In-Season Estimation of Wheat Response to Nitrogen Using Normalized Difference Vegetation Index

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Abstract
Applying fertilizer nitrogen (N) only when a crop response is predicted may enhance use efficiency and profitability while protecting the environment. The crop response index at harvest (RI-harvest, the ratio of the maximum grain yield and that of the plot in question) indicates the actual crop response to applied fertilizer N, although it is calculated after harvest. The objective of this study was to predict RI-harvest of wheat using normalized difference vegetation index (NDVI) response index (RI-NDVI, defined as the ratio of the NDVI in an N-sufficient plot and that in the field in question) captured at Feekes 6 stage. Field experiments were carried out across seven site-years (2017/18 to 2020/21) on wheat. In the first three seasons, the relationships between RI-harvest and RI-NDVI were established by applying a range of fertilizer N levels (0–320 kg N ha−1), whereas the fourth season was used for validation. The results indicated that RI-NDVI could explain 79% of the variation in RI-harvest using the linear relationship: RI-harvest = 7.077 × RI-NDVI – 6.4885. This model was satisfactorily validated in the fourth season using an independent data set in which a range of fertilizer N doses was applied before the Feekes 6 growth stage. Validation was also carried out by applying a fertilizer N dose corresponding to the predicted RI-harvest. In comparison to the general recommendation, the application of appropriate prescriptive fertilizer N dose along with a fertilizer N dose based on the predicted RI-harvest resulted in an 11% increase in fertilizer N recovery efficiency. It suggests that estimation of in-season RI-NDVI is a viable method for identifying fields that are likely to respond to additional fertilizer N.

Keywords Response index at harvest · NDVI · Nitrogen recovery efficiency · Wheat

Introduction
A variety of vegetation indices have been developed to reflect certain plant canopy conditions by combining reflectance in two or more bands of the electromagnetic spectrum. In several studies plant indices based on spectral reflectance have been shown to accurately predict crop physiological variables such as plant biomass (Tucker, 1979), photosynthesis (Zhao et al., 2003), chlorophyll content (Tucker, 1979), plant N status (Bronson et al., 2003; Ali et al., 2020), and yield (Raun et al., 2002; Zhao et al., 2003; Ali et al., 2014). Normalized difference vegetation index (NDVI) is one of the most used vegetation indices. It was established by Rouse et al. (1973) to measure vegetative cover. Because there is a chlorophyll absorption peak in the red (600–700 nm) region and a reflectance plateau in the near-infrared (NIR, 750–900 nm) region, NDVI is based on these regions. Plants are healthy when they reflect more NIR and absorb a large amount of red light. According to Ma et al. (1996), NDVI had a stronger relationship to different N treatments than the other indices.

The NDVI was first employed as an indirect indicator of crop yield, including wheat yield (Tucker et al., 1980; Pinter et al., 1981; Raun et al., 2001; Ali et al., 2020; Stone et al., 1996) demonstrated that wheat biomass could be quantified using early-season NDVI data recorded by an optical sensor. Furthermore, Lukina et al. (2001) found that early-season NDVI was a good predictor of final wheat grain yield across a variety of locations and years. Raun et al. (2001) demonstrated that mid-season NDVI sensor reflectance readings at the Feekes 4–6 stage in wheat could be used to estimate...
yield potential. Ali et al. (2020) investigated the relationship between N uptake and NDVI measured by a GreenSeeker optical sensor at the Feekes 6 growth stage of wheat, which is a critical time for making corrective fertilizer N decisions. They concluded that an exponential function based on the GreenSeeker sensor could explain 68.5% of the variance in N uptake at the Feekes 6 growth stage.

Fertilizer N recommendations for wheat in several countries, including Egypt, are typically fixed rates for large areas with comparable weather and landforms. In other countries, fertilizer N management is traditionally based on applying fertilizer N to reach yield goals averaged over previous years, along with a 10 to 30% increase to assure adequate N supply (Stanford, 1973; Johnson, 1991). However, in any given year, spatial and temporal variability may result in varying yields and, as a result, unrealistic fertilizer N application rates. Raun et al. (2019) argued that randomness has a role in yearly environmental variability, which influences soil N supply and crop N demand. Furthermore, in a given location, general fertilizer N recommendations are always linked to the risk of low profits and environmental deterioration (Fageria & Baligar, 2005; Ladha et al., 2005; Bijay-Singh, 2018). The worldwide N recovery efficiency in cereals is estimated to be approximately 35% (Omara et al., 2019), indicating that a substantial portion of the applied fertilizer N is prone to losses from the soil-plant system.

Understanding the crop response to N ahead of time helps in making in-season fertilizer N decisions to maintain high yield and N use efficiency. Applying N only when crops are responsive will increase yields while minimizing the possibility of overapplication (Lukina et al., 2001; Flowers et al., 2004), resulting in high N-use efficiency. Johnson et al. (2000) developed a response index to reflect the plant response to additional N, based on the proportion of yield between the plot that received adequate N and the yield in the tested plot. Despite its accuracy, this estimate is based on post-season measurements and does not address in-season N application since yield potential varies from year to year due to temporal variability. Since then, attempts have been undertaken to investigate the prospect of predicting RI-harvest at a time when management decisions can be made in-season.

Mullen et al., (2003) proposed the use of an in-season response index based on an NDVI ratio between an N adequate treated plot and a plot in question (RI-NDVI). They found that this index is positively associated with post-season response (RI-harvest). The RI-NDVI is then permitted to estimate the yield level that may be predicted by applying additional N. Johnson & Raun (2003) found that RI-NDVI, defined as the ratio of NDVI of the N rich strip to that of the test plot, was positively associated with the ratio of yield in the N rich strip to that of the test plot. Hodgson et al. (2005) also reported a significant positive correlation between RI-NDVI and RI-harvest in winter wheat. Using the same concept at Northwest India, Bijay-Singh et al. (2011) found high values of the R² between RI-NDVI and RI-harvest at Feekes 5–6 and Feekes 7–8 stages of wheat, suggesting that in-season response index based on optical sensor readings is a viable method for identifying the field locations with the potential to respond to additional fertilizer N.

The general recommendations that are widely used in Egypt and elsewhere, may result in unrealistic fertilizer N applications when current growing conditions and soil N supply are not taken into account. Therefore, there is a risk of over- or under-application of fertilizers N. Fertilizer N rates based on response estimates can assist in increasing in-season fertilizer application, N use efficiency, and yield, although this concept has yet to be implemented in Egypt. The objective of this study was to develop a prediction model that can quantify RI-harvest through RI-NDVI collected at Feekes 6 growth stage of wheat grown in the West Nile Delta of Egypt in order to prevent the over- or under-application of fertilizer N.

Materials and Methods

The Experimental Sites

Seven site-years experiments were conducted during four consecutive wheat seasons (2017/18–2020/21) at two locations in the West of Nile Delta in Egypt. The locations were at Mariout Research Station of the Desert Research Center (Location #1, 31° 0′ 12.2″ N, 29° 47′ 3.0″ E, and 15 m above sea level) and at a farmer field (Location #2, 30° 48′ 11.7″ N, 29° 44′ 59.8″ E, and 42 m above sea level). During the wheat growth season, the average maximum and minimum temperatures were 30 – 11, 24 – 7, 22 – 5, 27 – 6, 30 – 6, and 36 – 9 °C in November, December, January, February, March, and April, respectively. While the total monthly precipitation in these months were 18, 17, 17, 15, 47, and 36 − 9 mm, respectively. Before sowing, soil surface (0–30 cm) samples were collected from the experimental locations for physical and chemical analyses which are indicated in Table 1.

Experimental Design and Treatments

In 2017/18 to 2019/20 wheat seasons, six field experiments (two at both locations per season) were conducted to develop the relation between RI-harvest and RI-NDVI. The treatments consisted of nine fertilizer N rates (0, 40, 80, 120, 160, 200, 240, 280, and 320 kg N ha⁻¹) applied as ammonium nitrate in split doses. In these experiments, the fertilizer N doses were completed at 45 days after sowing.
and before the Feekes 6 stage (55 days after sowing). In the 2020/21 season, an experiment was carried out at Location #2 (the farmer field) to validate the established relation based on data collected from the three previous wheat seasons. To simulate patio-temporal variability, different doses of fertilizer N were applied before providing the corrective dose at the Feekes 6 stage. An N-rich plot was maintained in the validation experiment by applying fertilizer N at a rate of 250 kg ha\(^{-1}\) in two doses before the Feekes 6 growth stage. To compute the RI-NDVI, the NDVI data from the N-rich plots were required. The experiments were set up in all seasons and locations using a randomized complete block design with three replications.

Before sowing of wheat, the soil was ploughed twice, leveled, and split into 3 × 5 m\(^2\) plots. Wheat variety Giza 171 was manually sown in early November at a seeding rate of 155 kg ha\(^{-1}\) and harvested in mid-April. Phosphorus (60 kg P\(_2\)O\(_5\) ha\(^{-1}\) as single superphosphate) and potassium (50 kg K\(_2\)O ha\(^{-1}\) as potassium sulphate) fertilizers were applied following the general guidelines. Weeds, insects, and diseases were all controlled according to standard procedures.

### NDVI Measurements

The canopy reflectance of red and near-infrared radiations was measured using a handheld GreenSeeker active proximal sensor (Trimble, Sunnyvale, CA, USA) and expressed as NDVI. The sensor is equipped with a self-illumination system that captures reflectance from the plant canopy in the red (656 nm) and near-infrared (774 nm) bands. The sensor calculates NDVI instantly as follows:

\[
NDVI = \frac{F_{NIR} - F_{Red}}{F_{NIR} + F_{Red}}
\]

where \(F_{NIR}\) and \(F_{Red}\) are the fractions of NIR and red radiations reflected from the crop canopy to the sensor, respectively. The NDVI measurements were taken during the Feekes 6 stage of wheat (50–55 days after sowing) by walking over the plot at a speed of approximately 0.5 m s\(^{-1}\) and holding the sensor nearly 1 m above the canopy.

### Plant Sampling and Analysis

Wheat plants were manually harvested at maturity from a net area of 6 m\(^2\) in the middle of each plot in all the experiments. Grains were separated from straw using a small thresher and weighed, and samples for analysis were taken. The samples were ground after being dried to a constant weight in a hot air oven at 70 °C. The samples were digested in a sulfuric acid (H\(_2\)SO\(_4\))-hydrogen peroxide (H\(_2\)O\(_2\)) mixture, and total N was measured using the micro-Kjeldahl method (Kalra, 1997).

### Data Analysis

Excel software (a component of Microsoft Office 2019) was used for computations and curve fitting. The validation

| Season and location | Texture\(^a\) | pH\(^b\) | EC\(^c\) (dS m\(^{-1}\)) | CaCO\(_3\)\(^d\) (%) | Organic matter\(^e\) (%) | KCl extractable N\(^f\) (mg kg\(^{-1}\)) | NaHCO\(_3\) extractable P\(^g\) (mg kg\(^{-1}\)) | NH\(_4\)OAc extractable K\(^h\) (mg kg\(^{-1}\)) |
|---------------------|---------------|---------|-------------------------|----------------------|------------------------|-----------------------------|-----------------------------|-----------------------------|
| 2017/18, location #1 | Sandy loam    | 8.66    | 5.6                     | 19.5                 | 0.86                   | 61.4                        | 9.5                         | 224                         |
| 2017/18, location #2 | Loamy sand    | 8.37    | 4.7                     | 23.4                 | 1.51                   | 87.8                        | 10.8                        | 187                         |
| 2018/19, location #1 | Sandy loam    | 8.54    | 6.2                     | 24.6                 | 0.96                   | 59.3                        | 8.4                         | 231                         |
| 2018/19, location #2 | Loamy sand    | 8.42    | 5.4                     | 22.8                 | 1.59                   | 87.4                        | 11.2                        | 214                         |
| 2019/20, location #1 | Sandy loam    | 8.44    | 7.3                     | 23.7                 | 1.1                    | 63.4                        | 10.5                        | 241                         |
| 2019/20, location #2 | Loamy sand    | 8.13    | 5.1                     | 21.5                 | 1.67                   | 95.3                        | 12.3                        | 208                         |
| 2020/21, location #2 | Loamy sand    | 8.22    | 5.7                     | 22.7                 | 1.57                   | 81.4                        | 11.8                        | 219                         |

\(^a\)Using the pipette method (Page et al., 1982);
\(^b\)Potential of hydrogen measured in soil paste
\(^c\)Electrical conductivity measured in soil paste extract
\(^d\)Calcium carbonate using calcimeter (Nelson, 1983)
\(^e\)Walkely and Black (1934)
\(^f\)Available nitrogen following Bremner (1965)
\(^g\)Available phosphorus following Olsen (1954)
\(^h\)Available potassium following Pratt (1965)
experiment data (2020/21 wheat season) were evaluated using analysis of variance to identify the impacts of various fertilizer N treatments. Duncan’s multiple range test as described by Gomez & Gomez (1984) was used to identify differences between means at a probability threshold of <0.05. The N recovery efficiency (NRE) was calculated as described by Cassman et al. (1998):

\[
NRE(\%) = \frac{\text{Total N uptake in fertilized plot} - \text{Total N uptake in zero N plot}}{\text{Quantity of applied fertilizer N}}
\]

The RI-harvest was calculated as described by Johnson et al. (2000) using the following equation:

\[
RI{\text{-harvest}} = \frac{\text{Maximum grain yield in N rich plot}}{\text{Grain yield in N field rate plot}}
\]

The RI-NDVI was calculated using NDVI measurements captured at Feekes 6 growth stage of wheat using the following equation:

\[
RI{\text{-NDVI}} = \frac{\text{NDVI in N rich plot}}{\text{NDVI in N field rate plot}}
\]

**Results**

**Wheat Response to Fertilizer Nitrogen**

The purpose of the wide range in fertilizer N treatment levels in the first three seasons was to establish a wide variability in soil N supply and yield potentials across the plots. In response to the increasing rate of fertilizer N, average grain yields increased significantly, whereas NRE declined (Fig. 1). Derivative analysis of the quadratic function of grain yield response to fertilizer N indicated that a fertilizer N rate of 261 kg ha\(^{-1}\) resulted in a maximum grain yield of 8389 kg ha\(^{-1}\). At this level, the average NRE was around 34% (Fig. 1). The last 5% increase in grain yield (about 419 kg ha\(^{-1}\)) required an extra 80 kg N ha\(^{-1}\) to attain the maximum grain yield. Therefore, it has been computed that an economic grain yield of 7970 kg ha\(^{-1}\) (95% of the maximum yield) can be obtained by applying 180 kg N ha\(^{-1}\) and with an NRE of 42% (Fig. 1).

**Relationship Between NDVI at Feekes 6 Stage and Grain Yield of Wheat**

Variability in NDVI values in different treatments at the Feekes 6 growth stage was observed due to the application of an increasing rate of fertilizer N. Average relative grain yields (calculated as the ratio of actual to maximum yields) obtained over three seasons plotted against NDVI values at the Feekes 6 growth stage exhibited a significant linear relationship (Fig. 2). These findings indicate that wheat grain yield can be predicted satisfactorily using NDVI data gathered at the Feekes 6 growth stage.

**Prediction of Response Index at Harvest**

When the average RI-harvest was regressed against the fertilizer N rate, the inverse quadratic function best described the relationship, with an R\(^2\) value of 0.86 (Fig. 3). It suggests that when the supply of N fertilization rate increases, the RI-harvest decreases. It also implies that with a high

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**Fig. 1** Effect of fertilizer N application rate on wheat grain yield and N recovery efficiency. Relationship between N rate (x) and grain yield (y): \(y = -0.0801x^2 + 41.827x + 2928.7\), with R\(^2\) value of 0.97

**Fig. 2** Relationship between relative grain yields (calculated as the ratio between the grain yields in plots in question and the maximum grain yield) of wheat and NDVI (normalized difference vegetation index) readings at Feekes 6 growth stage
RI-harvest, the likelihood of obtaining a response to N fertilization is high. In the curve shown in Fig. 3, the N fertilizer rate required to shift the RI-harvest from 2 to 2.5 is 39 kg N ha$^{-1}$, and from 1.5 to 2 is 49 kg N ha$^{-1}$. Therefore if the RI-harvest could be predicted ahead of time, corrective N doses can be tailored, which will lead to increased N use efficiency at optimum yield levels.

Figure 4 depicts the linear relationship between RI-NDVI and RI-harvest at the Feekes 6 growth stage. RI-NDVI could explain around 79% of the variation in RI-harvest. Therefore, when the crop is sensed during the Feekes 6 growth stage, this index can be utilized to estimate RI-harvest using the equation: 

\[ \text{RI-harvest} = 7.077 \times \text{RI-NDVI} - 6.4885. \]

Validation of the Response Index

The regression model developed to predict RI-harvest using RI-NDVI was evaluated on an independent data set from another field experiment in which a range of fertilizer N doses were applied before the Feekes 6 growth stage. The predicted and observed RI-harvest values were plotted against each other, and a linear model was fitted (Fig. 5). The results revealed that the $R^2$ of the predicted RI-harvest using RI-NDVI versus the observed was 0.88. Furthermore, the generated linear model was close to the 1:1 line in the curve, indicating the proposed model’s effectiveness in predicting RI-harvest (Fig. 5).

Validation of predicted RI-harvest was also carried out by applying a dose of N at Feekes 6 stage estimated based on predicted RI-harvest (Table 2). An N-sufficient plot was maintained as a reference by applying fertilizer N at a rate of 250 kg ha$^{-1}$ to calculate RI-NDVI. Fertilizer N was applied at 0, 40, 80, 120, 160, and 200 kg N ha$^{-1}$ corresponding to RI-harvest values of less than 1, 1–1.5, 1.5–2, 2–2.5, 2.5–3, and greater than 3, respectively. In the field experiment carried out to evaluate the performance of the predicted RI-harvest based on RI-NDVI using this strategy, different doses of fertilizer N were applied before applying the corrective dose to induce variability in plant growth at Feekes 6 stage to simulate different spatio-temporal variability (Table 3). The data listed in Table 3 show that grain yield obtained in Treatments 6, 7, and 8 were statistically similar to the yield obtained in the general recommendation, but with less total fertilizer N rates. These findings demonstrated the usefulness of the suggested strategy based on predicted RI-harvest.
in increasing or decreasing fertilizer N levels based on plant needs. It also suggests that the proposed strategy was successful in overcoming wheat growth heterogeneity induced by varied prescriptive N management, therefore responding to the crop’s spatio-temporal variability.

Data on NRE show that the RI-guided N treatments resulted in higher values as compared to the general recommendation (Table 3). In comparison to the general recommendation, when appropriate prescriptive fertilizer N was applied (Treatment 6) followed by a corrective dose, an increase of 11.1% NRE and a saving of 50 kg N ha\(^{-1}\) were achieved. Therefore, using the predicted RI-harvest inferred from RI-NDVI in guiding N management could efficiently manage fertilizer N.

**Discussion**

It has been documented that applying fertilizer N more than the need of the crop results in substantial N losses and, as a consequence, low N use efficiency (Fageria & Baligar, 2005; Ladha et al., 2005; Bijay-Singh, 2018; Ali, 2020; Ali et al., 2021). The findings of the present study highlight the necessity for field-specific management strategies to synchronize fertilizer N supply with N demand by the crop. In the research carried out at the same location as the present study by Ali (2020) and Ali et al. (2021), the NRE by following the general recommendation for wheat was in the range of 43–55%. The lower values in the first three seasons of the present study could be due to the application of total fertilizer N dose in two split doses preceding the Feekes 6 growth stage of wheat. It was done to induce variability in crop growth because the response index being developed in the current study is based on Feekes 6 growth stage. As a result, applying N fertilizer doses during this growth stage was avoided in the first three seasons.

Forecasting yield at a crop growth stage when the plant can respond to N is essential for designing effective field-specific fertilizer N management strategies. Readings of NDVI were collected at the Feekes 6 growth stage since this stage was deemed appropriate for obtaining information and making in-season fertilizer N management decisions. Raun et al. (2001), for example, reported that the relationships between NDVI and wheat grain yield were

**Table 2** The suggested fertilizer nitrogen corrective doses based on the wheat response index at harvest

| RI-harvest (c/a) | Nitrogen corrective dose (kg ha\(^{-1}\)) |
|-----------------|--------------------------------------|
| < 1             | 0                                    |
| 1–1.5           | 40                                   |
| 1.5–2           | 80                                   |
| 2–2.5           | 120                                  |
| 2.5–3           | 160                                  |
| > 3             | 200                                  |

\(^{a}\) RI-harvest is response index at harvest and calculated as the ratio between the maximum grain yield and that in plots in question.

**Table 3** Total fertilizer N rates, wheat grain yields, total N uptake, and N recovery efficiency as influenced by different fertilizer N treatments tailored by predicted RI-harvest

| Treatment       | 10 DAS (kg N ha\(^{-1}\)) | 30 DAS (kg N ha\(^{-1}\)) | RI-NDVI | Predicted RI-harvest (c/a) | Corrective dose (kg N ha\(^{-1}\)) | Total amount of N fertilizer (kg N ha\(^{-1}\)) | Grain yield (kg ha\(^{-1}\)) | Total N uptake (kg ha\(^{-1}\)) | NRE (c/a) |
|-----------------|----------------------------|---------------------------|---------|---------------------------|------------------------------------|---------------------------------|-----------------------------|-------------------------------|-----------|
| T1 (zero-N)     | –                          | –                         | –       | –                         | –                                  | 2622 d                          | 78.1 f                      | –                            | –         |
| T2 (general recommendation) | 83.3 | 83.3 | – | – | 83.3 (fixed) | 250 | 7643 a | 198.2 a | 48.1 c|
| T3              | 0                          | 0                         | 1.35    | 3.1                       | 200                                | 200                            | 5249 c                      | 141.0 e | 31.5 e |
| T4              | 20                         | 20                        | 1.28    | 2.6                       | 160                                | 200                            | 6093 b                      | 162.3 d | 42.1 d |
| T5              | 40                         | 40                        | 1.23    | 2.2                       | 120                                | 200                            | 6298 b                      | 173.5 c | 47.7 c |
| T6              | 60                         | 60                        | 1.19    | 1.9                       | 80                                 | 200                            | 7563 a                      | 196.5 a | 59.2 a |
| T7              | 80                         | 80                        | 1.16    | 1.7                       | 80                                 | 240                            | 7658 a                      | 197.5 a | 49.8 c |
| T8              | 100                        | 100                       | 1.10    | 1.3                       | 40                                 | 240                            | 7499 a                      | 189.8 b | 56.5 b |

\(^{a}\) DAS days after sowing

\(^{b}\) RI-NDVI: response index of normalized difference vegetation index (NDVI) calculated as the ratio between NDVI in N sufficient treated plot and that in the plots in question.

\(^{c}\) RI-harvest: response index at harvest calculated as the ratio between the maximum grain yield and that in plots in question.

\(^{d}\) NRE: N recovery efficiency

Means were compared using Duncan’s multiple range test (DMRT) at \(p < 0.05\) level.
strongest between the Feekes 4 and 6 stages. Chung et al. (2010) also observed a consistent association between RI-NDVI and RI-harvest in wheat throughout the growing season. They found that until Feekes growth stage 7, the linear relationship between RI-harvest and RI-NDVI became stronger. Furthermore, several researchers have indicated that the Feekes 6 stage is the appropriate stage for deciding the amount of field-specific fertilizer N for wheat (Bijay-Singh et al., 2011; Varinderpal-Singh et al., 2017; Ali, 2020; Ali et al., 2021).

The concept of utilizing canopy reflectance to assess plant response during vegetative growth holds great potential. Generally, the higher the yield levels at which the soil will support the plant with N with any source, the lesser the fertilizer N requirement to achieve optimum yield. Consequently, it is important to identify fields where the response to applied N can be predicted. If a response to N is anticipated, N management strategies can be modified to apply N based on responsiveness. The following scenarios summarize the significance of estimating RI-harvest using in-season NDVI measurements. If the RI-harvest for a location is predicted to be low (≤ 1), the likelihood of a response to additional N is low, and so little, if any, fertilizer N is required. On the other hand, if the expected RI-harvest is high (> 2, for example), the likelihood of a response to additional N is high, and hence additional fertilizer should be applied. However, determining RI-NDVI for a given field will necessitate the establishment of a high N strip. Using this approach, N needs for every 1 m² in the field can be determined, reducing the influence of spatio-temporal variability and any agronomic management scenarios before Feekes 6 growth stage.

According to Shanahan et al. (2008), using an in-season monitoring approach to guide N management decisions in cereal production can increase the precision of N recommendations. The fact that N uptake in wheat is relatively slow at early growth stages and accelerates to a maximum around Feekes 6 growth stage supports the findings of this study (Doerge et al., 1991; Shukla et al., 2004; Tian et al., 2018; Ali et al., 2020). Several studies have found that using moderate doses of fertilizer N at planting and Feekes 2, followed by an adjustable dose at Feekes 6, worked better than the general recommendation (Bijay-Singh et al., 2002; Varinderpal-Singh et al., 2012; Ali et al., 2021). The findings of this study are also supported by the work of Bijay-Singh et al. (2011, 2017) and Ali (2020), who found that applying an NDVI-guided dose of N at the Feekes 5–6 stage of wheat produced yields equivalent to the general recommendation while using less total fertilizer N. An N management program that employs this concept will allow growers to determine the likelihood of an N response at harvest, thereby increasing their profit. However, to achieve maximum potential, an N reference strip should be maintained to reach the growth plateau at Feekes 6 growth stage, so that the N fertilizer rate can be customized.

Conclusions

This research provided insight into N management based on RI-harvest of wheat to achieve high yield and high NRE. The assumption is that when RI-harvest values are close to 1, the crop is unlikely to respond to additional N, but when they are relatively high, the crop is more likely to respond to N fertilization. This index, however, is derived after harvest, when N management during the season has already excreted its results on the crop. Based on the findings of the experiments with varying fertilizer N rates in this study, RI-NDVI at the Feekes 6 growth stage of wheat was found to be a satisfactory predictor of RI-harvest. This ability to determine the crop’s responsiveness to additional N at the appropriate vegetation stage enabled changing N management in-season to potentially increase yield and NRE. The use of this approach can prevent the over- or under-application of fertilizer N, increasing producers’ profits while minimizing environmental risk. However, this approach requires the establishment of an N-rich strip in the field to calculate RI-NDVI.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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