# Identifying an In-Season Response Index and the Potential to Increase Wheat Yield with Nitrogen

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## ABSTRACT

**Current nitrogen use efficiency (NUE) of cereal crop production is estimated to be near 33%, indicating that much of the applied fertilizer N is not utilized by the plant and is susceptible to loss from the soil–plant system. Supplying fertilizer N only when a crop response is expected may improve use efficiency and profitability. A response index using harvest data was recently proposed that indicates the actual crop response to additional N within a given year. This response index, $RI_{Harvest}$, is calculated by dividing the average grain yield of the highest yielding treatment receiving N by the average yield of a check treatment (0 N). Although theoretically useful, $RI_{Harvest}$ does not allow for in-season adjustment of N application. The objective of this work was to determine the relationship between $RI_{Harvest}$ and the response index measured in-season ($RI_{NDVI}$) using the normalized difference vegetative index (NDVI). Research was conducted in 23 existing field experiments in Oklahoma. Each field experiment evaluated crop response to varying levels of preplant N. At Feekes growth stages 5, 9, and 10.5, $RI_{Harvest}$ was accurately predicted using $RI_{NDVI}$ ($r^2 > 0.56$). These results indicated that the in-season response index based on sensor readings is a viable method for identifying environments (i.e., fields) where the potential to respond to additional N exists.**

Raun and Johnson (1999) estimated current nitrogen use efficiency (NUE) of worldwide cereal production to be near 33%, which suggests that current N strategies are extremely inefficient. Current Oklahoma N recommendations are calculated using the equation, $N_{rec}$ = Yield goal (kg $ha^{-1}$) $\times$ 0.033, where the yield goal is based on the average wheat (*Triticum aestivum* L.) yield for the past 5 yr and, on average, 33 kg of N is needed to produce 1000 kg of grain. Typically, all N is injected preplant as anhydrous ammonia between mid-August and mid-September. Avoiding excess application of N fertilizers in crop production is one way to increase NUE (Kanampiu et al., 1997). Application methods that avoid applying large amounts of N at any one time can also increase NUE (Wuest and Cassman, 1992). The soil–plant system is capable of loss via denitrification (Burford and Bremner, 1975; Olson et al., 1979, Burkart and James, 1999), runoff (Gascho et al., 1998; Burkart and James, 1999), or leaching (Goss and Goorahoo, 1995; Paramasivam and Alva, 1997). Thus, there is more N available for loss at any given time during the growing season if N is applied only once per season. Multiple timely inputs of N during the growing season, while potentially costly, could significantly increase NUE.

Recently, methods for estimating winter wheat N requirements based on early season estimates of N uptake and potential yield were developed (Lukina et al., 2001; Raun et al., 2002). Remote sensing collected by a modified daytime-lighting reflectance-sensor was used to estimate early season plant N uptake. The estimate was based on a relationship between NDVI and plant N uptake between Feekes physiological stage 4 (leaf sheaths lengthen) and 6 (first node of stem visible) (Large, 1954; Stone et al., 1996; Solie et al., 1996). The NDVI was calculated using the following equation:

$$\mathrm{NDVI} = [(\mathrm{NIR_{ref}}/\mathrm{NIR_{inc}}) - (\mathrm{Red_{ref}}/\mathrm{Red_{inc}})]/[(\mathrm{NIR_{ref}}/\mathrm{NIR_{inc}}) + (\mathrm{Red_{ref}}/\mathrm{Red_{inc}})] \quad [1]$$

where $NIR_{ref}$ and $Red_{ref}$ are the near-infrared and red reflected radiance of the crop, respectively, and $NIR_{inc}$ and $Red_{inc}$ are the near-infrared and red incident radiance, respectively. Further analyses showed that a reliable in-season estimate of yield (INSEY) could be obtained from dividing NDVI by the days from planting to sensing date (where growing degree days $> 0$) (Raun et al., 2002). This INSEY was subsequently used to estimate N uptake in the grain based on a predicted yield level. Finally, using predicted wheat N uptake (measured by NDVI) and projected grain N uptake from estimated yield (INSEY), topdress fertilizer N rates were determined (Grain N uptake − Early season plant N uptake) (Lukina et al., 2001).

Recently, a response index ($RI_{Harvest}$) was proposed that indicates the actual crop response to applied N (Johnson et al., 2000). The $RI_{Harvest}$ is calculated using the following equation:

$$\mathrm{RI_{Harvest}} = \frac{\text{(Highest mean yield N treatment)/}}{\text{(Mean yield check treatment)}} \quad [2]$$

Increased nonfertilizer N contribution via mineralization or rainfall are the most likely reasons for low $RI_{Harvest}$. The use of $RI_{Harvest}$ does not allow for in-season adjustment of N, thus its practical value to N management is minimal.

In-season sensor measurements of NDVI as an indicator of wheat N uptake between plots receiving N and those not receiving N can be used in the same way using the following equation:

$$\mathrm{RI_{NDVI}} = \frac{\text{(Highest mean NDVI N treatment)/}}{\text{(Mean NDVI check treatment)}} \quad [3]$$

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**Abbreviations:** NDVI, normalized difference vegetative index; NUE, nitrogen use efficiency.

**Table 1. Fertilizer rates of N, P, and K at Haskell, Hennessey, Lahoma, Perkins, and Stillwater, OK.**

| Stillwater AA | Stillwater 301† | Haskell 801 | Hennessey AA | Lahoma 502 | Perkins N & P | Stillwater 222 |
|---|---|---|---|---|---|---|
| | | | N–P–K, kg ha$^{-1}$ | | | |
| 0–0–0‡ | 0–0–0‡ | 0–58–111 | 0–0–0‡ | 0–19–56 | 0–29–0§ | 0–29–37 |
| 56–0–0 | 45–0–0 | 112–58–111 | 56–0–0 | 22–19–56 | 56–29–0 | 45–29–37 |
| 90–0–0 | 90–0–0 | 112–39–111 | 90–0–0 | 45–19–56 | 112–29–0 | 90–29–37 |
| 12–0–0 | 179–0–0 | 168–58–111 | 123–0–0 | 67–19–56 | 168–29–0 | |
| | | | | 90–19–56 | | |
| | | | | 112–19–56 | | |

† Ammonium nitrate was the N source, excluding AA experiments.
‡ Blanket application of P and K to 100% sufficiency.
§ Blanket application of K to 100% sufficiency.

Basing fertilizer rates on in-season estimate of yield (INSEY) and $RI_{NDVI}$ may help optimize in-season fertilizer application, which in turn could increase NUE and yield. The objective of this work was to determine if $RI_{NDVI}$ could accurately predict $RI_{Harvest}$ at Feekes growth stages 5, 9, 10.5, and 11.2.

## MATERIALS AND METHODS

Research was conducted at either an on-going long-term experiment (numbers assigned in the 1960s, 1970s, and 1990s as experiments 222, 301, 502, and 801), or a short-term (1–3 yr) field experiment that included the evaluation of preplant N rates (Tables 1 and 2). The soils at each of these locations follow: Perkins, Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll); Hennessey, Shellabarger sandy loam (fine-loamy, mixed, thermic Udic Argiustoll); Stillwater, Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll); Stillwater–Efaw, Norge silt loam (fine-silty, mixed, thermic Udic Paleustoll); Lahoma, Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll); Haskell, Taloka silt loam (fine, mixed, thermic Mollic Albaqualf); and Tipton, Tipton silt loam (fine-loamy, mixed, thermic Pachic Argiustoll). Each experiment had a different goal and start date. The anhydrous ammonia (AA) nitrogen use efficiency (NUE) experiments were initiated in 1999. The N rate by P rate (N × P) experiment at Perkins was initiated in 1996. Experiments 222, 301, 502, and 801 were initiated in 1969, 1993, 1971, and 1977, respectively. These experiments evaluate annual rates of applied N as ammonium nitrate at constant levels of P and K (Table 1). Winter wheat was planted at a 78 kg ha$^{-1}$ seeding rate using a 0.19-m row spacing. All field experiments where sensor and yield data were collected employed randomized complete block designs with 3 to 4 replications (depending on site).

During the winter months of 1998, 1999, 2000, and 2001 spectral reflectance readings at Feekes (Large, 1954) growth stage 5 were taken from 23 existing winter wheat experiments. Sensor measurements were taken from treatments with varying levels of N nutrition within each replication. Additional spectral reflectance readings were taken at Feekes growth stages 9, 10.5, and 11.2 from 14 existing winter wheat experiments during 2000 and 2001. Spectral reflectance was measured using a handheld sensor constructed at Oklahoma State University that included two upward and downward directed photodiode sensors that received light through cosine corrected Teflon windows fitted with red (671 ± 6 nm) and near-infrared (NIR) (780 ± 6 nm) interference filters (Stone et al., 1996). The sensor was placed approximately 1.5 m above the crop for all readings, and approximately 10 readings were collected per second resulting in approximately 40 readings taken per plot. Reflectance readings from all plots at each experiment were collected at one postdormancy date in 1998, 1999, and four postdormancy dates in 2000 and 2001. The date when readings were collected generally corresponded to Feekes growth stages 5 (pseudo-stem, formed by sheaths of leaves strongly erect), 9 (ligule of last leaf just visible), 10.5 (flowering), and 11.2 (mealy ripe, contents of kernel soft but dry) (Large, 1954). Consistent with different planting times and growing conditions, spectral reflectance readings were collected between January and May (Table 2). All reflectance readings from wheat were taken from a 4.0 m$^2$ area (same area as that harvested for grain yield) between 01000 and 1600 h under natural light.

After NDVI values were calculated using Eq. [1], $RI_{NDVI}$ was computed using Eq. [2]. Grain yield was determined using a self propelled combine, which harvested the same 4.0 m$^2$ area where spectral reflectance data were collected. From the yield data, $RI_{Harvest}$ was calculated using Eq. [3]. Linear and quadratic models were used to determine the relationships between $RI_{Harvest}$ and $RI_{NDVI}$ using SAS PROC REG (SAS Inst., 2000).

## RESULTS AND DISCUSSION

### $RI_{Harvest}$ vs. $RI_{NDVI}$ at Feekes 5

Average yield and NDVI values used in $RI_{NDVI}$ and $RI_{Harvest}$ calculation are reported in Table 3. In these experiments, $RI_{NDVI}$ measured at Feekes 5 was highly correlated to $RI_{Harvest}$ ($R^2$ = 0.56, $P < 0.001$) (Fig. 1). In this work, we recognized that after remote sensing is collected yield enhancing and limiting factors may occur that result in underestimation or overestimation of $RI_{Harvest}$ by $RI_{NDVI}$. For example, in 1999, early spring rains after a dry fall planting period improved growing conditions after the sensing dates. Timely rainfall may have increased the N response resulting in a larger $RI_{Harvest}$ than predicted by $RI_{NDVI}$.

### $RI_{Harvest}$ vs. $RI_{NDVI}$ at Feekes 9, 10.5, and 11.2

The relationships between $RI_{NDVI}$ and $RI_{Harvest}$ measured at Feekes growth stages 5 (Fig. 1), 9 (Fig. 2), and 10.5 (Fig. 3) were similar. Prediction of $RI_{Harvest}$ at Feekes 11.2 was poor, primarily due to early maturation of the check (0-N) plots relative to plots receiving N (data not shown). It is important to note that sensor readings taken at later stages of growth (near maturation) would most likely result in overestimation of $RI_{Harvest}$ due to early maturation of check (0-N) plots, resulting in low NDVI values, thus decreasing the value of the denominator in the calculation of $RI_{NDVI}$.

The ability to identify fields where responses to applied N can be expected is important. If a response to N is expected, then N management strategies can be altered to apply N based on responsiveness. To date,

**Table 2. Experiments where sensor and winter wheat grain yield data were collected, location, sampling date, and variety.**

| Experiment | Location | Year | Planting date | Sensing date | Harvest date | Variety |
|---|---|---|---|---|---|---|
| N × P† | Perkins, OK | 1998 | 21 Oct. 1997 | 2 Apr. 1998¶ | 16 June 1998 | Tonkawa |
| N × S‡ | Perkins, OK | 1998 | 21 Oct. 1997 | 2 Apr. 1998¶ | 16 June 1998 | Tonkawa |
| N × S‡ | Tipton, OK | 1998 | 10 Oct. 1997 | 1 Mar. 1998¶ | 3 June 1998 | Tonkawa |
| N × P† | Perkins, OK | 1999 | 12 Oct. 1998 | 4 Mar. 1999¶ | 9 June 1999 | Tonkawa |
| Exp. 222 | Stillwater, OK | 1999 | 13 Oct. 1998 | 24 Feb. 1999¶ | 15 June 1999 | Tonkawa |
| Exp. 301 | Stillwater, OK | 1999 | 15 Oct. 1998 | 24 Mar. 1999¶ | 15 June 1999 | Tonkawa |
| Efaw AA§ | Stillwater, OK | 1999 | 9 Nov. 1998 | 24 Mar. 1999¶ | 15 June 1999 | Tonkawa |
| Exp. 502 | Lahoma, OK | 1999 | 9 Oct. 1998 | 05 Mar. 1999¶ | 30 June 1999 | Tonkawa |
| Exp. 801 | Haskell, OK | 1999 | 16 Oct. 1998 | 23 Mar. 1999¶ | 6 June 1999 | 2163 |
| N × P† | Perkins, OK | 2000 | 8 Oct. 1999 | 8 Feb. 2000¶<br>4 Apr. 2000#<br>24 Apr. 2000††<br>22 May 2000‡‡ | 30 May 2000 | Custer |
| Exp. 301 | Stillwater, OK | 2000 | 7 Oct. 1999 | 10 Feb. 2000¶<br>4 Apr. 2000#<br>24 Apr. 2000††<br>22 May 2000‡‡ | 15 June 2000 | Custer |
| Exp. 222 | Stillwater, OK | 2000 | 7 Oct. 1999 | 10 Feb. 2000¶<br>30 Mar. 2000#<br>24 Apr. 2000††<br>22 May 2000‡‡ | 6 July 2000 | Custer |
| Efaw AA§ | Stillwater, OK | 2000 | 7 Oct. 1999 | 15 Feb. 2000¶<br>4 Apr. 2000#<br>24 Apr. 2000††<br>22 May 2000‡‡ | 7 July 2000 | Custer |
| Exp. 502 | Lahoma, OK | 2000 | 12 Oct. 1999 | 15 Feb. 2000¶<br>28 Mar. 2000#<br>27 Apr. 2000††<br>22 May 2000‡‡ | 13 June 2000 | Custer |
| Exp. 801 | Haskell, OK | 2000 | 8 Oct. 1999 | 14 Mar. 2000¶<br>2 Apr. 2000¶<br>25 Apr. 2000††<br>16 May 2000‡‡ | 2 June 2000 | 2137 |
| Hennessey AA§ | Hennessey, OK | 2000 | 7 Oct. 1999 | 15 Feb. 2000¶<br>28 Mar. 2000#<br>27 Apr. 2000††<br>22 May 2000‡‡ | 7 June 2000 | Custer |
| N × P† | Perkins, OK | 2001 | 17 Nov. 2000 | 13 Apr. 2001¶<br>30 Apr. 2001#<br>10 May 2001††<br>24 May 2001‡‡ | 7 June 2001 | Custer |
| Exp. 301 | Stillwater, OK | 2001 | 16 Nov. 2000 | 13 Apr. 2001¶<br>30 Apr. 2001#<br>10 May 2001††<br>24 May 2001‡‡ | 11 June 2001 | Custer |
| Exp. 222 | Stillwater, OK | 2001 | 20 Nov. 2000 | 13 Apr. 2001¶<br>30 Apr. 2001#<br>10 May 2001††<br>24 May 2001‡‡ | 12 June 2001 | Custer |
| Efaw AA§ | Stillwater, OK | 2001 | 22 Nov. 2000 | 13 Apr. 2001¶<br>30 Apr. 2001¶<br>10 May 2001††<br>24 May 2001‡‡ | 11 June 2001 | Custer |
| Exp. 502 | Lahoma, OK | 2001 | 1 Nov. 2000 | 13 Apr. 2001¶<br>28 Apr. 2001#<br>10 May 2001††<br>24 May 2001‡‡ | 15 June 2001 | Custer |
| Exp. 801 | Haskell, OK | 2001 | 4 Oct. 2000 | 15 Apr. 2001¶<br>29 Apr. 2001#<br>10 May 2001††<br>24 May 2001‡‡ | 6 June 2001 | 2137 |
| Hennessey AA§ | Hennessey, OK | 2001 | 21 Nov. 2000 | 13 Apr. 2001¶<br>30 Apr. 2001#<br>10 May 2001††<br>24 May 2001‡‡ | 13 June 2001 | Custer |

† N × P = N rate by P rate experiment.
‡ N × S = N rate by spacing experiment.
§ Anhydrous ammonia rate experiment.
¶, #, ††, ‡‡ Corresponds to Feekes growth stages 5, 9, 10.5, and 11.2, respectively.

many researchers have struggled to develop indices that assess N mineralization potential. The basic concept is that if N mineralization potential could be determined, N recommendations could be refined.

Utilizing the crop to assess N contribution from the soil without N fertilization within the growing season, whether by increased rainfall N or mineralization, is novel. The higher the yield level the soil will support without N fertilization (low $RI_{NDVI}$), in general, the lower the amounts of fertilizer N that will be needed to reach maximum yields. This is not to say that soil testing for ammonium and/or nitrate before fertilizer application is not a reliable tool for assessing N need, but rather that the soil test information determined at a point in

**Table 3. Mean NDVI values and yield levels of check treatments and treatments receiving preplant N for 23 winter wheat experiments.**

| Experiment | Year | Check NDVI (0-N) | NDVI of N-fertilized | Check NDVI (0-N) | NDVI of N-fertilized | Check NDVI (0-N) | NDVI of N-fertilized | Check yield (0 N) | Maximum yield (N-fertilized) |
|---|---|---|---|---|---|---|---|---|---|
| | | Feekes 5 | | Feekes 9 | | Feekes 10.5 | | kg ha$^{-1}$ | |
| Perkins N × S† | 1998 | 0.56 | 0.77 | – | – | – | – | 1332 | 2375 |
| Perkins N × P‡ | 1998 | 0.43 | 0.64 | – | – | – | – | 1214 | 1921 |
| Tipton N × S† | 1998 | 0.74 | 0.89 | – | – | – | – | 3285 | 5466 |
| Efaw AA§ | 1999 | 0.63 | 0.78 | – | – | – | – | 2169 | 3708 |
| Efaw 301 | 1999 | 0.34 | 0.78 | – | – | – | – | 939 | 2662 |
| Haskell 801 | 1999 | 0.72 | 0.87 | – | – | – | – | 1990 | 2600 |
| Lahoma 502 | 1999 | 0.62 | 0.87 | – | – | – | – | 1680 | 4443 |
| Perkins N × P‡ | 1999 | 0.43 | 0.63 | – | – | – | – | 1077 | 2568 |
| Stillwater 222 | 1999 | 0.54 | 0.66 | – | – | – | – | 926 | 1724 |
| Efaw AA§ | 2000 | 0.77 | 0.86 | 0.82 | 0.91 | 0.71 | 0.80 | 2184 | 3053 |
| Efaw 301 | 2000 | 0.17 | 0.65 | 0.23 | 0.90 | 0.19 | 0.80 | 975 | 3382 |
| Haskell 801 | 2000 | 0.73 | 0.88 | 0.73 | 0.88 | 0.65 | 0.81 | 2399 | 3070 |
| Hennessey AA§ | 2000 | 0.86 | 0.89 | 0.91 | 0.93 | 0.84 | 0.86 | 3800 | 4064 |
| Lahoma 502 | 2000 | 0.52 | 0.89 | 0.49 | 0.90 | 0.42 | 0.88 | 1954 | 3543 |
| Perkins N × P‡ | 2000 | 0.52 | 0.71 | 0.73 | 0.87 | 0.59 | 0.74 | 2605 | 3898 |
| Stillwater 222 | 2000 | 0.45 | 0.81 | 0.48 | 0.90 | 0.41 | 0.81 | 1282 | 2450 |
| Efaw AA§ | 2001 | 0.51 | 0.69 | 0.64 | 0.70 | 0.55 | 0.69 | 2693 | 3488 |
| Efaw 301 | 2001 | 0.20 | 0.45 | 0.28 | 0.50 | 0.24 | 0.43 | 922 | 2096 |
| Haskell 801 | 2001 | 0.65 | 0.78 | 0.65 | 0.77 | 0.61 | 0.76 | 3695 | 4200 |
| Hennessey AA§ | 2001 | 0.39 | 0.60 | – | – | 0.47 | 0.62 | 1905 | 2952 |
| Lahoma 502 | 2001 | 0.34 | 0.33 | – | – | 0.56 | 0.60 | 821 | 946 |
| Perkins N × P‡ | 2001 | 0.62 | 0.60 | 0.55 | 0.55 | 0.49 | 0.51 | 2751 | 2498 |
| Stillwater 222 | 2001 | 0.35 | 0.55 | 0.45 | 0.58 | 0.41 | 0.54 | 1165 | 1944 |

† N × P = N rate by P rate experiment.
‡ N × S = N rate by spacing experiment.
§ AA = anhydrous ammonia experiment.

time is static and provides no prediction of mineralization and/or immobilization, which can occur throughout the growing season.

The importance of determining RI using in-season measurements of NDVI can be summarized in the following scenarios. First, if $RI_{NDVI}$ for a location is relatively low ($RI < 1.1$) meaning that the check (0-N) NDVI and NDVI from N fertilized treatments are similar, the probability of a response to additional N will be low, and thus little, if any, fertilizer N is required. Conversely, if the NDVI of the check treatment is low and the NDVI of N fertilized treatments is high, resulting in a high $RI_{NDVI}$ ($RI > 1.1$), the probability of a response to additional N is good, and thus additional fertilizer should be applied. Considering that final grain yield differences due to applied N are being predicted from midwinter readings at Feekes 5, this information becomes increasingly useful.

The ability of remote sensing at relatively high resolutions (4 m$^2$) to quantify differences in N treatment is an exciting prospect. Demonstrated spatial variability within a field shows that differences in moisture holding capacity, soil test P, organic C, nitrate, and ammonium can exist at resolutions of 1 m$^2$ (Raun et al., 1998). Determination of $RI_{NDVI}$ for a specific environment (i.e., field) will be computed using a high N strip on a field-size scale. Using this $RI_{NDVI}$ value and determining the yield potential of each 1 m$^2$ using INSEY, N requirement could be determined and applied at a 1-m$^2$ resolution.

Current work out of Nebraska utilizes chlorophyll meter readings to calculate a sufficiency index determined by dividing an as-needed N treatment by a well-fertilized treatment (Varvel et al., 1997). Their reference is a well-fertilized treatment and not a check treatment as suggested in this article. Mathematically, the response index is simply the inverse of the sufficiency index, but theoretically the concepts are different. Utilizing the sufficiency concept, one applies N fertilizer in an attempt to match the tissue N concentration of a well fertilized strip (assumed to be 100% sufficient) without recognizing yield potential. Our approach has been to first recognize yield potential and then to fertilize based on the likelihood of obtaining a response (Raun et al.,

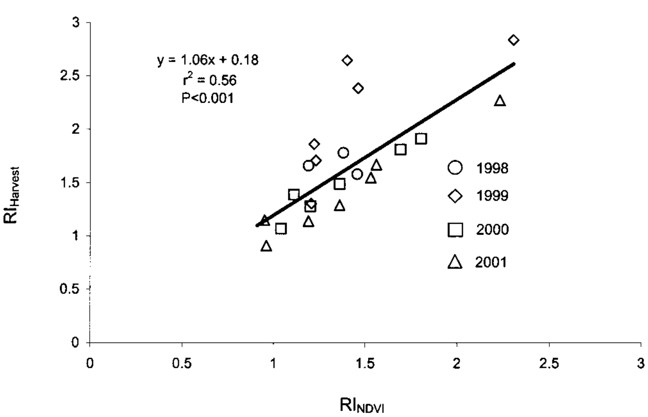


**Fig. 1. Relationship between $RI_{NDVI}$ and $RI_{Harvest}$ at Feekes growth stage 5 over 22 locations in 1998, 1999, 2000, and 2001.**

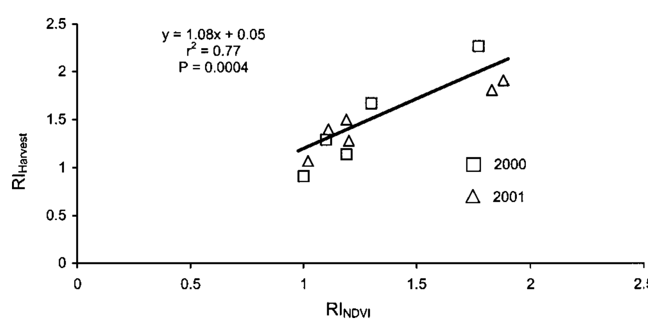


**Fig. 2. Relationship between $RI_{NDVI}$ and $RI_{Harvest}$ at Feekes growth stage 9 over 12 locations in 2000 and 2001.**

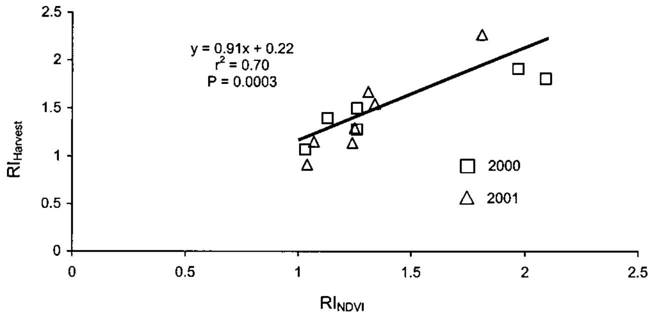


**Fig. 3. Relationship between $RI_{NDVI}$ and $RI_{Harvest}$ at Feekes growth stage 10.5 over 14 locations in 2000 and 2001.**

2002). The response index is indicative of the percentage increase in yield that could be obtained via N fertilization, but by itself says nothing about what N rate should be applied, whereas the sufficiency concept is bound directly to an actual fertilizer N rate. Our approach partitions the response index and an estimate of yield potential (Lukina et al., 2001) into two separate components. The first step is to predict potential yield with no added N fertilizer, and then determine N removal (potential yield multiplied times average percent N in the grain, e.g., 2.35 for winter wheat in the central Great Plains). With the prediction of potential yield with no N fertilization ($YP_0$), the response index allows us to project the potential yield that could be achieved with added N fertilization ($YP_N$), multiplying $YP_0 \times RI$. In any given year, fertilizer N requirements are determined by subtracting grain N uptake at $YP_0$ from grain N uptake at $YP_N$, and dividing by a theoretical maximum use efficiency of topdress N of 0.70.

## CONCLUSION

Based on analysis of 23 winter wheat experiments conducted from 1998 to 2001 under different growing conditions, $RI_{NDVI}$ was found to provide good prediction of $RI_{Harvest}$ at Feekes growth stages 5, 9, and 10.5. This ability to determine the responsiveness of the crop to additional N at early stages of growth (i.e., Feekes 5) allows altering N management schemes to potentially increase yield and NUE. Application of the response index strategy may prevent over application of fertilizer N when yield increases are not likely, thus increasing returns to producers while decreasing environmental risk.

## REFERENCES


Burford, J.R., and J.M. Bremner. 1975. Relationships between the denitrification capacities of soils and total, water-soluble and readily decomposable soil organic matter. Soil Biochem. 7:389–394.

Burkart, M.R., and D.E. James. 1999. Agricultural-nitrogen contributions to hypoxia in the Gulf of Mexico. J. Environ. Qual. 28:850–859.

Gascho, G.J., R.D. Wauchope, J.G. Davis, C.C. Truman, C.C. Dowler, J.E. Hook, H.R. Sumner, and A.W. Johnson. 1998. Nitrate-nitrogen, soluble, and bioavailable phosphorus runoff from simulated rainfall after fertilizer application. Soil Sci. Soc. Am. J. 62:1711–1718.

Goss, M.J., and D. Goorahoo. 1995. Nitrate contamination of groundwater: Measurement and prediction. Fert. Res. 42:331–338.

Johnson, G.V., W.R. Raun, and R.W. Mullen. 2000. Nitrogen use efficiency as influenced by crop response index. p. 291. *In* Agronomy abstracts. ASA, CSSA, and SSSA, Madison, WI.

Kanampiu, F.K., W.R. Raun, and G.V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. J. Plant Nutr. 20:389–404.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128–129.

Lukina, E.V., K.W. Freeman, K.J. Wynn, W.E. Thomason, R.W. Mullen, A.R. Klatt, G.V. Johnson, R.L. Elliott, M.L. Stone, J.B. Solie, and W.R. Raun. 2001. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. J. Plant Nutr. 24:885–898.

Olson, R.V., L.S. Murphy, H.C. Moser, and C.W. Swallow. 1979. Fate of tagged fertilizer nitrogen applied to winter wheat. Soil Sci. Soc. Am. J. 43:973–975.

Paramasivam, S., and A.K. Alva. 1997. Leaching of nitrogen forms from controlled-release nitrogen fertilizers. Commun. Soil Sci. Plant Anal. 28:1663–1674.

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357–363.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Whitney, H.L. Lees, H. Sembiring, and S.B. Phillips. 1998. Microvariability in soil test, plant nutrient, and yield parameters in bermudagrass. Soil Sci. Soc. Am. J. 62:683–690.

SAS Institute. 2000. SAS/STAT user's guide. Release 8.1 ed. SAS Inst., Cary, NC.

Solie, J.B., W.R. Raun, R.W. Whitney, M.L. Stone, and J.D. Ringer. 1996. Optical sensor based field element size and sensing strategy for nitrogen application. Trans. ASAE 39:1983–1992.

Stone, M.L., J.B. Solie, R.W. Whitney, W.R. Raun, and H.L. Lees. 1996. Sensors for detection of nitrogen in winter wheat. SAE Tech. Pap. Ser. 961757. Soc. of Automotive Eng., Warrendale, PA.

Varvel, G.E., J.S. Schepers, and D.D. Francis. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. Soil Sci. Soc. Am. J. 61:1233–1239.

Wuest, S.B., and K.G. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant versus late-season application. Agron. J. 84:682–688.