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Relationship Between Response Indices Measured In-Season and at Harvest in Winter Wheat

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ABSTRACT

Current methods for making nitrogen (N) recommendations in winter wheat (*Triticum aestivum* L.) do not adjust for in-season temporal variability of plant available non-fertilizer N sources. The purpose of this study was to compare the use of different N response indices determined in-season (RI_{NDVI} and $RI_{PLANTHEIGHT}$) to the N response index measured at harvest ($RI_{HARVEST}$). In addition, this study evaluated the use of the in-season response indices for determining topdress N rates for winter wheat. Nine experiments were conducted over two years at eight different locations. A randomized complete block design with nine different treatments and four replications was used at each location. Preplant N source was ammonia nitrate (34-0-0). At Feekes 4–6, RI_{NDVI} was measured to determine the topdress N rates. Both RI_{NDVI} and $RI_{PLANTHEIGHT}$ were able to predict $RI_{HARVEST}$ ($r^2 = 0.75$ and $r^2 = 0.74$, respectively). Because the sensor-based approach for making N recommendations relies on information obtained from in-season sensor readings, RI_{NDVI} should be used to estimate a site's potential for response to additional N. Use of the response index will allow producers to move away from reliance on preplant application of N and start managing N based on the likelihood of achieving an economical response to N fertilizer.

INTRODUCTION

Common fertility management implemented by producers includes taking a composite soil sample of an area, usually from 2.5 to 160 acres, evaluating

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nitrate (N) in the soil system through a soil test, subtracting this amount from that needed to reach a certain yield goal, and fertilizing that area based on this information. This research aims to look at a new tool that can be used to manage N inputs for hard red winter wheat cropping systems.

After reviewing yield data from a long-term soil fertility research trial in dryland winter wheat, Johnson and Raun (2003) proposed a response index, which measures the plant response to N fertilizer in terms of grain yield in a particular growing season. A response index was calculated by taking the highest yielding fertilized grain plot and dividing by the control yield (0 N applied).

The ability to predict the magnitude at which winter wheat will respond to additional topdress fertilizer during the growing season would provide one way of increasing nitrogen use efficiency (NUE). Furthermore, given the low prices for hard red winter wheat and associated high prices of N fertilizer (due to shortages of natural gas, a key component used to manufacture N fertilizer), wheat producers are looking for methods to cut fertilizer costs and maintain yield levels. A 1% increase in NUE would save approximately $234,658,462 worldwide, while a 20% increase would have savings in excess of $4.7 billion per year (Raun and Johnson, 1999).

In 1999, the United States used more than 11,165,310 Mg of N (FAO, 2001). It is believed that a large portion of environmental pollution from N sources comes from their use in agriculture cropping systems. The pollution results when producers apply excess N to insure against a change in growing conditions where the crop might benefit from the extra N that might otherwise result in reduced yield. Goolsby et al. (2001) reported that the mean annual discharged flux of all forms of N in the Mississippi and Atchafalaya River Basin was 1,568,000 Mt yr^{-1} for the time period 1980–1996. Jaynes et al. (2001) reported in a study of N in tile drainage that even at the lowest N treatment rate (67 kg N ha^{-1}), NO_3—N levels exceeded the maximum contaminant limit of 10 mg NO_3—N L^{-1} set by the U.S. Environmental Protection Agency (USEPA) for drinking water. With these pollution problems, methods for applying N to a cropping system that will increase efficiency and maintain or increase yield while lowering the amount of N contamination in fresh water supplies must be developed by researchers and employed by agriculture producers.

Many scientists have made an effort to predict N mineralization rates throughout the growing season as an indirect indication of potential N response. One such method is a pre-side-dress soil nitrate test (PSNT) (Magdoff et al., 1984). Evanylo and Alley (1997) reported that only 5 out of 17 corn sites in 1990 and 8 out of 30 sites in 1991 responded significantly to a side-dress application of N fertilizer in Virginia. They attributed this insignificant N fertilizer response to amendments made to the soil with organic N sources and low soil test inorganic N. They also noted that prior to soil sampling, the environment may have provided poor conditions for the N mineralization process (heavy leaching rain, cool soils and/or extremely dry or wet soils), although conditions could have improved after the samples were taken.

Methods of visually observing plant conditions are often the only diagnostics used to determine nutrient deficiencies in season. Johnson and Raun (2003) developed a method to assist winter wheat producers in determining in-season response to additional N fertilizer. This method involved installing a strip of N fertilizer that is twice the rate (or non-N-limiting) used during pre-plant fertilization. Implementing this zone allows the producer to quantify visually the likelihood of achieving an in-season response to N fertilizer. If the non-N-limiting strip is not visible to the producer, it would indicate that minimal or no N response is likely since adequate N was already available from pre-plant fertilization, N mineralization, and/or rainfall.

With the further development of optical sensing technology, many researchers have been investigating the possibility of predicting crop yield by light absorbance (Coldwell, 1956; Jorden, 1969; Tucker, 1979; Seller, 1985, 1987; Stone et al., 1996a, 1996b; Shanahan et al., 2001). Ma et al. (1996) reported that canopy light reflectance values at 600 nm (red light) and 800 nm (NIR light), could be used to calculate the normalized difference vegetative index (NDVI). NDVI is defined as [(NIR − RED)/(NIR+RED)] and was found to be strongly correlated with grain yield. This correlation increased up to anthesis. They also stated that NDVI was better at differentiating N treatment effects than any other wave bands and that NDVI was also correlated with leaf area and leaf chlorophyll.

Mullen et al. (2003) reported that computing an in-season response index (RI) from N induced NDVI differences (RI_{NDVI}) at Feekes 5 (1954) over four years taken from 22 locations was well-correlated ($r^2 = 0.56$) with RI measured at harvest ($RI_{HARVEST}$). The RI_{NDVI} was determined by dividing plots that were non-N-limiting by a 0 N check plot. A method for finding a reliable, in-season estimate of the crop's response to additional top-dress N that does not rely on an induced N non-limiting area would be desirable. This method could reliably predict the final response without incurring additional costs of installing a non-N-limiting strip or area, thus improving overall profitability. Work done on the field element size, and the micro-variability of mobile and immobile soil nutrients, illustrates the highly variable nature of soil nutrients (Solie et al., 1999; Raun et al., 1998). Knowing the optical sensor field element size (Solie et al., 1996) for measuring plant N uptake using light reflectance is <1.5 m^2, it may be possible to develop a reliable in-season estimate of RI based on spatial variability (RI_{SV}) of plant available soil N. RI_{SV} is defined by the equation: (mean NDVI + 1 standard error)/(mean NDVI – 1 standard error). The mean and the standard error for NDVI are calculated from all randomly selected field element sizes measured. RI_{SV} can be determined from sensor readings collected anywhere within fields not having the non-N-limiting (N-rich) strip.

Furthermore, a method for producers to measure reliably a site's potential response to additional N without using a sensor to measure RI_{NDVI} needs further evaluation. This non-sensor based in-season RI would be of benefit to farmers in developing countries or a farmer in a developed country who cannot afford a sensor or who is skeptical of its use in a N management scheme. A potential non-sensor based in-season response index could be based on differences in any crop characteristic that responds to N. Crop canopy height ($RI_{PLANTHEIGHT}$) is responsive to N availability and should be a good measure right before making a top-dress N application, which is the same time one would measure RI_{NDVI} with a sensor. $RI_{PLANTHEIGHT}$ would be measured the same way as RI_{NDVI}, (mean plant height of N-rich)/(mean plant height of check). The objectives of this experiment were (1) to determine the relationship between in-season spectral reflectance measured response index (RI) and the RI measured at harvest and (2) to determine the relationship between crop canopy height at the time of application of top-dress N fertilization and RI based on spectral reflectance.

MATERIALS AND METHODS

In the fall of 2001, five short-term winter wheat experiments were established; three of these trials were placed in selected wheat farmers fields in Kingfisher County, Oklahoma, and two at the Stillwater Experiment Station in Stillwater, Oklahoma. In the fall of 2002, three different sites were used in addition to the one at the Efaw upland site. The soils of these eight selected sites are reported in Table 1, along with pre-plant soil test data. Plot management dates, varieties, and harvest information for all sites and years are reported in Tables 2 and 3.

A randomized complete block design was used with nine different N management treatments replicated four times at each site. The treatment structure is provided in Table 4. Plot sizes are 1.52 m × 1.52 m. The NDVI was measured between Feekes growth stages 4–6 (Large, 1954) on all plots in both years. The different N treatments in this study had varied amounts of pre-plant and/or top-dress N applications. The focus of this paper is on Treatment 1 (check, 0 N) and Treatment 8 (90 kg N ha^{-1}) for estimating the in-season response index based on differences of a non-N-limiting area and a check (0 N). Furthermore, Treatments 1–5 (top-dress N only) were used for estimating RI_{SV} before top-dress N was applied.

An RI based on NDVI (RI_{NDVI}) was determined by taking sensor readings in the induced non-N-limiting plots (pre-plant application of 90 kg N ha^{-1}) and dividing by the check treatment (0 N). RI_{SV} was calculated from NDVI readings of Treatments 1–5 using the same NDVI readings taken for calculating top-dress rates using the NFOA algorithms. These treatments had 0 additions of N fertilizer either pre-plant or top-dress when the sensor readings were taken. This allowed for simulation of NDVI readings taken from 20 randomly selected 1.5 m^2 field element sizes in the same field. The NDVI of 20 plots' means (5 treatments × 4 replications = 20) were used to calculate an overall average and a standard error. Thus, RI_{SV} = (overall mean NDVI + 1 standard error)/(overall mean NDVI − 1 standard error).

Table 1
Surface (0–15 cm) soil test data by location for 2001–2003 prior to experiment establishment

	mg kg^{-1}				
Location	NH_4—N	NO_3—N	P	K	pH
2001–2002 crop year sites					
Marshall	8	12	20	273	5.6
Classification: Kirkland silt loam; Fine, mixed, thermic, Vertic Paleustolls					
Hennessey	6	20	35	199	5.5
Classification: Pond Creek silt loam 1–3% slopes; Fine silty, mixed, thermic, Udic Argiustolls					
Kingfisher	6	17	41	292	5.8
Classification: Fine, mixed, thermic, Vertic Paleustolls					
Efaw Upland	8	13	26	164	5.4
Classification: Norge soil series: Fine silty, mixed, thermic Udic Paleustolls					
Efaw Bottom	7	39	36	186	6.3
Classification: Easpur soil series: Fine loamy, mixed, thermic Fluventic Haplustolls					
2002–2003 crop year					
Tipton	5	9	24	324	6.36
Classification: Tipton silt loam: fine loamy, mixed, thermic, Pachic Urgiustoll					
Perkins	3	12	15	146	5.47
Classification: Teller sandy loam: fine loamy, mixed, thermic Udic Argstoll					
Lake Carl Blackwell	3.35	10	18	107	5.28
Classification: Port-oscar: silt loam, fine silty, mixed, super active, thermic Cumulic Haplustolls					

[†]Composite soil samples were taken at random from the site area before any fertilizer was applied.
[‡]NH_4-N and NO_3—N—2 *M* KCl extraction.
[§]P and K—Mehlich III extraction.
[#]pH—1:1 soil:water.

$RI_{PLANTHEIGHT}$ was determined using the same treatments as RI_{NDVI}. Plant height was measured with a meter stick by recording the length from the base immediately above the soil and extending leaves along the meter stick to the nearest millimeter. Five measurements were taken from each plot and a mean was figured for each of the two treatments used to determine the response index. $RI_{HARVEST}$ was determined by dividing the grain yield of Treatment 8 by the grain yield of Treatment 1 (Table 4).

Table 2
Dates of field activities, seeding rates, and varieties planted for the 2001–2002 crop year

	Location				
	Efaw Upland	Efaw Bottom	Hennessey	Marshall	Kingfisher
Pre-plant fertilization date	09/24/01	09/28/01	09/20/01	09/20/01	09/20/01
Planting date (mm/dd/year)	10/01/01	10/04/01	10/19/01	10/19/01	10/01/01
Variety	Jagger	Custer	Jagger	Jagger	Jagger
(Seeding rate $Lbs^{-1}ac$)	(90 $kg^{-1}ha$)	(90 $kg^{-1}ha$)	(90 $kg^{-1}ha$)	(90 $kg^{-1}ha$)	(100 $kg^{-1}ha$)
Sensing date	03/11/02	03/11/02	03/28/02	03/28/02	03/28/02
Days from planting to sensing ($GDD > 0$)	109	106	101	101	124
Top-dress fertilization date	03/13/02	03/13/02	03/29/02	03/29/02	03/29/02
Harvest date	06/07/02	06/07/02	06/07/02	06/07/02	06/07/02

Table 3
Dates of field activities, seeding rates, and varieties planted for 2002–2003 crop year

	Location			
	Efaw Upland	Tipton	Perkins	Lake Carl Blackwell
Pre-plant fertilization date (mm/dd/year)	09/04/02	09/17/02	09/12/02	09/05/02
Planting date (mm/dd/year)	10/05/02	09/26/02	10/14/02	10/01/02
Variety	2174	Custer	Jagger	Jagger
(Seeding rate $Lbs^{-1}ac$)	(90 $kg^{-1}ha$)	(80 $kg^{-1}ha$)	(90 $kg^{-1}ha$)	(90 $kg^{-1}ha$)
Sensing date (mm/dd/year)	03/07/03	03/06/03	03/12/03	03/07/03
Days from planting to sensing ($GDD > 0$)	92	115	91	99
Top-dress fertilization date	03/07/03	03/06/03	03/12/03	03/07/03
Harvest date	05/30/03	05/29/03	05/30/03	05/26/03

Table 4
Grain yield and plant height at Feekes 4–6 at five sites for 2001–2002

	kg ha^{-1}		Location									
			Efaw Upland		Efaw Bottom		Hennessy		Marshall		Kingfisher	
Trt #	Preplant N	Top-dress N	Grain yield kg ha^{-1}	Plant Ht. cm	Grain yield kg ha^{-1}	Plant Ht. cm	Grain yield kg ha^{-1}	Plant Ht. cm	Grain yield kg ha^{-1}	Plant Ht. cm	Grain yield kg ha^{-1}	Plant Ht. cm
1	0	0	1305	9.50	2361	13.40	2467	13.15	2792	9.85	3167	18.10
2	0	Variable rate[1]	1710 (13)	8.85	2618 (14)	14.60	2255 (14)	13.25	2134 (2)	9.85	2785 (0)	17.25
3	0	Variable rate[1]	1877 (10)	10.25	1831 (4)	13.70	2406 (12)	13.55	2285 (3)	9.15	2391 (1)	17.40
4	0	2 × Variable rate[2]	2633 (61)	9.70	2508 (69)	14.30	2860 (66)	13.60	2800 (29)	11.35	3076 (65)	17.25
5	0	45	2013	9.30	2554	14.45	2452	14.35	2694	10.35	3072	17.80
6	45	45	2508	9.40	2656	15.88	2599	14.60	2981	11.45	3133	18.00
7	45	0	1986	12.40	2421	15.75	2134	13.85	2981	11.20	3360	18.40
8	90	0	1573	10.95	2482	16.15	2255	14.15	2921	10.10	2962	18.25
9	45	Variable rate[1]	1986 (11)	10.70	2452 (4)	15.50	2785 (12)	13.90	2331 (3)	11.10	2894 (1)	19.00
		SED[4]	245	1.6	172	1.7	173	1.4	264	1.6	211	1.5
$RI^{5}_{PLANTHEIGHT}$			1.15		1.21		1.08		1.03		1.01	
RI^{6}_{NDVI}			1.27		1.06		1.23		1.11		1.01	
RI^{7}_{SV}			1.41		1.14		1.37		1.4		1.04	
$RI^{8}_{HARVEST}$			1.57		1.06		0.92		1.07		1.06	

[1]Variable N rate management.
[2]Variable N rate management assuming a NUE of 35% for top-dress N fertilizer.
[3]Numbers in parentheses indicates the average amount of top-dress N applied in kg^{-1} ha.
[4]SED = Standard error of the difference between two equally replicated means.
[5]$RI_{PLANTHEIGHT}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8/Plant height of treatment 1).
[6]RI_{NDVI} = Response index measured in-season using NDVI readings (NDVI treatment 8/NDVI treatment 1).
[7]RI_{SV} = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED)/(mean NDVI − 1 SED)).
[8]$RI_{HARVEST}$ = Response index measured using highest grain yield of a pre-plant N treatment only divided by grain yield of treatment 1.

NDVI was measured using a GreenSeeker ™ hand-held optical sensor unit. The hand-held optical sensor unit measures NDVI using self-contained illumination in both the red [650 ± 10 nm full width half magnitude (FWHM)] and NIR (770 ± 10 nm FWHM) light bands. The device measures the fraction of the emitted light in the sensed areas that is returned to the sensor (reflectance). These fractions are used with the sensor to compute NDVI according to the following formula: $NDVI = (F_{NIR} - F_{RED})/(F_{NIR} + F_{RED})$, where F_{NIR} is the fraction of emitted NIR radiation returned from the sensed area, and F_{RED} is the fraction of emitted red radiation returned from the sensed area. The area sensed by this hand-held unit is 0.6×0.01 m. The sensor was passed over the entire plot area and an average NDVI was determined from all readings taken (approximately 15 readings per plot). The sensor outputs an NDVI value at a rate of 10 readings per second. The sensor was held at a height of approximately 0.9 m above the crop canopy.

All pre-plant treatments used ammonium nitrate (34-0-0) as the fertilizer N source. Pre-plant treatments were incorporated by hand after application. All sites were planted in a 19 cm row spacing using a Tye® small grain drill except for the Tipton 2003 site, which was planted in a 25 cm row spacing. A light tillage operation, using a field cultivator, was used on an as-needed basis prior to planting for weed control. All plots were harvested by hand, removing the center 1 m^2 from of each plot. All plots were cut at ground level, and dry weights taken before grain was threshed. All statistical analysis was completed using SAS (SAS, 2000).

RESULTS AND DISCUSSION

Based on two years and nine experimental sites over eight different locations, the degree of response to N varied by year and location (Fig. 1). This implies a need for N recommendations to have the flexibility to encompass temporal variations at different locations. RI_{NDVI} was a good indicator of a site's potential responsiveness to additional N. Across nine sites, different environments, and two years, RI_{NDVI} was positively and significantly correlated with (Fig. 1). The slope of this line is greater than that reported by Mullen et al. (16) which was close to one (1.06).

However, looking at that set of data, six of the points for both RI_{NDVI} and $RI_{HARVEST}$ are below 1.25 and 1.26 respectively. This was encouraging, as RI_{NDVI} indicated that a site might be marginally responsive to additional N, and was confirmed with a low $RI_{HARVEST}$. A site was considered non-responsive if the RI_{NDVI} was from 1.0 to 1.10 and marginally responsive from $>1.10 <1.25$. At the marginally responsive range, the increase in grain yield from additional N may not have an economical return on the expenditure for the N fertilizer. In the non-responsive range, it is very unlikely that the producer would observe

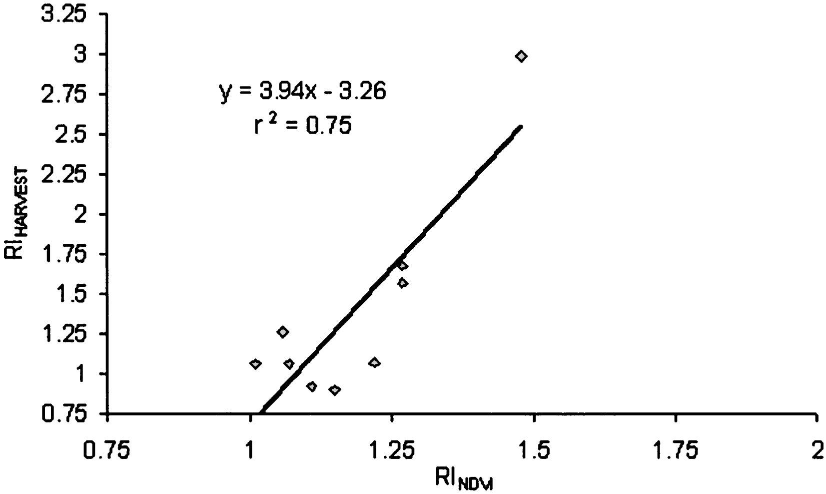

Figure 1. RI_{NDVI} at Feekes 4–6 versus $RI_{HARVEST}$ at nine sites for 2001–2003 crop years.

an economic return on the N fertilizer dollar spent to obtain this small increase in grain yield.

It was interesting to note that the slope of RI_{NDVI} versus $RI_{HARVEST}$ is not close to 1.0. Lukina et al. (2001) found that at Feekes 4–6, winter wheat can take up more than 45 kg N ha^{-1}. This amount represented over half of the total N that would be in the grain at harvest. So, at early growth stages, winter wheat has taken up a large portion of the N that the plant needs to meet its yield potential. Thus, one would expect that the relationship between the response indices would be very similar to and would have a slope of 1.0.

$RI_{PLANTHEIGHT}$ over all nine locations was strongly correlated with $RI_{HARVEST}$ ($r^2 = 0.74$) (Fig. 2). This is very encouraging as it allows for producers to make a reliable estimate of $RI_{HARVEST}$ without the use of a hand-held sensor. This option could be very useful to producers in developing countries that farm only a few hectares and cannot afford a hand-held sensor, but can still capitalize on the use of managing N for temporal variability by using a N-rich strip. $RI_{PLANTHEIGHT}$ was also correlated with RI_{NDVI} over nine sites and two years ($r^2 = 0.61$) (Fig. 3, Tables 4 and 5).

RI_{SV} was poorly correlated with both with $RI_{HARVEST}$ and RI_{NDVI} (Figs. 4 and 5). The failure of RI_{SV} to predict $RI_{HARVEST}$ or estimate RI_{NDVI} could be due to not having enough samples of <1.5 m^2 measured in this study. Further investigation is needed to determine how many field elements <1.5 m^2 would be needed to reliably predict and estimate both $RI_{HARVEST}$ and RI_{NDVI} in a given field. In addition, RI_{SV} assumes that the variability measured by the sensor is due to spatial difference in N. RI_{SV} should be measured only when a crop stand visually appears uniform and is not affected by any other factors that

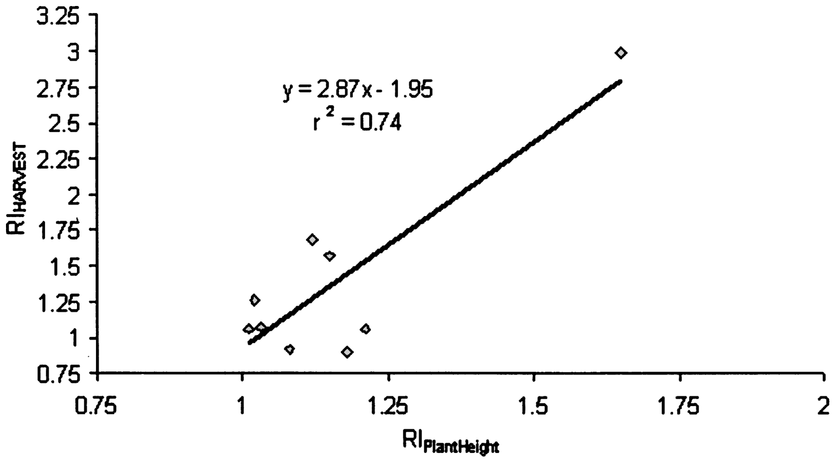

Figure 2. $RI_{PLANTHEIGHT}$ at Feekes 4–6 versus $RI_{HARVEST}$ at nine sites for 2001–2003 crop years.

could affect the variation in NDVI measured in random field elements. Factors that could contribute to the failure of RI_{SV} to predict $RI_{HARVEST}$ could include uneven plant stands, variations in tiller density, differences in plant available water in the soil solution, drainage, and degree and direction of facing slope.

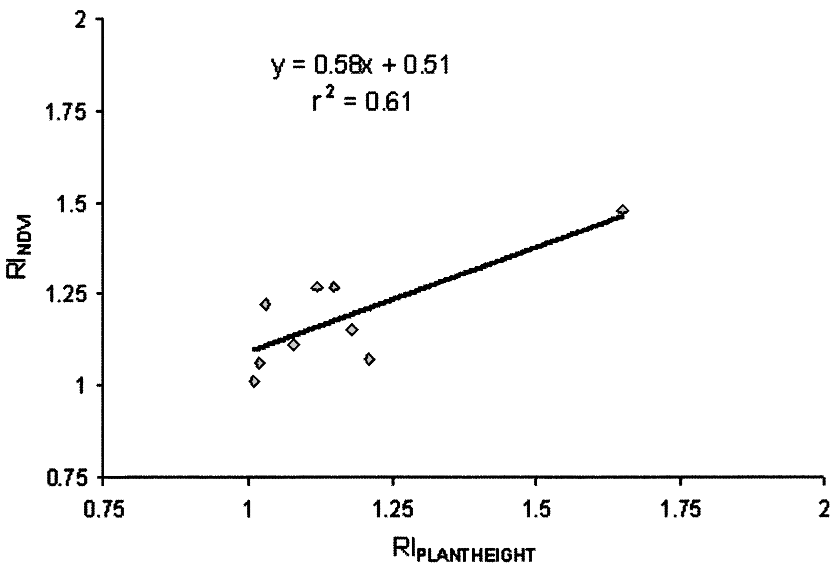

Figure 3. $RI_{PLANTHEIGHT}$ at Feekes 4–6 versus RI_{NDVI} at nine sites for 2001–2003 crop years.

Table 5
Grain yield and plant height at Feekes 4–6 at four sites for 2002–2003

	kg ha^{-1}		Location							
			Efaw		Tipton†		Perkins		Lake Carl Blackwell	
Trt #	Preplant N	Top-dress N	Grain yield kg ha^{-1}	Plant height cm	Grain yield kg ha^{-1}	Plant height cm	Grain yield kg ha^{-1}	Plant height cm	Grain yield kg ha^{-1}	Plant height cm
	0	0	830	6.20	698	14.95	2757	15.90	2435	12.25
2	0	Variable rate[1]	1848 (59)	6.20	978 (54)	16.10	3363 (47)	15.90	3530 (65)	12.10
3	0	Variable rate[1]	1223 (23)	6.05	735 (7)	15.70	3235 (4)	15.95	3117 (22)	12.40
4	0	2 × Variable rate[2]	2355 (93)	6.50	1326 (72)	15.30	3330 (71)	15.30	4417 (119)	11.65
5	0	45	1845	7.35	958	14.75	3393	14.95	3605	12.85
6	45	45	2900	9.10	1260	16.75	3698	16.50	4143	12.80
7	45	0	1613	8.90	793	16.00	3583	16.10	3037	12.55
8	90	0	2480	10.20	630	17.65	3480	16.25	4083	13.70
9	45	Variable rate[1]	2457 (31)	8.60	750 (7)	15.90	3373 (4)	15.90	3503 (24)	13.05
		SED[4]	158	1.11	103	1.3	242	1.25	190	1.0
$RI^{5}_{PLANTHEIGHT}$			1.65		1.18		1.02		1.12	
RI^{6}_{NDVI}			1.48		1.15		1.06		1.27	
RI^{7}_{SV}			1.39		1.52		1.7		1.25	
$RI^{8}_{HARVEST}$			2.99		0.90		1.26		1.68	

[1]Variable N rate management.
[2]Variable N rate management assuming a NUE of 35% for top-dress N fertilizer.
[3]Numbers in parentheses indicates the average amount of top-dress N applied in kg^{-1} ha.
[4]SED = Standard error of the difference between two equally replicated means.
[5]$RI_{PLANTHEIGHT}$ = Response index measured in-season using mean canopy height (plant height of treatment 8/plant height of treatment 1).
[6]RI_{NDVI} = Response index measured in-season using NDVI readings (NDVI treatment 8/NDVI treatment 1).
[7]RI_{SV} = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED)/(mean NDVI − 1 SED)).
[8]$RI_{HARVEST}$ = Response index measured using highest grain yield of a pre-plant N treatment only grain yield of Treatment 1.

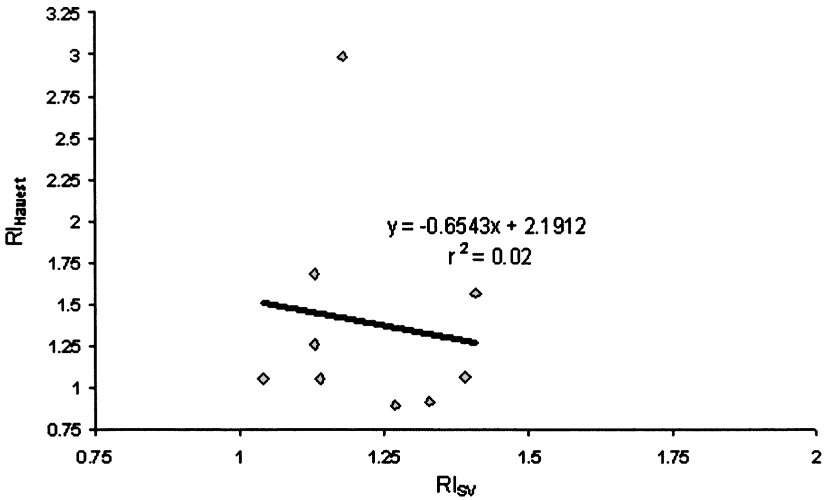

Figure 4. RI_{SV} at Feekes 4–6 versus $RI_{HARVEST}$ at nine sites for 2001–2003 crop years.

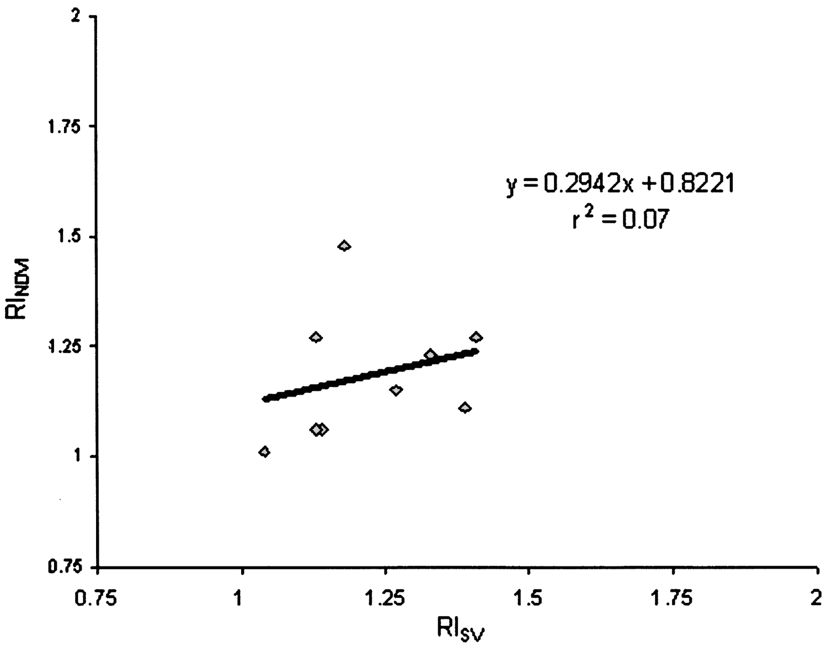

Figure 5. RI_{SV} at Feekes 4–6 versus RI_{NDVI} at nine sites for 2001–2003 crop years.

Any soil parameter that affects the growth of the crop other than N status of the soil from one field element to another would make RI_{SV} an unreliable estimate of the crop's potential responsiveness to additional N.

In-season N management schemes that incorporate an in-season response index (RI_{NDVI} or $RI_{PLANTHEIGHT}$) will allow for producers to quantify the likelihood of achieving an economical response to additional N, tailored to that site, for that growing season. If producers are to realize full potential of this system, pre-plant N rates must be reduced. By reducing pre-plant N rates, they can start to take advantage of years where little or no N is needed to achieve maximum yields. This helps support the effectiveness of using a sensor-based approach for making N recommendations over the current industry standard of yield goals and pre-plant soil samples for residual nitrate. Even if producers do not treat within field spatial variability, the use of an N-rich strip and a check plot will allow them to adjust for temporal variability and large-scale variability (by field). This option will help to improve their NUE over current N management practices.

CONCLUSION

RI_{NDVI} was related to $RI_{HARVEST}$ over nine locations and two years. Use of the response index will allow producers to move away from reliance on pre-plant application of N and to start managing N based on the likelihood of achieving an economical response to N fertilizer. This can only be done when a N-rich strip is installed and the N management practice allows for N rates to be adjusted by season and location.

$RI_{PLANTHEIGHT}$ could be a very useful tool for small farmers in developing countries who cannot or do not want to undergo the initial investment in a hand-held sensor. Furthermore, $RI_{PLANTHEIGHT}$ should continue to be evaluated as a potential aid when using RI_{NDVI}. An example could be at a site where RI_{NDVI} has indicated that it would be marginal in its response to additional N, and that assessment could be confirmed with $RI_{PLANTHEIGHT}$. The fact that $RI_{PLANTHEIGHT}$ was strongly correlated with $RI_{HARVEST}$ indicates that it can be used instead of RI_{NDVI}. Yet, the N recommendations used in this study rely solely on information derived from the sensors to generate NDVI. Thus, RI_{NDVI} is still a reliable tool that should be used because the measurements are easily and rapidly obtainted. For a producer that has many fields to evaluate in a short time, taking 40–50 plant measurements per site with a meter stick, and then calculating averages from the data collected, could take up valuable time and labor. RI_{SV} should not be used to determine RI_{NDVI} or $RI_{HARVEST}$. Of the three response indices for predicting a site's potential responsiveness to N, this was the poorest. One of the limitations in this study was possible insufficiency of data collected to obtain enough samples of the total population in the field. Also, this response index assumes that the variability measured by the sensor is due to N status of the soil alone. That can be a risky assumption when all the possible factors that could be affecting the measured variability are examined.

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