scharf and Lory, 2000). Accumulation of residual N occurs as a result of applying a greater rate than necessary to maximize yields (Herron et al., 1971). Over time, soils can become oversupplied with nutrient inputs, especially when nutrient supply exceeds crop removal, resulting in nutrient leaching and runoff (Daniel et al., 1998; Sims, 1998). Several studies have shown that NO_3–N losses continue even with typical N rates (Baker and Johnson, 1981; Kanwar et al., 1988).

Efficient use of N fertilizer has raised concerns in modern crop production systems. Environmental concerns continue to be intertwined with the growing costs of N fertilizer production and use. Accurate N fertilizer rates, along with higher N use efficiency (NUE), remain important for maximizing returns while simultaneously protecting the environment and water quality. Nitrogen use efficiency for maize in the United States has increased more than 30% over the last 20 yr (Fixen and West, 2002). Early ^{15}N work with maize showed that 24.1 and 26.4% of the applied N was accounted for in the grain at N rates of 50 and 150 kg N ha^{-1}, respectively (Olson, 1980). Similar studies by Wienhold et al. (1995) reported that maize grain use of N applied averaged 35%. Cassman et al. (2002) noted that N recovery efficiency (RE_N) described N use and reported this value at 37% for the northcentral United States for maize grown in different rotations. Using global statistics from the Food and Agriculture Organization, Raun and Johnson (1999) found average NUE for worldwide cereal production to be 33%. An increase of 1% in global NUE for cereal production could save 234 million USD worldwide (Raun and Johnson, 1999). Added work from this group found that NUE could be improved by 15% when N fertilization was based on optically sensed in-season estimated grain yield (Raun et al., 2002). Related research from Dobermann (2005) calculated average partial factor productivity for NUE in cereal production to be 44%.

Ideal nutrient management would provide a balance between nutrient input and output over longer periods of time (Bacon et al., 1990). Several factors affect grain yield, such as growing season, soil fertility, soil moisture, and environmental changes year to year. This implies that accurate N rate recommendations should have a reliable estimate of those parameters that affect maize grain yield and/or that have a negative environmental and economic impact.

Determining optimum time, rate, and method of N fertilizer application for maize is crucial to minimize N losses. The synchronization of time of fertilizer application with plant N demand is also important. Fall N application creates a substantial risk of N loss and lower yield. Excess residual NO_3–N in the soil profile in the fall can end up in ground water, especially in humid regions of the United States (Lory et al., 1995). Keeney (1982) recommended the use of ammonium fertilizers and delaying time of application until soil temperatures are 10°C for fall application. Spring-applied N versus fall N can minimize the risk of N loss from the soils and optimize the profitability irrespective of the tillage system (Vetsch and Randall, 2004). Randall et al. (2003) found that on poorly drained Mollisols, the best application time strategies for anhydrous ammonia were fall N with nitrapyrin, spring preplant, and split application.

Nitrogen fertilizer needs for maize vary between fields (Bundy and Andraski, 1995) and within fields (Malzer et al., 1996). Fiez et al. (1995) suggested that the different N response between and within fields was due to spatial and temporal variations in crop demand. The optimum N fertilizer rate changes dramatically from one maize field to the next because it is affected by the complex interactions of spring precipitation, temperature patterns, soil organic matter, and crop development (Scharf, 2001; Scharf et al., 2005).

Research performed over the last few decades has focused on improving N fertilizer rate recommendations (Andraski and Bundy, 2002; Hanway and Dumenil, 1955; Schmitt and Randall, 1994; Vanotti and Bundy, 1994; Varvel et al., 2007). Before 1957, most N rate recommendations were based on soil criteria and crop management. Since 1970, the yield goal approach has been a popular method for maize in the Midwest; it converts the expected yield to N rate recommendations using fixed factors (Fernández et al., 2009). Yield goals are determined from a recent 5-yr crop yield average, increased typically by 10 to 30%, assuring adequate N for above-average growing conditions (Johnson, 1991). Maximum return to N is a procedure for estimating economically optimum N rates. It has been used in the Midwest across the Corn Belt and determines preplant N rates by estimating the yield increase to applied N using current grain and fertilizer prices (Sawyer et al., 2006). This approach provides generalized N rate recommendations over large areas and years. However, it fails to address the issue of year-to-year variability in temperature and rainfall (Shanahan, 2011; Van Es et al., 2006) and does not provide site-year recommendations.

Although optimal N rates can vary substantially within and between fields, most US maize producers apply the same rates to entire farms (Scharf et al., 2005). Limiting application rates is the most important factor in reducing environmental impacts; nonetheless, inappropriate methods and poor timing continue to pose the risk of N loss to the environment (Ribaudo et al., 2012). Additionally, the inability to accurately estimate optimum N rates results in overfertilization for some years and fields and underfertilization in others and a lower NUE (Shanahan, 2011). Consequently, there is a clear need to improve N fertilizer management. Early work from Van Es et al. (2006) noted that accurate estimation of optimum N rates year-to-year and field-to-field remains elusive. Nonetheless, in more recent work, Franzen et al. (2016) report that viable midseason sensor-based options are available for maize and wheat producers in many regions of the world.

In recent years, the use of normalized difference vegetation index (NDVI) crop sensors, such as Greenseeker (Trimble Navigation Ltd., Sunnyvale, CA) and Crop Circle (Holland Scientific, Lincoln, NE), have taken precision agriculture to a different level via the ability to detect N deficiencies and to prescribe environment-specific, mid-season N rates. Sensor-based N rate recommendations can vary spatially and temporally, have been further refined by location and crop (Oklahoma State University, 2016), and are currently available to producers (Franzen et al., 2016). Researchers have studied and validated in-season yield potential prediction using NDVI sensors (Crain et al., 2012; Teal et al., 2006). A very similar approach in Missouri was found to outperform the producer rate for maize (Scharf et al., 2011).

It is critical to understand that yield level and N response are unrelated (Arnall et al., 2013; Raun et al., 2011). Several researchers from the Midwest have substantiated that optimum N demand changes radically year to year and over locations, which is why applying the optimum N rates at the peak crop demand remains challenging. Furthermore, current N management decisions overlook year-to-year weather variations, thus failing to account for soil N mineralized in warm, wet years and ignoring indigenous N supply (Shanahan et al., 2008). Although optimum N rates vary widely, insufficient work is being done to encourage maize growers to apply different N fertilizer rates from one year to the next.

The Gulf of Mexico hypoxic zone reached 15,126 km^2 in 2013 (USEPA, 2014) and is expected to grow with continued nutrient loading rates coming from exceedingly high N fertilization rates in maize. Therefore, it is important to reconsider the common practice of applying the same N rate year after year. Rates of N tailored to temporal and spatial variability would deliver higher economic returns to maize farmers and a sound, sustainable environment. The objective of this work was to document the relationship between maize grain yield levels and optimum N rates over a wide range of locations and years from published literature.

MATERIALS AND METHODS

Grain yield and N fertilizer rate data from five different long-term (>15 yr) and nine short-term (2–7 yr) experiments in maize-growing regions of the United States were analyzed. This information was compiled from published papers and included added analysis. If the percent N in maize grain was reported in the paper, that value was used; if not, the percent maize N grain value was set at 1.2 (Shapiro et al., 2008). The difference in N uptake between the highest-yielding plots and check plots was calculated, and the optimum N rates were computed as:

$$\text{Optimum N rate} = \frac{\left[\text{Yield}\left(\text{high N rate}\right) - \text{Yield}\left(\text{check} 0-\text{N}\right)\right] \times \%\text{grain N}}{\text{NUE average } (0.33)}$$

Yield is expressed as kg ha^{-1} and grain N as a decimal (0.01 = 1%). A fixed NUE value of 33% (0.33) was used to reflect shared findings in cereals and with a derivation coming from a wide range of locations and years (Olson and Swallow, 1984; Raun and Johnson, 1999). Changing this value either higher or lower will result in a predictable bias. For example, an effective NUE of 0.40 would reduce the predicted N rate when compared with 0.33. Using a fixed NUE for these trials when combining over locations and years would likely compress the variability in optimum N rates reported. Other estimates of NUE exist and are in the 30 to 40% range (Cassman et al., 2002; Olson, 1980; Olson and Swallow, 1984). Also, computing NUE by individual site was not possible because grain N concentrations were only reported in a few of the papers included in this work. Optimum N fertilizer rates using 0.33 NUE over the 213 site-years ranged from 0 to 458 kg N ha^{-1}. All primary sources of data, years, range in observed yields, and the predicted optimum N rate for all locations are reported in Table 1. Substantive published research has shown dramatic changes in optimum N rates varying from year to year at the same location (Al-Kaisi and Yin, 2003; Bundy et al., 2011; Eck, 1984; Fenster et al., 1978; Gehl et al., 2005; Ismail et al., 1994; Jokela and Randall, 1989; Mallarino and Ortiz-Torres, 2006; Meisinger et al., 1985; Olson et al., 1986; Peterson and Varvel, 1989; Randall et al., 2003; Rice et al., 1986; Shapiro and Wortmann, 2006; Stecker et al., 1993; Varvel et al., 2007; Vetsch and Randall, 2004; Woodruff et al., 1984). Nonetheless, given the importance of N for both crop production and the environment, no single document addresses the comprehensive nature of the problem or provides realistic and accurate estimates of the present variability in N rate recommendations.

Optimum N rates were calculated for each site-year using the difference in N uptake between the maximum yielding plot and the check plot and assuming a fixed level of fertilizer use efficiency. This permitted including the entire range of experiments, locations, and years. This work further concedes that that NUEs are expected to change for all sites and years; even so, it was essential for by-location and over-site analysis to use an average. Also, the high–N-rate yield and 0-N check yields were plotted against the calculated optimum N rate. The relationship between optimum N rate and grain yield was established using simple linear regression analysis. Regression equations and R^2 values were identified for the high N yield and check plot yield using PROC GLM (SAS Institute, 2011). Published maize grain yield data from long-term (>15 yr) and short-term (2–7 yr) experiments were used for the added analysis included in this study (Table 1). For each trial, the response index (RI) was computed using the high–N-rate yield as the numerator and 0-N check plot (RI 0-N) and medium–N-rate plot (RI Mid-N) as the denominator. The medium-N rate was that rate used in each respective experiment that was at or near the middle of the range of N rates applied. This approach was also used by Arnall et al. (2013). Both RI 0-N and RI Mid-N were plotted as a function of time (Fig. 2–7). The relevance/use of RI and how it has been used over time has been described elsewhere (Arnall et al., 2013; Mullen et al., 2003; Raun et al., 2011). The computed RI, whether based on mid-season NDVI sensor readings (RI_{NDVI}) or determined using harvest data ($RI_{Harvest}$), indicates the actual crop response to additional N within a given year (Mullen et al., 2003). The work of Mullen et al. (2003) further showed that $RI_{Harvest}$ could be predicted using RI_{NDVI}.

Table 1. Maize grain yield for the 0-N treatment (check plot), high-N treatment, and a computed optimum N rate in 26 field experiments that included 198 site years of published data in maize growing regions of the United States 1958–2010.

Source†	Location	Years	Time period	Yield range		Optimum N rate¶			
				0-N‡	High N§	Min.	Max.	Avg.	SD
				——— Mg ha^{-1} ———		——— kg ha^{-1} ———			
Bundy et al. (2011)	WI	21	1958–1983	1.6–7.6	4.3–8.8	50	233	130	53
Bundy et al. (2011)	WI	9	1984–1997	2.7–5.6	5.7–9.96	58	235	179	51
Mallarino and Ortiz-Torres (2006)	IA	20	1979–2003	0.8–5.9	5.1–12.4	81	237	165	49
Mallarino and Ortiz-Torres (2006)	IA	14	1985–2010	1.4–6.2	5.3–12.8	134	239	197	32
Varvel et al. (2007)	NE	5	1995–2005	6.6–10.9	10.4–13.3	73	193	131	49
Jokela and Randall (1989), Carroll	MN	3	1982–1984	5.5–7.3	7.1–9.1	5	131	84	69
Jokela and Randall (1989), Webster	MN	3	1982–1984	1.7–5.6	1.8–8.7	70	113	91	21
Fenster et al. (1978), Waseca	MN	5	1970–1975	3.2–7.4	7.1–10.6	60	199	135	50
Fenster et al. (1978), Martin A	MN	7	1970–1976	3.8–8.2	4.0–9.6	23	126	69	36
Fenster et al. (1978), Martin B	MN	6	1971–1976	6.2–11.3	6.2–12.0	0	37	18	15
Al-Kaisi and Yin (2003)	CO	3	1998–2000	5.6–10.2	8.3–10.8	66	111	91	23
Ismail et al. (1994), NT	KY	20	1998–2000	2.1–7.4	5.2–10.9	35	230	128	46
Ismail et al. (1994), CT	KY	20	1970–1990	1.9–9.5	3.5–10.4	0	203	98	52
Rice et al. (1986), NT	KY	15	1970–1985	3.1–4.9	5.7–9.2	102	178	144	30
Rice et al. (1986), CT	KY	15	1970–1985	1.9–6.1	5.0–8.8	69	204	124	47
Stecker et al. (1993), Columbia	MO	3	1988–1990	3.3–5.6	6.0–10.1	99	194	153	49
Stecker et al. (1993), Novelty	MO	3	1988–1990	4.5–7.2	6.7–9.9	45	182	103	71
Stecker et al. (1993), Corning	MO	2	1989–1990	5.0–6.0	8.2–8.5	90	117	104	20
Peterson and Varvel (1989)	NE	4	1983–1986	2.1–6.4	3.9–10.0	11	218	104	88
Eck (1984)	TX	2	1977–1978	2.7–4.4	5.6–5.9	59	116	88	40
Shapiro and Wortmann (2006), RS 51 cm	NE	3	1996–1998	6.2–8.9	9.4–11.1	69	96	83	13
Shapiro and Wortmann (2006), RS 76 cm	NE	3	1996–1998	5.0–8.9	7.1–11.0	13	114	75	54
Meisinger et al. (1985) MT	MD	4	1974–1977	1.8–2.6	5.8–8.2	127	233	183	45
Meisinger et al. (1985) PT	MD	4	1974–1977	2.7–4.2	5.1–8.1	36	196	142	75
Gehl et al. (2005) Rossville	KS	2	2001–2002	6.4–7.9	11.3–12.6	182	204	193	15
Gehl et al. (2005) Scandia	KS	2	2001–2002	2.7–7.4	3.8–11.5	51	160	105	77
Olson et al. (1986)	NE	15	1969–1983	2.6–9.4	7.3–11.4	90	270	174	79
Total		213							
Average						63	177	122	46
SD						44	55	43	20

† CT, conservation tillage; Martin A, yield data from continuous maize experiment; Martin B, yield data from virgin soil experiment; MT, minimal tillage; NT, no tillage; PT, moldboard plow tillage; RS, row spacing.

‡ Range in the recorded maize grain yields for the check plot where no N was applied.

§ Range in the recorded maize grain yields for the high N rate treatment in each experiment. These high N rates ranged from 1.8 to13.3 Mg ha^{-1}.

¶ Optimum N rates determined by subtracting the yield the check (0N) treatment from the yield in the high N treatment, multiplying by a known N concentration, and dividing by a fixed nitrogen use efficiency (NUE), set at 0.33.

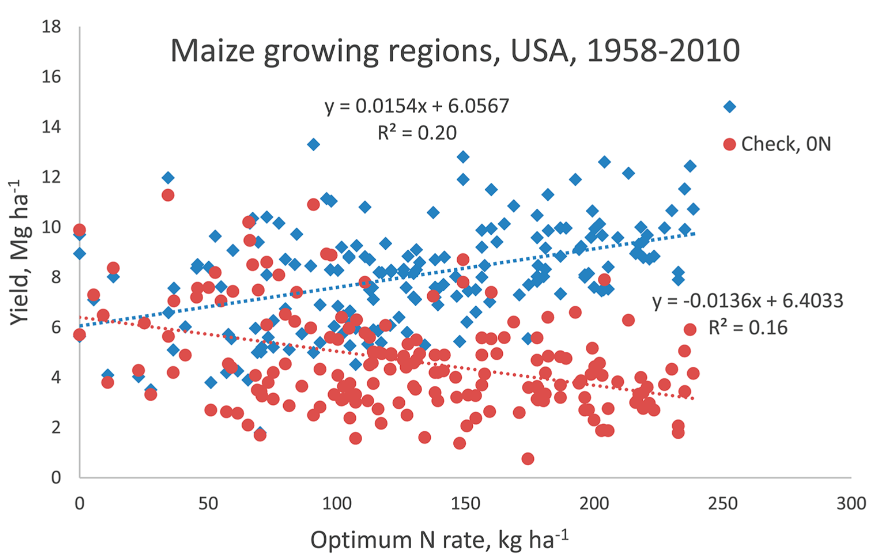

Fig. 1. Relationship between maize grain yield and optimum N rate computed using the 0-N check and the high N rate in maize growing regions of the United States, 1958–2010.

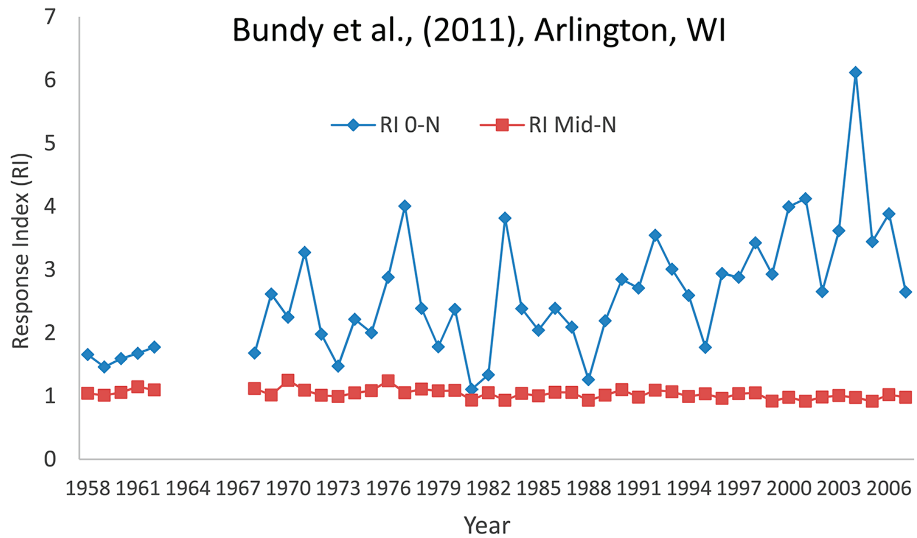

Fig. 2. Nitrogen response index (RI) in a conventional-till experiment over 49 yr, Arlington, WI (RI 0-N determined by dividing high N rate yield by 0-N check; RI Mid-N determined by dividing high–N rate yield by mid–N rate yield).

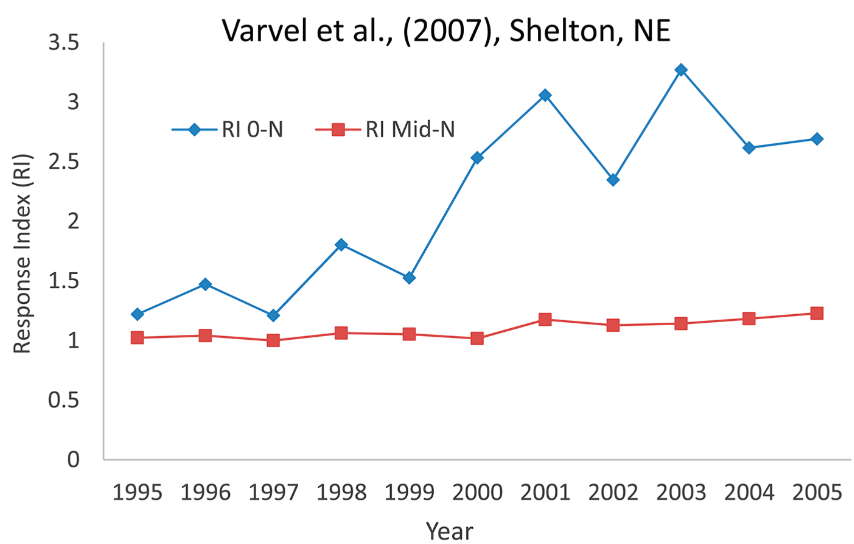

Fig. 3. Nitrogen response index (RI) in a conventional-till maize experiment over 11 yr, Shelton, NE (RI 0-N determined by dividing high–N rate yield by 0-N check; RI Mid-N determined by dividing high–N rate yield by mid–N rate yield).

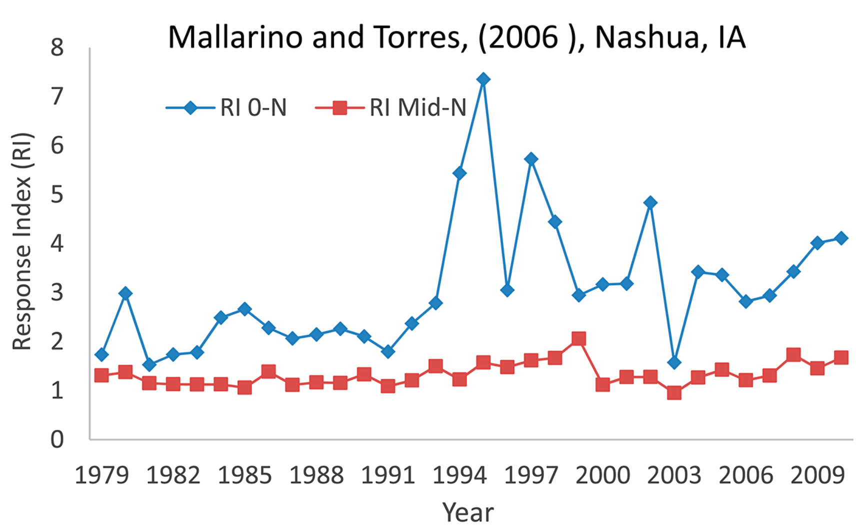

Fig. 4. Nitrogen response index (RI) in a conventional-till maize experiment over 32 yr, Nashua, IA (RI 0-N determined by dividing high–N rate yield by 0-N check; RI Mid-N determined by dividing high–N rate yield by mid–N rate yield).

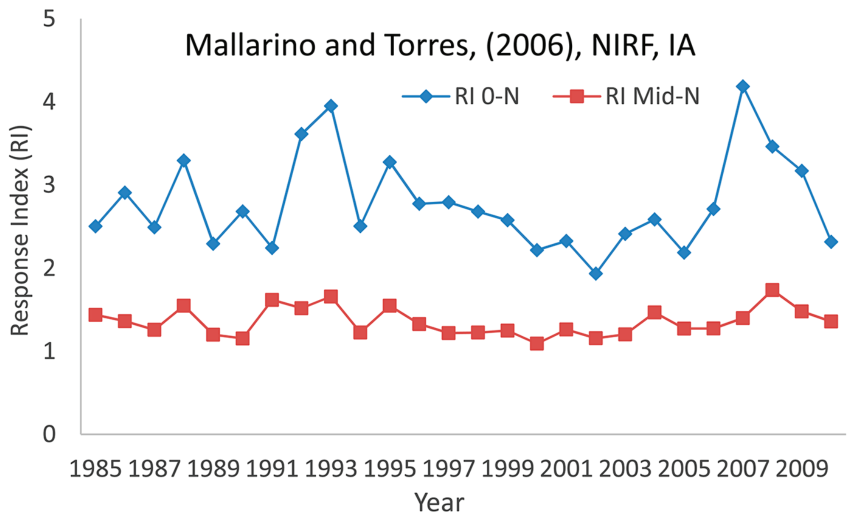

Fig. 5. Nitrogen response index (RI) in a conventional-till maize experiment over 25 yr, NIRF, Kanawha, IA (RI 0-N determined by dividing high–N rate yield by 0-N check; RI Mid-N determined by dividing high–N rate yield by mid N rate yield).

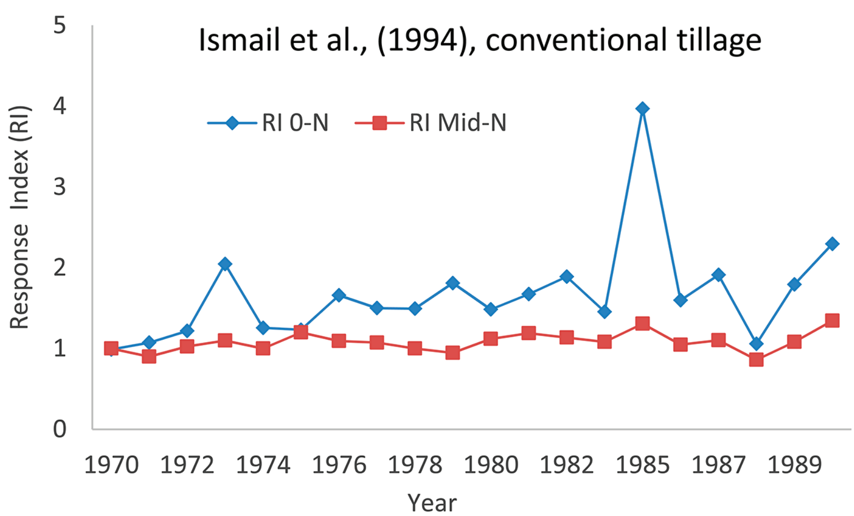

Fig. 6. Nitrogen response index (RI) in a conventional till maize experiment over 20 yr, Lexington, KY (RI 0-N determined by dividing high–N rate yield by 0-N check; RI Mid-N determined by dividing high–N rate yield by mid–N rate yield).

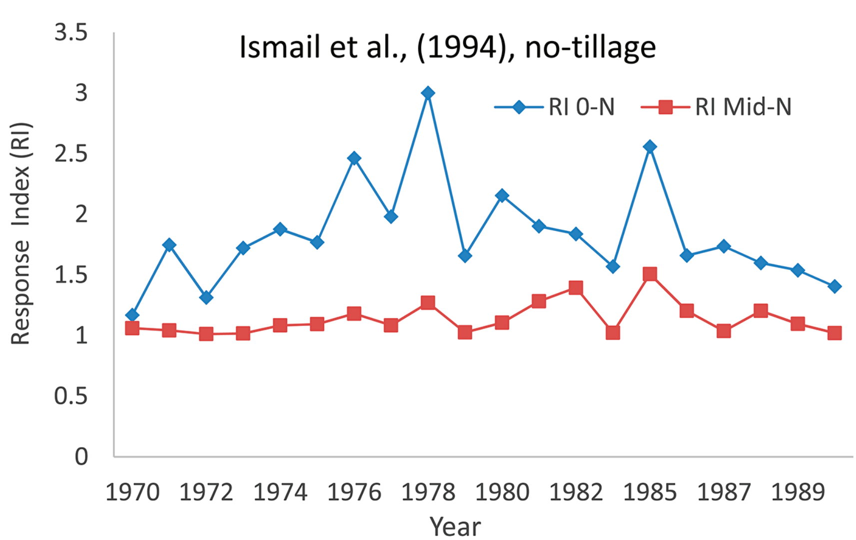

Fig. 7. Nitrogen response index (RI) in a no-tillage maize experiment over 20 yr, Lexington, KY (RI 0-N determined by dividing high–N rate yield by 0-N check; RI Mid-N determined by dividing high–N rate yield by mid–N rate yield).

RESULTS

Yield levels for the check plots (0-N applied) and high–N-rate plots were highly variable at all sites (Table 1). By-site yield ranges in the 0-N check treatment and the high-N treatment were extreme. For one of the long-term trials, yields from the 0-N check ranged from 1.6 to 7.6 Mg ha^{-1}, and yields from the high-N treatment ranged from 4.3 to 8.8 Mg ha^{-1} (Bundy et al. (2011). For the 26 short- and long-term trials, comprising a total of 213 sites years of data, wide yield ranges were common (Table 1). The combined data reported in Table 1 reveal that these maize trials encompassing a wide range of states and climates had highly variable optimum N rates, with an average low of 62 ± 44 kg N ha^{-1} and average high of 173 ± 55 kg N ha^{-1}. The overall average optimum N rate was 120 ± 43 kg N ha^{-1} (Table 1). Using 1 SD from the average optimum N rate computed in this work results in an expected range of 77 to 163 kg N ha^{-1} (the complete database for computed optimum N rates was 0–239 kg N ha^{-1}) (Table 1). Because only maize sites from the United States were included, this is troubling when considering regional publications that do not consider the potential for improved environment-specific recommendations and because they report that there was no clear indication of a change in N rates over time (Sawyer et al., 2006).

Including all site years, optimum N rates were not correlated with the high–N-rate yield and/or the check plot yield (Fig. 1). The calculated R^2 value for optimum–N-rate versus high–N-rate yield and check plot yield was poor (0.20 and 0.16, respectively) (Fig. 1). This was also consistent with the accompanied research articles that document year-to-year variability in optimum N rate. Several optimum N rates in excess of 240 kg N ha^{-1} were treated as outliers and were not included in this analysis. These data, although favorable for a paper highlighting dramatic ranges in optimum N rates, were omitted. Slope and intercept components for high–N-rate yield and check plot yield on optimum N rate were statistically significant ($P_r > |t|$) at the 0.10% level (Fig. 1). As expected, for all long-term experiments, RI 0-N was higher and fluctuated over the years, whereas RI Mid-N was lower and less variable over time (Fig. 2–7).

DISCUSSION

The data included in this paper report year-to-year and by-site variation in grain yield for the high–N-rate and 0-N plots. Factors that affect variable N demand are indirectly linked to yield variability. At some sites, the check plot where no N had ever been applied yielded almost the same as the high–N-rate plot after years of maize production (Wisconsin, 1958, 1959, 1981, and 1982 [Bundy et al., 2011]; Nebraska, 1995 [Varvel et al., 2007]). In fact, some check plots surpassed the yield recorded for the high–N-rate plot (Kentucky, 1970 and 1988 [Ismail et al., 1994]; Martin County, Minnesota, 1971–1976 [Fenster et al., 1978]). The study by Mamo et al. (2003) is one of several documenting temporal variability and resultant maize grain yields. Expected differences in by-site rainfall and temperature contributed to the reported differences in grain yields and by-year and by-site optimum N rates (Table 1). As noted by Leiros et al. (1999), environmental variability can result in higher and lower N mineralization from soil organic matter, which influences N demand. Other reasons for the differing estimates of N response include the actual yield level, which changes from year to year and affects final demand (Gehl et al., 2005). Highly variable levels of atmospheric N deposition from one year to the next (Huang et al., 2016) can also affect N need. Tremblay et al. (2012) suggested that abundant and well-distributed rainfall can increase the N response of corn in fine-textured soil in terms of yield. It is thus not surprising that optimum fertilizer N rates will change from year to year and site to site. By-year soil testing for inorganic soil N is encouraged due to the relationship with changing yield levels (Binford et al., 1992). As such, maize producers should consider the unpredictable weather patterns that affect N mineralization, inorganic N, and the resultant grain/plant N uptake. Fluctuating yields can also be the consequence of variable soil-supplied N across the field and/or spatial variability (Crain et al., 2013; Holland and Schepers, 2010). Several researchers have noted how current N recommendations provide an estimate of how much N to apply but fail to account for soil N and maize N uptake, which can be influenced by in-season weather changes (Scharf et al., 2006; Van Es et al., 2006; Vanotti and Bundy, 1994).

CONCLUSIONS

Yield level and N response contribute to the final optimum N rate. Nonetheless, yield level and N response need to be considered independent of one another before deciphering N rate recommendations for maize. If the same N rates are applied each year, they will not include accurate accounting for variability in soil N and maize N uptake, which are dramatically influenced by the changing growing conditions from one year to the next. Published results coming from an array of sources and from multiple sites and years have revealed extensive variability in optimum N rates for maize that should be reflected in current day N recommendations.

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