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RED EDGE AS A POTENTIAL INDEX FOR DETECTING DIFFERENCES IN PLANT NITROGEN STATUS IN WINTER WHEAT

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□ *Under certain conditions normalized difference vegetative index (NDVI) has low sensitivity; therefore red-edge position (REP) has been tested as an alternative vegetative index. The objective of this study was to determine if REP could be useful for detecting differences in N status for winter wheat compared to NDVI. A spectrometer, and the SPAD meter were used to measure N status. Sensitivity to plant N response and different growth stages was found for NDVI and REP, but NDVI sensitivity tended to decrease as N rate increased and REP sensitivity tended to increase with increased N rate and advancing growth stage. Both NDVI and REP were linearly correlated at all growth stages (r2 = 0.85). REP and SPAD meter readings were highly correlated (r2 = 0.62) as were NDVI and SPAD (r2 = 0.56). Overall, REP and NDVI sensitivity at high plant biomass were similar for winter wheat.*

Keywords: NDVI, red edge, wheat

INTRODUCTION

Nitrogen (N) is one of the major limiting mineral nutrients for plant growth. Raun and Johnson (1999) estimated worldwide cereal nitrogen use efficiency (NUE) to be approximately 33%. Due to the continuous increase in fertilizer costs and growing environmental concerns associated with fertilizer use, application of N fertilizer according to plant need has become increasingly popular due to its potential for increasing NUE and reducing input costs. To determine the optimum N rate based on plant need, optical

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sensing technologies have been developed to detect N status in plants. Normalized difference vegetative index (NDVI) computed from optical sensing is one of the most widely used vegetative indices for the evaluation of plant N status.

There are however, some drawbacks to using NDVI. It has been reported to have low sensitivity at high chlorophyll content or abundant biomass. Gitelson et al. (2002) listed several possible reasons for low sensitivity of NDVI. Decreased NIR reflectance was associated with changes in leaf orientation from one growth stage to the next, reduction in chlorophyll content at senescence, and increasing soil moisture. This also results in the poor estimation of biomass once soil is covered by vegetation (Clevers et al., 2001).

To overcome these limitations, wavebands called "red-edge" were employed as new spectra to evaluate plant N conditions. Red-edge wavebands are between RED (670nm) and NIR (780 nm). These bands were shown to have greater sensitivity at higher chlorophyll content, which was detected as greener biomass. Red edge position (REP) is influenced by chlorophyll content, leaf mesophyll structure, and leaf area index (LAI) (Meer and Jong, 2006). On the other hand, leaf orientation, solar angle and soil background had a small influence on REP. Also by combining plant growth models with REP, they improved the estimation of yield in sugarcane (Meer and Jong, 2006).

Several methods have been developed to find the REP. One is detecting the inflection point of the reflectance curve which is the maximum slope between RED and NIR (Meer and Jong, 2006). It uses the first derivative analysis to detect REP (Chen and Elvidge, 1993). Another method is the linear method which estimates the maximum inflection point by interpolating among four bands; 670, 700, 740, and 780 nm (Guyot and Baret, 1988). Shafri et al. (2006) reported that this linear method has more soil background noise than the Lagrangian interpolation technique which is based on the spectrum derivative analysis. With the linear method, the overestimation of REP by about 10 nm was found compared with the first derivative method (Dawson and Curran, 1998). However, Dawson and Curran (1998) also reported that both methods were correlated at differing chlorophyll levels and the correlation coefficient of REP determined by different methods was high ($R^2 > 0.99$). Mutanga and Skidmore (2007) drew attention to the double points for the red-edge especially in the high N-treated plant using the first derivative method. If double REP exists, the linear method is not appropriate to detect the red-edge position. Cho and Skidmore (2006) also developed another method where REP is determined by the intersection of the far-red and red lines on the first derivative reflectance. REP determined by this method increased the linear relationship with N concentration compared with the first derivative method or linear method.

Oklahoma State University (OSU) has been developing algorithms for N fertilization for various crops since the early 1990s. The algorithms are based on the use of an optical, active light, handheld GreenSeeker^{TM} sensor (NTech Industries, Ukiah, CA, USA) which detects the fraction of light being reflected from the plant. The OSU algorithm uses GreenSeeker^{TM} NDVI values as the key input for calculation of the optimum mid-season N fertilization rate. Due to reported limitations indicating NDVI is insensitive to high chlorophyll concentrations or plant biomass, it was necessary to evaluate the potential of red edge for detecting N differences. From an agronomic perspective, it is crucial that timing of N application as well as the rate of N fertilizer be considered. The optimum time to make a decision for mid-season N application in winter wheat is at Feekes 4 to 5 (Large, 1954). It was reported that when mid-season N was applied between Feekes 3 and 4, there was no yield loss (Boman et al., 1995). After Feekes 4, tissue damage and lower forage yields were detected from having applied foliar N. Rapid N uptake occurs between Feekes 2 to 4 and by Feekes 7, wheat takes up more than a third of the total accumulated (Waldren and Flowerday, 1979). Therefore, in winter wheat, it is essential to determine the N rate for mid-season application at or before Feekes 4. At this time, the wheat plant does not completely cover the ground; there it can be assumed that NDVI is still sensitive to plant biomass. It is, thus, essential to investigate how NDVI and REP behave differently for early season growth of winter wheat.

The SPAD meter is also commercially available and has been used for detecting N differences in winter wheat (Fox et al., 1994). This device emits light at 650 and 940 nm. The transmittance ratio is then used for estimation of chlorophyll content which is ultimately related with the N status in plants. Therefore, it is essential to evaluate how it behaves differently from REP.

The objective of this paper was to determine whether the red-edge index has the potential to be a useful index for detecting differences in N status for winter wheat compared to NDVI and SPAD meter.

MATERIALS AND METHODS

A spectrometer and a chlorophyll meter (SPAD-502; Minolta, Tokyo, Japan) were used to collect data in winter wheat. Measurements were taken at different growth stages (Feekes growth stages 4, 5, 7, and 10) for two cropping seasons.

Data were collected from long-term winter wheat experimental plots located at Stillwater (Experiment #222) and Perkins (N & P Study), Oklahoma. Experiment #222 was established in 1969 under conventional tillage on a Kirkland silt loam (fine, mixed, superactive, thermic Udertic Paleustoll). The N & P study was initiated in 1996, also under conventional tillage on a Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll). These experiments are long-term nitrogen (N)-phosphorus (P)-potassium (K) trials consisting of thirteen treatments (Experiment #222) with four replications, and twelve treatments (N & P study) with three replications, respectively.

Both were arranged in a randomized complete block design (RCBD). Four N treatments (0, 40, 90, and 135 N kg ha^{-1}) and (0, 56, 112 and 168 kg N ha^{-1}) were evaluated in Experiment #222 and the N & P study, respectively.

Two instruments were used to obtain data for this study: the Minolta SPAD 502 meter and an Ocean Optics USB4000 spectrometer (Ocean Optics, Dunedin, FL, USA). All of the readings were taken from a 1 m^2 area in each plot. The Minolta SPAD 502 chlorophyll meter determines the relative amount of chlorophyll by measuring light transmitted or absorbed by plant leaves. The SPAD 502 is a compact meter that measures chlorophyll using optical density differences at two wavelengths (650 nm and 940 nm) with a measurement area of 2 mm × 3 mm. Twenty SPAD readings were randomly taken from winter wheat plant leaves within the 1 m^2 sampling area, and subsequently averaged. The Ocean Optics USB4000 spectrometer operates with Spectrasuite (cross-platform spectroscopy software) to measure reflectance. This spectrometer can detect reflectance from 200–1100 nm at a high resolution (optical resolution of 1.5 nm full width half maximum). Reflectance of the plant canopy was computed by (the reflected light from the surface of the plant canopy minus black measurement to eliminate noise)/(incident light minus black measurement). Incident light was determined by measuring reflectance of a $1m^2$ white plate composed of barium sulfate. Dark current was measured by covering the sensor with a cap and fabric material.

Spectral Calculation

Red-Edge Position (REP)

For the REP, two methods were applied: Derivative method by curve fitting techniques and the linear method. For the derivative method, spectrometer reflectance from 650 nm to 750 nm were collected and transported into SYSTAT Table Curve 2.D. software (SYSTAT Inc., San Jose, CA, USA) and interpolated using a curve fitting formula. By using the formula, the maximum point of the first derivative was recorded as REP. For the linear method (Figure 1), the interpretation by Clevers (1994) was used.

$$\rho_{\mathrm{REP}} = \frac{\rho_{670} + \rho_{780}}{2} \tag{1}$$

$$\mathrm{REP} = 700 + 40 * \frac{(\rho_{\mathrm{REP}} - \rho_{700})}{(\rho_{740} - \rho_{700})} \tag{2}$$

NDVI and Simple Ratio

NDVI and simple ratio computed as follows:

$$\mathrm{NDVI}_{\mathrm{RED}} = \frac{\rho_{780} - \rho_{670}}{\rho_{780} + \rho_{670}} \tag{3}$$

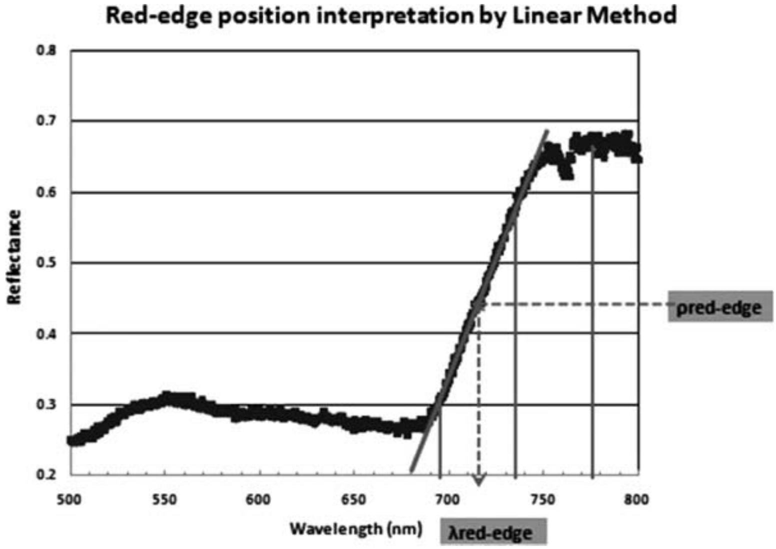

FIGURE 1 Red-edge position determined by the linear method (Meer and Jong, 2006).

$$\mathrm{NDVI}_{\mathrm{GREEN}} = \frac{\rho_{780} - \rho_{560}}{\rho_{780} + \rho_{560}} \tag{4}$$

$$\mathrm{SR}_{\mathrm{RED}} = \frac{\rho_{780}}{\rho_{670}} \tag{5}$$

$$\mathrm{SR}_{\mathrm{GREEN}} = \frac{\rho_{780}}{\rho_{560}} \tag{6}$$

RESULTS

Stillwater

In 2007, spectrometer measurements at Feekes 10 were excluded due to measurement errors.

Overall, REP was highly correlated with all others at all growth stages (Table 1). High correlation between REP and $\mathrm{NDVI}_{\mathrm{RED}}$ was found. In both 2008 and 2009, the relationship between REP and SPAD increased with advancing plant growth. Compared with $\mathrm{NDVI}_{\mathrm{GREEN}}$, $\mathrm{NDVI}_{\mathrm{RED}}$ had a better relationship with REP. REP tended to have a higher relationship with $\mathrm{SR}_{\mathrm{RED}}$ and $\mathrm{SR}_{\mathrm{GREEN}}$ (simple ratio) than $\mathrm{NDVI}_{\mathrm{RED}}$ and $\mathrm{NDVI}_{\mathrm{GREEN}}$ (normalized index). It was found that there was slightly higher correlation between REP and SPAD compared with correlation between $\mathrm{NDVI}_{\mathrm{RED}}$ and SPAD (Tables 1 and 2). It possibly indicates that REP has higher sensitivity to chlorophyll concentration than $\mathrm{NDVI}_{\mathrm{RED}}$. $\mathrm{SR}_{\mathrm{RED}}$ is widely recognized to detect plant biomass on the ground (Bellairs et al., 1996; Serrano et al., 2000; Babar

TABLE 1 Simple correlation coefficients between REP and each index (linear method), Stillwater, OK, 2008–2009

	$NDVI_{RED}$	$NDVI_{GREEN}$	SR_{RED}	SR_{GREEN}	SPAD
2008					
Feekes 4	0.766	0.667	0.769	0.677	0.719
Feekes 5	0.865	0.872	0.914	0.904	0.83
Feekes 7	0.835	0.918	0.872	0.925	0.846
Feekes 10	—	—	—	—	—
2009					
Feekes 4	0.83	0.767	0.81	0.75	0.326
Feekes 5	0.774	0.697	0.776	0.697	0.518
Feekes 7	0.531	0.579	0.48	0.48	0.608
Feekes 10	0.83	0.814	0.843	0.824	0.637

*Significant at the 0.001 probability level $NDVI_{RED} = \frac{\rho_{780}-\rho_{670}}{\rho_{780}+\rho_{670}}$, $NDVI_{GREEN} = \frac{\rho_{780}-\rho_{560}}{\rho_{780}+\rho_{560}}$, $SR_{RED} = \frac{\rho_{780}}{\rho_{670}}$, $SR_{GREEN} = \frac{\rho_{780}}{\rho_{560}}$ SPAD = SPAD meter readings.

et al., 2006). $NDVI_{RED}$ tended to have higher correlation with SR_{RED} than REP which indicated that $NDVI_{RED}$ could be more sensitive to plant biomass.

There was a significant influence of N rate on REP at all growth stages both in 2008 and 2009 crop years ($P < 0.05$, Figure 2). Nitrogen rate and REP had significant linear relationships at all growth stages ($P < 0.05$). Quadratic relationships between N rates and REP were found at Feekes 7 in 2008 and Feekes 4 and 5 in 2009 ($P < 0.05$). The REP shifted to longer wavelengths with the increase in N rates. The range of REP increased as plant growth progressed in 2008 (4.33, 3.88 and 5.39 nm at Feekes 4, 5, and 7, respectively). At high N rates, shifts of REP to longer wavelengths were clearly detected as growth stage increased.

There was a significant influence of N rate on $NDVI_{RED}$. Nitrogen rate and $NDVI_{RED}$ had a significant linear relationship at all growth stages. Quadratic relationships between N rates and $NDVI_{RED}$ were not found in

TABLE 2 Simple correlation coefficients between $NDVI_{RED}$ and each index, Stillwater, OK, 2008–2009

	$NDVI_{GREEN}$	SR_{RED}	SR_{GREEN}	SPAD
2008				
Feekes 4	0.978	0.988	0.976	0.482
Feekes 5	0.978	0.97	0.968	0.787
Feekes 7	0.956	0.956	0.918	0.709
Feekes 10	—	—	—	—
2009				
Feekes 4	0.956	0.994	0.949	0.396
Feekes 5	0.986	0.98	0.974	0.367
Feekes 7	0.962	0.924	0.937	0.345
Feekes 10	0.988	0.966	0.97	0.408

*Significant at the 0.001 probability except SPAD, $NDVI_{GREEN} = \frac{\rho_{780}-\rho_{560}}{\rho_{780}+\rho_{560}}$, $SR_{RED} = \frac{\rho_{780}}{\rho_{670}}$, $SR_{GREEN} = \frac{\rho_{780}}{\rho_{560}}$ SPAD = SPAD meter readings.

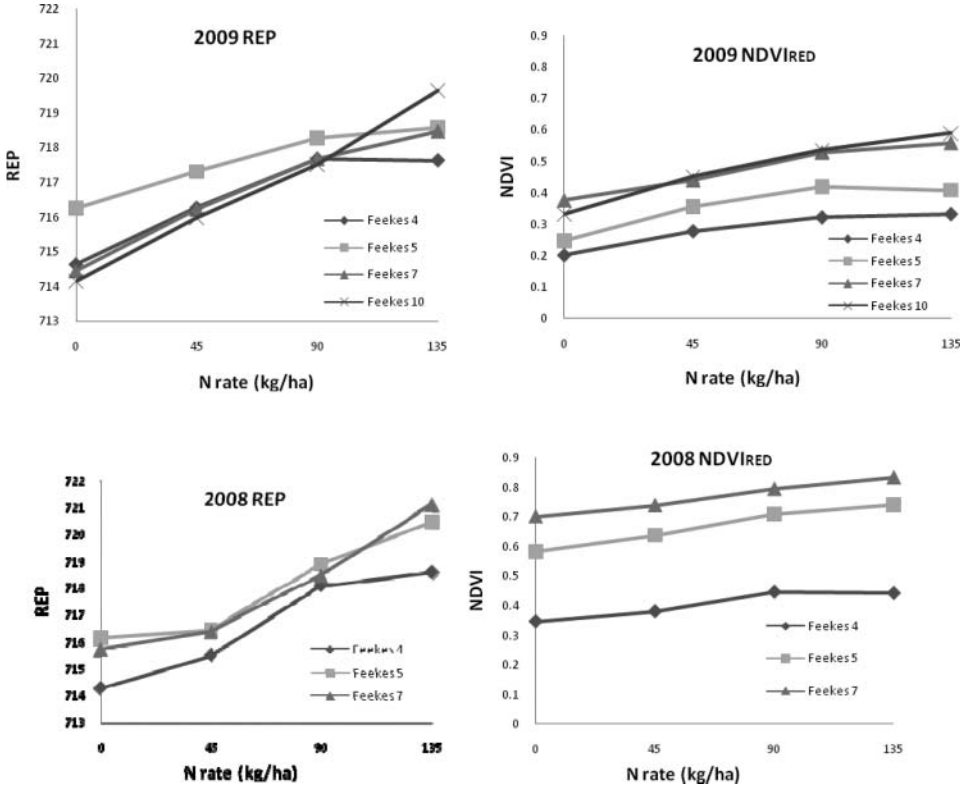

FIGURE 2 $NDVI_{RED}$ and REP plotted against N rate, Stillwater, OK, 2008–2009.

2008 but found at Feekes 4 and 5 in 2009 ($\alpha = 0.05$). In 2009, Experiment #222 had a heavy rye grass infestation, and as a result, plant growth was limited. This could explain the low $NDVI_{RED}$ values in 2009 compared with 2008 at whole growth stages. $NDVI_{RED}$ tended to be more sensitive for detecting differences in growth stages than REP (Figure 2). These results showed that $NDVI_{RED}$ better detected differences in plant growth at the same N rates, especially at early growth stages.

Perkins

At Feekes 7 in 2008, spectrometer data were excluded due to measurement error. At Feekes 5 in 2009, all data were excluded due to measurement error.

Overall, REP was highly correlated with all others at all growth stages except SPAD in 2008 (Table 3). The REP and $NDVI_{RED}$ were highly correlated. As recorded in Stillwater the correlation between REP and SPAD increased with advancing plant growth. REP tended to be more highly correlated with SR_{RED} and SR_{GREEN} (simple ratio) than $NDVI_{RED}$ and $NDVI_{GREEN}$ (normalized index) at Stillwater but this was not detected at Perkins. Higher

TABLE 3 Simple correlation coefficients between REP and each index (linear method), Perkins, OK, 2008–2009

	$NDVI_{RED}$	$NDVI_{GREEN}$	SR_{RED}	SR_{GREEN}	SPAD
2008					
Feekes 4	0.924	0.918	0.887	0.878	0.238
Feekes 5	0.863	0.878	0.83	0.776	0.265
Feekes 7	—	—	—	—	—
Feekes 10	0.941	0.953	0.931	0.924	0.261
2009					
Feekes 4	0.686	0.593	0.618	0.702	0.74
Feekes 5	—	—	—	—	—
Feekes 7	0.955	0.955	0.941	0.935	0.745
Feekes 10	0.814	0.856	0.771	0.748	0.812

*Significant at the 0.001 probability level except SPAD, $NDVI_{RED} = \frac{\rho_{780}-\rho_{670}}{\rho_{780}+\rho_{670}}$, $NDVI_{GREEN} = \frac{\rho_{780}-\rho_{560}}{\rho_{780}+\rho_{560}}$, $SR_{RED} = \frac{\rho_{780}}{\rho_{670}}$, $SR_{GREEN} = \frac{\rho_{780}}{\rho_{560}}$ SPAD = SPAD meter readings.

correlation between REP and SPAD was found compared with correlation between NDVI and SPAD at both Stillwater and Perkins (Tables 1 and 2, for Stillwater, and Tables 3 and 4 for Perkins), suggesting that REP has higher sensitivity to chlorophyll concentration than NDVI.

There was a significant influence of N rate on REP only at Feekes 10 in 2008 and at all growth stages in 2009 ($P < 0.05$, Figure 3). Nitrogen rate and REP were linearly correlated at all growth stages ($P < 0.05$). The REP shifted to longer wavelengths with increased N rates but the shifts were not found with advancing plant growth. The range of REP increased as plant growth progressed in 2008 (2.10, 3.0.3 and 5.64 nm at Feekes 4, 5, and 10 respectively) and in 2009 (3.12, 8.41, and 7.76 at Feekes 4, 7 and 10 respectively).

TABLE 4 Simple correlation coefficients between $NDVI_{RED}$ and each index, Perkins, OK, 2008–2009

	$NDVI_{GREEN}$	SR_{RED}	SR_{GREEN}	SPAD
2008				
Feekes 4	0.994	0.99	0.99	0.149
Feekes 5	0.994	0.974	0.951	0.108
Feekes 7	—	—	—	—
Feekes 10	0.99	0.962	0.968	0.199
2009				
Feekes 4	0.982	0.978	0.992	0.918
Feekes 5	—	—	—	—
Feekes 7	0.994	0.972	0.972	0.689
Feekes 10	0.978	0.893	0.92	0.75

*Significant at the 0.001 probability except SPAD, $NDVI_{GREEN} = \frac{\rho_{780}-\rho_{560}}{\rho_{780}+\rho_{560}}$, $SR_{RED} = \frac{\rho_{780}}{\rho_{670}}$, $SR_{GREEN} = \frac{\rho_{780}}{\rho_{560}}$ SPAD = SPAD meter readings.

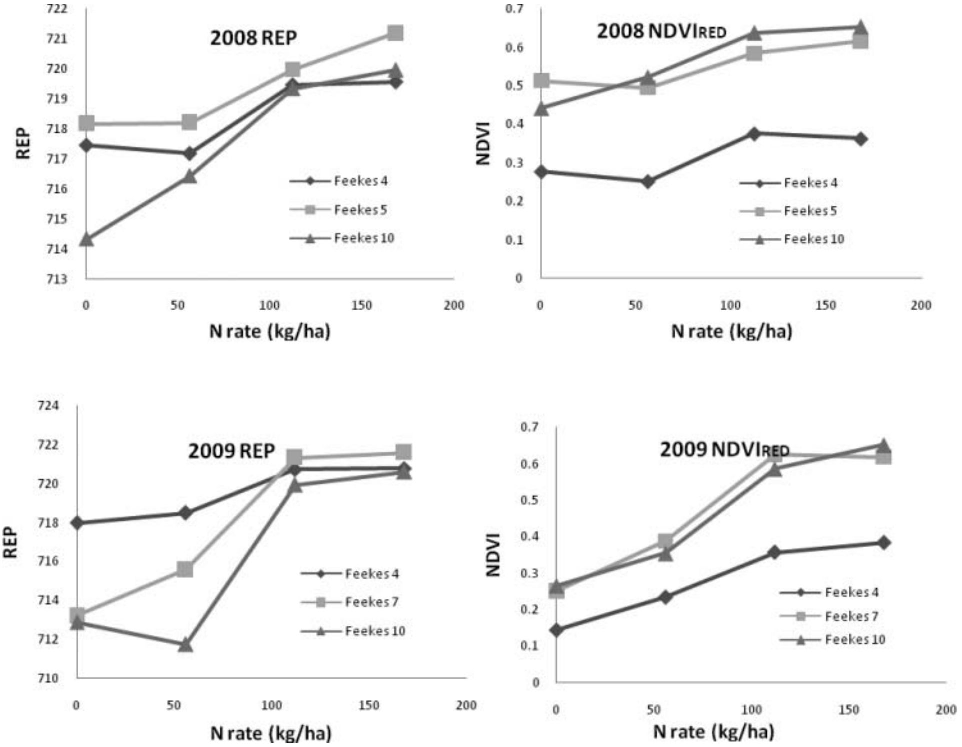

FIGURE 3 $NDVI_{RED}$ and REP plotted against N rate, Perkins, OK, 2008–2009.

There was a significant influence of N rate on $NDVI_{RED}$ at all growth stages and in both years excluding Feekes 4 in 2008 ($P < 0.05$) (Figure 3). A quadratic relationship between N rate and $NDVI_{RED}$ was found at Feekes 4 and 7 in 2009 ($P < 0.05$). In general sensor values for $NDVI_{RED}$ detected differences in plant N response and growth stage for both years. Once plant growth was sufficient to provide complete plant cover (beyond Feekes 7), it was still possible to detect N rate differences using $NDVI_{RED}$ or REP (Figure 3, Feekes 10).

DISCUSSION

First, the relationship between NDVI and REP needs to be discussed. Researchers have noted that REP is an alternative index and could have higher sensitivity under dense green biomass. In this research, NDVI and REP were linearly related. The relationship between NDVI and N rate, and REP and N rate were processed in Table Curve 2D v5.01.01 (Systat Software, San Jose, CA, USA) to acquire linear, logarithmic, exponential, and sigmoid models. Then parameters of each model including, r^2, adjusted r^2, standard error, and F score, were tested with a t-test comparison to determine if REP and NDVI were different in terms of detecting differences in N rates. Results in Tables 5 and 6 show that there was no significant difference

TABLE 5 Model parameters between REP and different N rates or between NDVI$_{\mathrm{RED}}$ and different N rates

	Variable	Index	Mean	Std dev	Std error
Linear (y = ax + b)	r^2	NDVI$_{\mathrm{RED}}$	0.661	0.201	0.058
	r^2	REP	0.733	0.112	0.032
	r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.071	0.163	0.067
	Adjusted r^2	NDVI$_{\mathrm{RED}}$	0.6125	0.2619	0.0726
	Adjusted r^2	REP	0.6632	0.1684	0.0467
	Adjusted r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.0507	0.2202	0.0864
	Standard Error	NDVI$_{\mathrm{RED}}$	0.0545	0.0203	0.00564
	Standard Error	REP	1.1899	0.5836	0.1619
	Standard Error	Difference (NDVI$_{\mathrm{RED}}$-REP)	−1.1354	0.4129	0.162
	F score	NDVI$_{\mathrm{RED}}$	59.1929	44.1177	12.2361
	F score	REP	72.5746	66.0809	18.3275
	F score	Difference (NDVI$_{\mathrm{RED}}$-REP)	−13.3817	56.183	22.0368
Logarithm (y − ax + b In(x))	r^2	NDVI$_{\mathrm{RED}}$	0.6422	0.2126	0.059
	r^2	REP	0.7077	0.1338	0.0371
	r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.0656	0.1776	0.0697
	Adjusted r^2	NDVI$_{\mathrm{RED}}$	0.5926	0.2513	0.0697
	Adjusted r^2	REP	0.6625	0.1661	0.0461
	Adjusted r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.0699	0.213	0.0835
	Standard Error	NDVI$_{\mathrm{RED}}$	0.0564	0.02	0.00555
	Standard Error	REP	1.1783	0.5585	0.1549
	Standard Error	Difference (NDVI$_{\mathrm{RED}}$-REP)	−1.1219	0.3952	0.155
	F score	NDVI$_{\mathrm{RED}}$	52.9866	42.0479	11.662
	F score	REP	77.7351	86.0683	23.871
	F score	Difference (NDVI$_{\mathrm{RED}}$-REP)	−24.7485	67.7339	26.5674
Exponential (y = a * exp(bx))	r^2	NDVI$_{\mathrm{RED}}$	0.6614	0.2011	0.0581
	r^2	REP	0.7328	0.1128	0.0326
	r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.0714	0.1631	0.0666
	Adjusted r^2	NDVI$_{\mathrm{RED}}$	0.6179	0.2336	0.0674
	Adjusted r^2	REP	0.694	0.1399	0.0404
	Adjusted r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.0761	0.1926	0.0786
	Standard Error	NDVI$_{\mathrm{RED}}$	0.0571	0.0215	0.00621
	Standard Error	REP	1.1566	0.594	0.1715
	Standard Error	Difference (NDVI$_{\mathrm{RED}}$-REP)	−1.0995	0.4203	0.1716
	F score	NDVI$_{\mathrm{RED}}$	55.7023	42.5734	12.2899
	F score	REP	78.5833	65.9384	19.0348
	F score	Difference (NDVI$_{\mathrm{RED}}$-REP)	−22.881	55.4994	22.6575
Sigmoid	r^2	NDVI$_{\mathrm{RED}}$	0.725	0.2133	0.0592
	r^2	REP	0.7732	0.1515	0.0392
	r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.048	0.181	0.071
	Adjusted r^2	NDVI$_{\mathrm{RED}}$	0.6467	0.2799	0.0776
	Adjusted r^2	REP	0.6866	0.228	0.632
	Adjusted r^2	Difference (NDVI$_{\mathrm{RED}}$-REP)	−0.04	0.2553	0.1001
	Standard Error	NDVI$_{\mathrm{RED}}$	0.0503	0.0233	0.0065
	Standard Error	REP	1.0705	0.4432	0.1229
	Standard Error	Difference (NDVI$_{\mathrm{RED}}$-REP)	−1.02	0.3138	0.1231
	F score	NDVI$_{\mathrm{RED}}$	29.564	26.349	7.3079
	F score	REP	33.732	35.379	9.8124
	F score	Difference (NDVI$_{\mathrm{RED}}$-REP)	−4.168	31.192	12.235

TABLE 6 Results of T-test between REP and NDVI models

	Parameter	df	t value	P > ItI
Linear ($y = ax + b$)	r^2	24	−0.68	0.09
	Adjusted r^2	24	−0.59	0.56
	Standard Error	24	−7.01	<0.0001
	F score	24	−0.61	0.55
Logarithm ($y - ax + b\ \mathrm{In}(x)$)	r^2	24	−0.94	0.36
	Adjusted r^2	24	−0.84	0.41
	Standard Error	24	−7.24	<0.0001
	F score	24	−0.93	0.36
Exponential ($y = a * \exp(bx)$)	r^2	22	−1.07	0.3
	Adjusted r^2	22	−0.97	0.34
	Standard Error	22	−6.41	<0.0001
	F score	22	−1.01	0.32
Sigmoid	r^2	21	0.75	0.46
	Adjusted r^2	21	1.15	0.03
	Standard Error	21	−6.93	<0.0001
	F score	21	0.1	0.92

between indices for the parameters reported, excluding standard error for all models. The significant difference between indices for the standard error could be explained by the difference in units between REP and NDVI. REP is described by a 3 digit number (e.g., 724 nm) while NDVI is described by 3 decimals (e.g., 0.455). Therefore, the standard deviation of REP should be larger and as a result, significant differences between indices were recorded for the standard error. Other than that, there were no significant differences of indices between r^2, adjusted r^2, and F score. There was also no difference between NDVI and REP models for detecting differences in plant N.

In Oklahoma, farmers apply N, midseason at Feekes 4 and 5. But, in general, they need to make the fertilizer N rate decision before Feekes 5. At that time, the ground is not fully covered by biomass (Figure 4). Therefore, low sensitivity of NDVI to plant biomass is not a problem. However with the decreased biomass on the ground, other problems arise. With a decrease in plant cover on the ground, the soil is more exposed and it might increase the noise for NDVI. In Figure 5, the relationship between REP and NDVI is described at Feekes 4. At the high N rate where more surface biomass was expected, the correlation between REP and NDVI was high, but decreased as N rate decreased. The decrease in correlation could be explained by the reduction of plant biomass which ultimately increases the area of soil exposed, and directly influences REP and NDVI values. Some research reports that there is less influence of soil background on REP (Meer and Jong, 2006). Therefore, NDVI might be more influenced by soil background and as such would behave differently than REP. Detection of biomass amounts using different soil backgrounds will require further study.

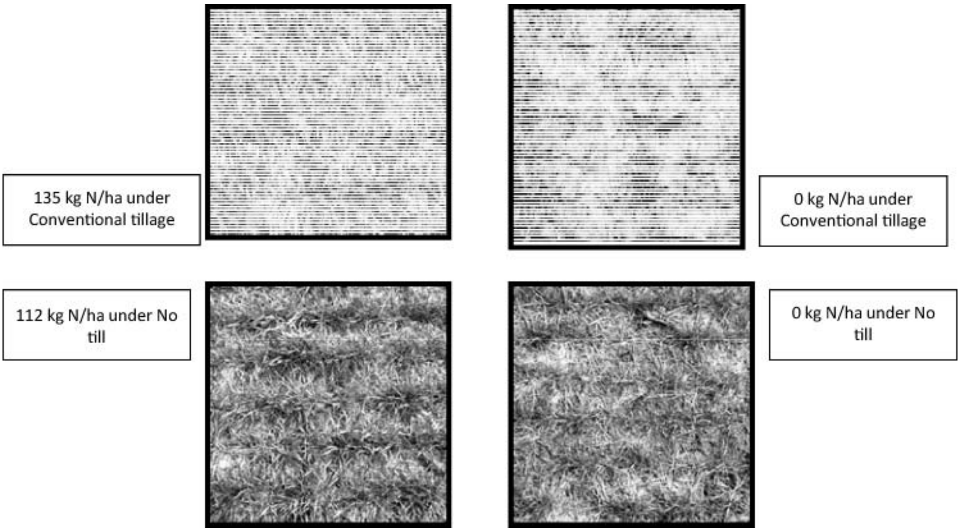

FIGURE 4 Visual image of winter wheat at Feekes 4 under conventional tillage and no-tillage, Stillwater and Perkins, OK, 2008.

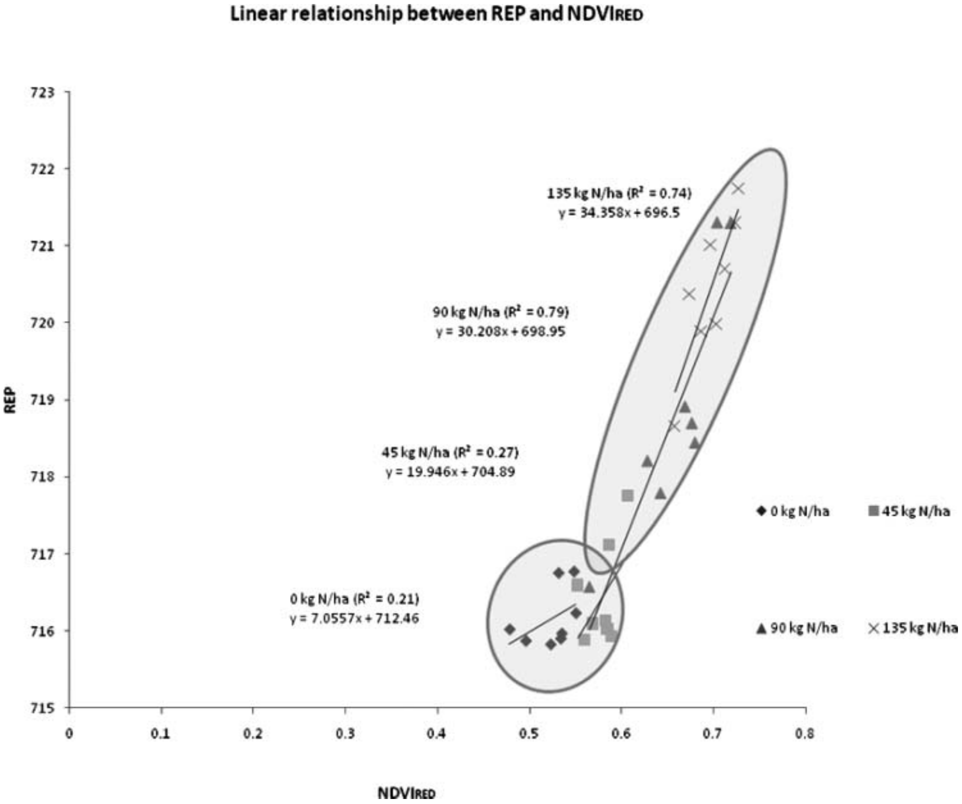

FIGURE 5 Linear relationship between REP and $NDVI_{RED}$ at Feekes 4 at different N rates, Stillwater, OK, 2008.

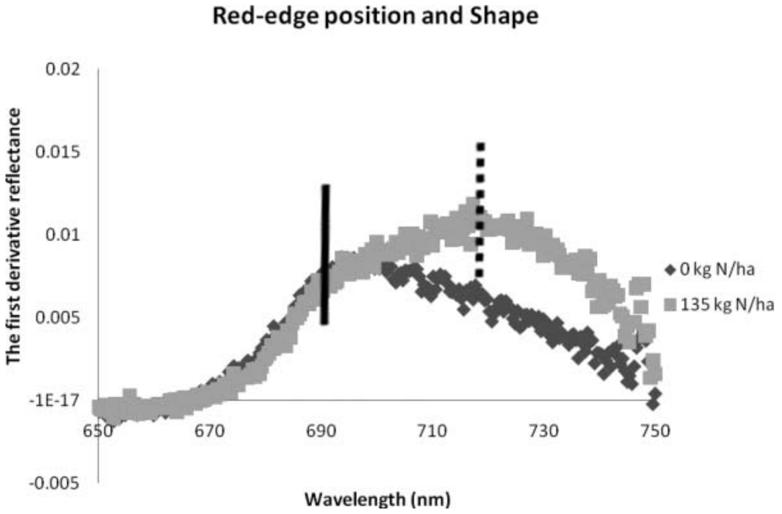

FIGURE 6 Shape of red-edge and its position at Feekes 4 in the 0 kg N/ha and 135 kg N/ha plots, Stillwater, OK, 2008.

The advantages and/or disadvantages of REP in field based research need to be discussed. Studies showed that REP was highly correlated with chlorophyll content at the plant canopy level (Chappelle et al. 1991; Cho and Skidmore 2006). It was also shown in our research that REP was highly correlated with SPAD chlorophyll meter readings. The position and shape of the first derivative spectrum provides more opportunity to differentiate plant N response (Cheng et al., 2005; Kupfer and et al., 1990). As illustrated in Figure 6, the shape of the first derivative reflectance is more clearly defined in low N rates than high N rates. Two points where maximums occur are shown for the 0 kg N/ha rate. At the same plant growth stage, you can differentiate plant N status by “the shape” of the first derivative reflectance, and can also distinguish “the position” of the maximum point of the first derivative reflectance. The basic point is that you can manipulate two outcomes, “the position and the shape” of the first derivative reflectance, from red-edge bands which does not happen with NDVI or simple ratio. Filella and Penuelas (1994) showed that the area of the first derivative reflectance has strong correlation with plant biomass. Another advantage is that under high biomass, red-edge position could give more accurate estimates of biomass (Filella and Penuelas, 1994; Mutanga and Skidmore, 2004a, 2004b). The results show that NDVI is sensitive to different plant N response as well as different plant growth stages but the sensitivity tended to be higher for REP, especially with advancing growth stage.

There are also disadvantages when using REP. Using the Ocean Optics USB4000 spectrometer, REP was very sensitive to noise, or in other words,

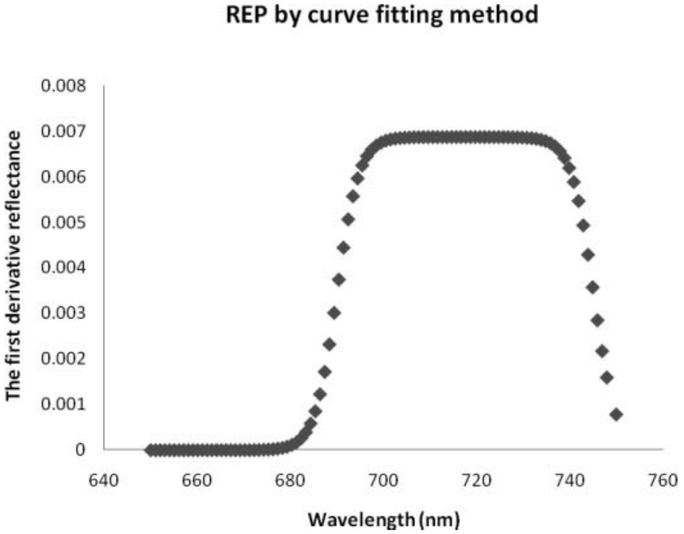

FIGURE 7 Shape of red-edge by derivative method with curve fitting techniques at Feekes 5 in 135 kg N/ha plots, Stillwater, OK, 2009.

it is hard to find the position of red edge. Red-edge could be obtained using a hyperspectrometer but because of high contents of information per pixel, the analysis of derivative system requires the right techniques and time (Ruffin and King, 1999). In this wheat study, the range of red-edge position was narrow, not more than 15 nm, between non-N treated palnts and high N treated plants (Figures 2 and 3). Also as described in Figure 7, some plot samples show that red-edge position using the curve fitting method has equal probability for any value wavelength within 710 nm to 730 nm. To facilitate more simplified capture of information from clearly very narrow wavebands, better spectrometers will be required.

CONCLUSIONS

The REP behaved very similar to NDVI in winter wheat. Because of the costs associated with capturing and using REP data in sensor based technology, and since there were no clear benefits over that of NDVI, widespread use of REP at present stifled. More evidence from work on a range of crops and is needed to verify if REP is significantly better than NDVI. Modifying existing sensors to include REP may not be worth the investment in winter wheat. Further research is needed to evaluate REP with biomass at early growth stages. In general, these results showed that $\mathrm{NDVI}_{\mathrm{RED}}$ better detected differences in plant growth at the same N rates, especially at early growth stages when compared to REP.

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