Predicting Sugarcane Response to Nitrogen Using a Canopy Reflectance-Based Response Index Value

J. Lofton, B. S. Tubana,* Y. Kanke, J. Teboh, and H. Viator

ABSTRACT

In Louisiana, sugarcane (*Saccharum officinarum* L.) N rate recommendations are established based on N response trials and further refined for specific crop age and soil type. Without accounting for current growing conditions and soil N levels, these recommendations can potentially lead to under- or over-application of N fertilizers. The objective of this study was to determine if N response index at harvest ($RI_{Harvest}$) can be predicted using normalized difference vegetative index (NDVI) response index value (RI_{NDVI}). Sensor and yield data were collected from different N field trials from 2008 to 2010 in St. Gabriel and Jeanerette, LA. Nitrogen fertilization treatments ranged between 0 to 201 kg N ha^{-1}. A GreenSeeker Hand Held Optical Active Sensor (Trimble Navigation, Ltd., Sunnyvale, CA) was used to obtain NDVI readings for each of three consecutive weeks beginning 3 wk after fertilization. There was a strong relationship between RI_{NDVI} and $RI_{Harvest}$ using the traditional method of determining RI, comparing plots that received high N rates to check plots, with coefficient of determination (r^2) values of 0.92 for cane tonnage and 0.81 for sugar yield ($P < 0.05$). When using a modified RI value, which compared all N rates to the check plot, relationships between RI_{NDVI} and $RI_{Harvest}$ were comparable, with r^2 values of 0.85 and 0.81 for cane tonnage and sugar yields, respectively ($P < 0.05$). Our results suggest that NDVI collected 4 wk after N fertilization can be used to predict sugarcane yield response to fertilizer N using the relationships established by either the traditional or modified RI methods.

Sugarcane is one of the most important row-crops in Louisiana with economic values exceeding more than $2 billon (Legendre et al., 2000). Sugarcane is an integral part of Louisiana's economy thus it is essential to employ production technologies which will help decrease cost of production and environmental risk while maximizing yields. Applying N only when the crops are responsive will not only improve production, but also decrease the potential of overapplication (Lukina et al., 2000; Flowers et al., 2004). Overapplication of N fertilizers can lead to excess NO_3–N accumulation in the soil, potentially leading to pollution of ground and surface waters (Embelton et al., 1986; Vyn et al., 1999; Chen et al., 2004). Goolsby et al. (2001) reported that mean annual discharge of all forms of N down the Mississippi was approximately 1,568,000 MT yr^{-1}.

Sugarcane is a semi-perennial crop and is harvested for at least two additional years after the first harvest, which are termed plant cane for the first crop after planting and stubble cane for the subsequent crops after the first harvest. Plant cane is generally not responsive to N fertilization; however, this does not apply to the following stubble cane crops. In Louisiana, N fertilizer recommendations are established based on multi-site and multi-year response trials using the most prevalent cane varieties in the state. The recommendations are further refined for specific crop age, that is, plant and stubble cane, and soil type, generalized as either light-textured soil or heavy-textured soil (Legendre et al., 2000). Unlike most other cropping systems, current growing conditions and soil N levels are not accounted for when determining N recommendations. Therefore, there is a potential risk of over- or under-application of N fertilizers. Shanahan et al. (2008) reported that implementation of in-season monitoring approach to guide N management decision, in cereal production, can improve the precision of N recommendation. Similarly in sugarcane, a more robust approach to guide N fertilizer recommendation that can be adjusted based on current growing conditions is needed to minimize this risk.

One way to derive an N recommendation, specifically in grain crops production, is based on pre-plant established yield goal and soil NO_3–N level (Meisinger et al., 2008). To determine N recommendation rate, the soil NO_3–N level is subtracted from the crop's total N requirement associated with a specified yield goal (Meisinger et al., 2008). The soil sample can be obtained either before planting, pre-plant soil testing (PPST), or before sidedress application, pre-sidedress soil test (PSST). Meisinger et al. (2008) noted that while PSST may achieve a higher degree of accuracy over PPST in determining crop N demand, these soil tests generally will have limited application in humid regions where there is high leaching

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Abbreviations: NDVI, normalized difference vegetative index; NIR, near infrared; RI, response index.

potential. Evanylo and Alley (1997) reported that only 13 out of 47 sites over 2 yr showed a significant response to sidedress application of N, in corn (*Zea mays* L.) This lack of response was attributed to high plant available N from mineralization of organic sources.

Due to the reported limitations of soil-test based N recommendation, research has been centered to develop in-season monitoring approach as a guide to N management decisions. Several studies reported that hand-held chlorophyll meters can accurately predict N requirement based on a sufficiency index (Wood et al., 1992; Blackmer and Schepers, 1995; Waskom et al., 1996):

$$\text{Sufficiency index (\%)} = [(\text{fertilizer needed plot})/(\text{well fertilized plot})] \times 100$$

According to Varvel et al. (1997), additional N is recommended when sufficiency index values fall below 95%. One major limitation of using chlorophyll meters to determine N fertilizer recommendations is obtaining a representative sample across a highly variable field (Blackmer and Schepers, 1995). In addition to field scale variability, chlorophyll meters can produce highly variable values within a single plant (Peterson et al., 1993). Therefore, obtaining accurate values in highly variable environments can be costly and time consuming.

Several reports have shown that plant indices based on spectral reflectance can be used to accurately predict crop physiological variables, including plant biomass (Tucker, 1979), photosynthesis (Zhao et al., 2003), chlorophyll content (Tucker, 1979), plant N status (Bronson et al., 2003), and yield (Raun et al., 2002; Zhao et al., 2003). One of the most widely used plant indices is NDVI. According to Rouse et al. (1973), NDVI is calculated by comparing reflectance at the red and near infrared regions of the electromagnetic spectrum based on the following equation:

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{Red}})/(\rho_{\text{NIR}} + \rho_{\text{Red}})$$

where:

ρ_{NIR} = reflectance at the near infrared (NIR) region
ρ_{Red} = reflectance at the red region

Ma et al. (1996) reported that NDVI showed a stronger relationship to different N treatments compared to other indices. Also, NDVI values were well correlated with both leaf chlorophyll and leaf area.

Johnson and Raun (2003) introduced RI as a measure of the plant's response to additional N fertilizer. According to Mullen et al. (2003) and Hodgen et al. (2005), midseason NDVI readings can be used to determine RI. The RI is determined by comparing a check plot (0 N applied) with a reference plot, traditionally used as a high N rate plot where N is not the most limiting factor (Johnson and Raun, 2003). They determined RI using in-season estimates of biomass (RI_{NDVI}) and yield at harvest ($\text{RI}_{\text{Harvest}}$) where:

$$\text{RI}_{\text{NDVI}} = (\text{NDVI}_{\text{Nonlimiting}})/(\text{NDVI}_{\text{Check}})$$

$$\text{RI}_{\text{Harvest}} = (\text{Yield}_{\text{Nonlimiting}})/(\text{Yield}_{\text{Check}})$$

Mullen et al. (2003) reported a strong correlation between RI_{NDVI} and the $\text{RI}_{\text{Harvest}}$, in winter wheat (*Triticum aestivum* L.). Hodgen et al. (2005) reported similar results, in winter wheat, showing that RI_{NDVI} and $\text{RI}_{\text{Harvest}}$ were well correlated. The relationship between RI_{NDVI} and $\text{RI}_{\text{Harvest}}$ as a function of time was also evaluated by several researchers. Chung et al. (2010) found that the relationship between RI_{NDVI} and $\text{RI}_{\text{Harvest}}$ in winter wheat was not constant throughout the growing season. They found that the linear relationship between RI_{NDVI} and $\text{RI}_{\text{Harvest}}$ became stronger until Feekes growth stage 7, at which point the relationship stabilized. Hodgen et al. (2005), reported a decrease in the strength of the relationship between RI_{NDVI} and $\text{RI}_{\text{Harvest}}$ at later growth stages, specifically Feekes stage 11, due to early maturation of the check plots.

The RI_{NDVI} is a component of an in-season N decision tool developed by Raun et al. (2002), in which an area that has received either a small amount or no N applications (check) is compared to a reference plot. The reference plots are areas which have received a high rate of N to represent an area which is not limited by N. Many researchers have substantiated the value of this decision tool as a practical technology to improve N management in crop productions in the United States, Canada, and other countries (Olfs et al., 2005; Bernsten et al., 2006; Biermacher et al., 2006; Tremblay and Belec, 2006; Zillmann et al., 2006). Based on these recent reports, the concept of RI_{NDVI} offers a considerable promise to improve N management in sugarcane production. However, there is no existing information on the use of canopy reflectance to estimate RI in sugarcane. The objectives of this study were to: (i) determine if sugarcane yield response to N fertilizer ($\text{RI}_{\text{Harvest}}$) can be predicted using in-season canopy reflectance readings (RI_{NDVI}), and (ii) determine the minimum number of weeks from the time of N fertilization when RI_{NDVI} could be used to estimate $\text{RI}_{\text{Harvest}}$.

MATERIALS AND METHODS

Field data were collected from different N fertility field research trials in St. Gabriel (30°15′13″ N, 91°06′05″ W) and Jeanerette (29°54′59″ N, 91°40′21″W), LA, from 2008 to 2010 (Table 1). Soils for each trial are as follows: Commerce silt loam (fine-silty, mixed, superactive, non-acid, thermic Flucaquentic Endoaquept) for Exp. 1, 2, 3, and 4; Canciene silty clay loam (fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquept) for Exp. 5, 6, and 7; and Baldwin silty clay loam (fine, smectitic, hyperthermic, Chromic Vertic Epiaqualf) for Exp. 8 and 9. Average monthly temperatures and rainfall for each site are provided in Fig. 1 and 2.

All experiments were independent trials with different purpose and treatment structure. Descriptions of the experiments, planting date, harvest date, and time of fertilization are detailed in Table 1. Trials were planted on three-bed plots, measuring 2 m wide with length ranging from 8 to 15 m long. The specific lengths for each plot are as follows: Plot length for Exp. 1, 2, 3, 4, 5, and 8 was 15 m; Exp. 7, 13.3 m; Exp. 6, 11.6 m; and Exp. 9, 8 m. Except for Exp. 6, all trials were planted by hand using whole stalks. Each opened planting furrows were filled with whole stalks at the rate of three stalks side-by-side, that is, three-whole stalks were placed with an overlap of 8 cm

Table 1. Field activity information of all the experiments established in St. Gabriel and Jeanerette, LA, 2008 to 2010

Experiment no.	Year	Crop	Description	Location	Planting date	Spring fertilization date	Harvest date
1	2008	second stubble†	Foliar fertilization × N rate	St. Gabriel, LA	Aug. 2006	15 Apr. 2008	27 Oct. 2008
2	2008	second stubble	N Response Study	St. Gabriel, LA	Aug. 2006	15 Apr. 2008	27 Oct. 2008
3	2008	first stubble	Foliar fertilization × N rate	St. Gabriel, LA	Aug. 2007	15 Apr. 2008	4 Nov. 2008
	2009	second stubble	Foliar fertilization × N rate	St. Gabriel, LA	Aug. 2007	15 Apr. 2009	4 Nov. 2009
4	2008	first stubble	Variety × N rate	St. Gabriel, LA	Aug. 2006	17 Apr. 2008	5 Nov. 2008
	2009	second stubble	Variety × N rate	St. Gabriel, LA	Aug. 2006	29 Apr. 2009	4 Nov. 2009
5	2008	plant cane	Variety × N rate	St. Gabriel, LA	Sept. 2007	14 Apr. 2008	17 Nov. 2008
	2009	first stubble	Variety × N rate	St. Gabriel, LA	Sept. 2007	6 Apr. 2009	18 Nov. 2009
6‡	2010	plant cane	N rate × N timing	St. Gabriel, LA	Sept. 2009	15 Apr. 2010	8 Dec. 2010
	2010	plant cane	N rate × N timing	St. Gabriel, LA	Sept. 2009	29 Apr. 2010	8 Dec. 2010
	2010	plant cane	N rate × N timing	St. Gabriel, LA	Sept. 2009	13 May 2010	8 Dec. 2010
	2010	plant cane	N rate × N timing	St. Gabriel, LA	Sept. 2009	27 May 2010	8 Dec. 2010
7	2010	plant cane	Variety × N rate	St. Gabriel, LA	Sept. 2009	22 Apr. 2010	22 Nov. 2010
8	2008	second stubble	Variety × N rate	Jeanerette, LA	Aug. 2006	25 Apr. 2008	13 Nov. 2008
9	2010	plant cane	Variety × N rate	Jeanerette, LA	Nov. 2009	23 Apr. 2010	17 Nov. 2010

† Stubble crop indicates the crop grown after the first year's harvest.

‡ Four values are for the different spring N fertilization times, which yield was calculated separately for each timing.

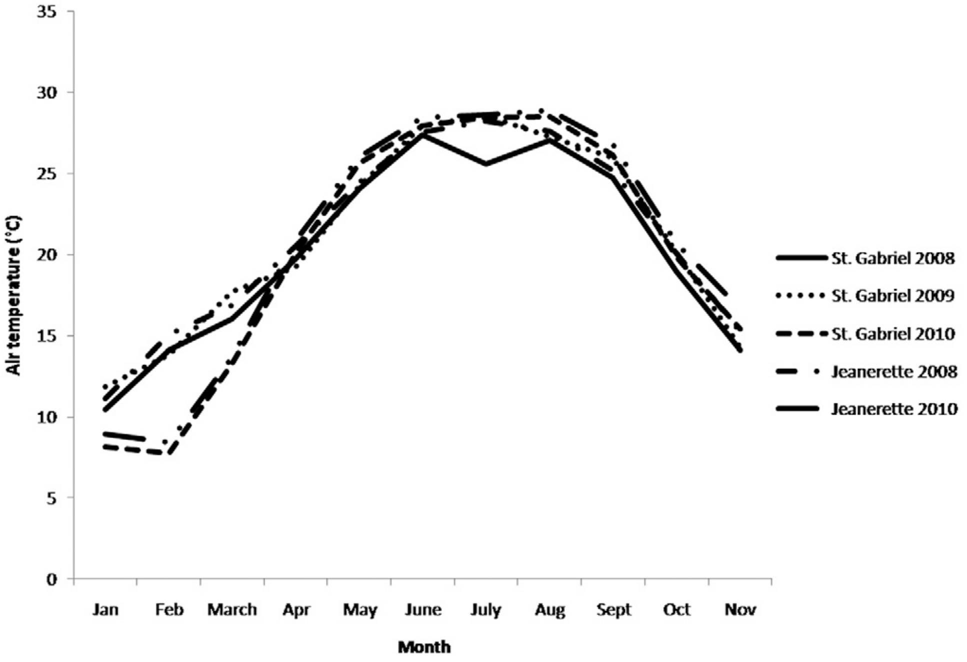

Fig. 1. Average monthly temperatures from the beginning of the season until harvest observed in 2008 to 2010 at St. Gabriel and Jeanerette, LA (LAIS, 2011).

or minimum of two mature internodes on the next three-whole stalks. Experiment 6 was planted using billets, sugarcane stalk cut into approximately 50-cm sections, at the rate of six billets across the planting furrow. The sugarcane in each row was covered with approximately 6 cm of soil and pressed firmly using a custom roller packer. Trials received the same N fertilization rates (0, 45, 90, and 135 kg N ha^{-1}) applied as urea-ammonium nitrate (UAN; 32–0–0) with the exception of Exp. 2, 3, 5 (2008), and 8 (Table 2), which received the following N rates: Exp. 2, received 0 and 135 kg N ha^{-1}; Exp. 3, received 0, 45, and 90 kg N ha^{-1}; Exp. 5, received 0, 17, 67, 135, and 201 kg N ha^{-1}; Exp. 8, received 0, 45, 90, 135, and 180 kg N ha^{-1}. Weeds in plots were controlled according to Louisiana State University AgCenter's current herbicide recommendations where metribuzin (4-amino-6-tert-butyl-4,5-dihydro-3-methyltio-1,2,4-triazin-5-one) was applied in early spring before emergence of the current sugarcane crop and atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) was applied when beds were rebuilt in late spring (lay-by), approximately middle of May.

GreenSeeker Hand Held Optical Active Sensor was used to collect NDVI readings at all locations. The sensor measured within red (670 ± 10 nm) and NIR (780 ± 10 nm) regions and calculated NDVI based on Eq. [1]. Sensor readings were taken

Table 2. Average cane tonnage and sugar yield at different nitrogen fertilizer rates for all experiments in St. Gabriel and Jeanerette, LA, 2008 to 2010.

Experiment no.	Year	Cane tonnage				Sugar yield			
		0 N†	45	90	135	0	45	90	135
		Mg ha^{-1}							
1	2008	68	71	**73‡**	71	8.53	8.76	**9.06**	8.68
2§	2008	39	–	–	**68**	5.21	–	–	**7.54**
3§	2008	71	74	**77**	–	8.72	8.94	**9.20**	–
	2009	54	55	56	–	6.05	6.17	6.36	–
4	2008	56	62	63	61	6.87	7.34	7.35	7.17
	2009	51	69	**76**	75	5.13	7.13	**7.66**	7.49
5¶	2008	83	75	85	83	10.52	9.46	10.49	10.25
	2009	49	**54**	48	53	2.25	2.52	2.82	**3.16**
6#	2010	97	88	89	91	12.45	11.43	11.40	11.66
7	2010	83	90	85	91	10.20	11.94	12.87	13.27
8††	2008	31	51	**53**	44	4.19	6.79	**7.35**	6.0
9	2010	66	68	70	65	8.26	8.38	8.98	7.86

† Indicate applied N rates in kg N ha^{-1}.

‡ Bolded values indicate the highest significant yield in response to applied N within an experiment ($P < 0.05$).

§ Data points were not available due to particular plots did not receive designated N rates.

¶ N rates used were 0, 17, 67, 135, and 201 kg N ha^{-1}. Yield values for the 45 and 90 kg N ha^{-1} columns were plots which received 17 and 67 kg N ha^{-1}, respectively. Additionally 201 kg N ha^{-1} yielded 83 MT ha^{-1} and 10,463 kg ha^{-1} for cane tonnage and sugar yield, respectively.

Indicate a significant response ($P < 0.05$); however, the highest significant yield was the check plot.

†† Additionally 180 kg N ha^{-1} yielded 64 and 8.8 Mg ha^{-1} for cane tonnage and sugar yield, respectively.

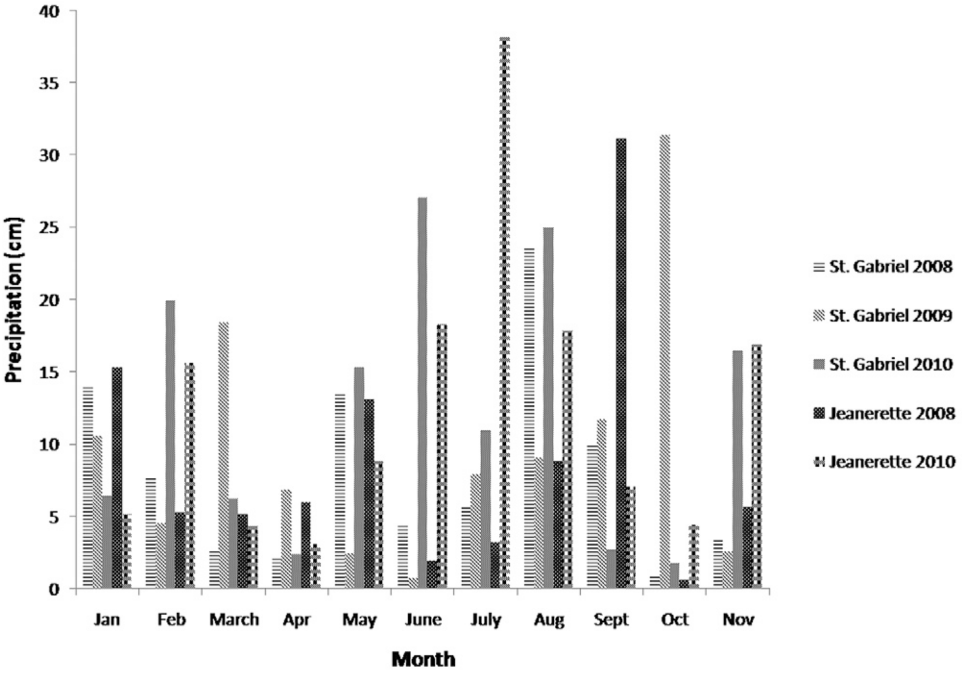

Fig. 2. Average monthly precipitation from the beginning of the season until harvest observed in 2008 to 2010 at St. Gabriel and Jeanerette, LA (LAIS, 2011).

weekly for 3 wk beginning in May, approximately 3 wk after fertilization. The RI_{NDVI} were calculated by taking average values of NDVI readings from the nonlimiting N rate plots, between 90 and 201 kg N ha^{-1}, and dividing by the check plot, 0 kg N ha^{-1} (Johnson and Raun, 2003). The $\text{RI}_{\text{Harvest}}$ was calculated for both cane tonnage and sugar yield. Both were calculated similar to RI_{NDVI}, that is, by dividing the yield from the nonlimiting N plots by the yield of the check plot.

Plots were mechanically harvested using a Cameco C2500 chopper harvester (Cameco Industries, Thibodaux, LA). Total plot yield was determined by obtaining the millable stalks from each of the three rows in each plot using a weigh wagon fitted with load cells. Ten stalks were randomly selected from the middle row; leaves were stripped from the stalks that were cut approximately 10 to 12 cm below the apical meristem. After mean 10-stalk weight determination, these samples were shredded and analyzed for sugar quality measurements using a Spectracane Near Infrared System (Bruker Coporation, Billerica, MA). Statistical analysis was performed using the SAS program for Windows (SAS, 2009). For each individual experiment, ANOVA was performed for cane tonnage and sugar yield using PROC MIXED with a Satterthwaite approximation, where fixed effect was N rate and random effect was replication. Differences between N fertilized plots and the check plots were analyzed using a Dunnett's test. The variety by N rate interaction effect for Exp. 4, 5, 7, 8, and 9 was not significant therefore values were reported across variety. For Exp. 1 and 3, the result of ANOVA showed no significant effect of either the foliar treatment or foliar × N rate interaction; therefore, values were reported across foliar treatment. Regression analysis was performed using PROC REG to determine the relationship between $\mathrm{RI}_{\mathrm{NDVI}}$ and $\mathrm{RI}_{\mathrm{Harvest}}$.

RESULTS AND DISCUSSION

Sugarcane Response to Nitrogen Fertilization

Cane tonnage and sugar yields were highly variable across the experiments (Table 2). Sugarcane yields ranged from 31 to 97 Mg ha^{-1} for cane tonnage and 4.19 to 12.45 Mg ha^{-1} for sugar yields. Experiment 6 in 2010 yielded the greatest (0 kg N ha^{-1}) while Exp. 8 in 2008 yielded the least (0 kg N ha^{-1}) (Table 2). Johnson and Richard (2005) reported similar variability between sugarcane yields. This variability in cane tonnage and sugar yield can be partially explained by the differences in the amount of precipitation (Fig. 2). St. Gabriel in 2010 received the highest rainfall in the month of June during the initiation of grand growth, at which time water consumption is highest (Gascho, 1985). In addition to low moisture, the lower yields for Exp. 8 for 2008 can be attributed to the age of the sugarcane, being second stubble. Johnson and Richard (2005) reported that sugarcane yield tended to decrease with crop age.

Sugarcane yields did not consistently respond to applied N with highest significant yield differing between years (Table 2). All plant cane experiments did not significantly respond to applied N ($P < 0.05$), which is consistent with earlier reports by Carnauba (1990) and Wiendenfield (1995). This lack of yield response, which is commonly observed in Louisiana sugarcane, is due to planting normally occurring after a fallow period, which allows for natural process to increase soil N reserves (Thorburn et al., 2005). Conversely, stubble cane in Exp. 3 (2009) and Exp. 4 (2008) did not significantly ($P < 0.05$) respond to applied N which can be attributed to either high natural N additions or a more limiting growth factor such as temperatures, precipitation, or essential plant nutrients. For N responsive site-years, it can be observed that increases in cane tonnage and sugar yields due to applied N were highly variable. For example, increases in sugarcane yield, when comparing between the highest N rate plot and the check plot, ranged from 5 to 25 Mg ha^{-1} for cane tonnage while for sugar yield, ranged between 0.48 to 3.16 Mg ha^{-1}. These results demonstrate the variability of N response between growing season and within growing season. Johnson and Raun (2003) found similar variability in winter wheat yield response to applied N. They attributed this variability to differences in both moisture and temperature, as well as other environmental conditions that influence supply of nonfertilizer N including natural deposition and organic mineralization. The high amount of variability of sugarcane yield response, as shown in Table 2, suggests that a more dynamic means of determining in-season N fertilization is needed to account for spatiotemporal variability across Louisiana sugarcane growing region. The concept of using canopy reflectance to evaluate RI during the vegetative growth (Mullen et al., 2003) holds considerable promise. This approach has the ability to obtain spatial differences in crop biomass while accounting for climatic conditions which affect crop growth from planting to the time of N application (Raun et al., 2002; Shanahan et al., 2008).

Response Index Determination using Normalized Difference Vegetative Index

In essence, $\mathrm{RI}_{\mathrm{NDVI}}$ is an estimate of $\mathrm{RI}_{\mathrm{Harvest}}$, which is the actual response of sugarcane to applied N. The $\mathrm{RI}_{\mathrm{Harvest}}$ is the ratio between the highest yielding N fertilized plots to the check plot. It is important to note that for this study, the actual response of sugarcane to applied N is expressed as increases in cane tonnage and sugar yield thus there were two sets of $\mathrm{RI}_{\mathrm{Harvest}}$ values that were regressed with $\mathrm{RI}_{\mathrm{NDVI}}$ (Fig. 3, 4, 5, and 6). Table 3 shows the relationship of $\mathrm{RI}_{\mathrm{Harvest}}$ to $\mathrm{RI}_{\mathrm{NDVI}}$ which were computed from NDVI readings collected at 3, 4, and 5 wk after N fertilization. Based on the r^2 and P values, the earliest time where $\mathrm{RI}_{\mathrm{NDVI}}$ can accurately predict $\mathrm{RI}_{\mathrm{Harvest}}$ was at 4 wk after N fertilization. The implications of timing for RI estimation will be discussed further in the next section.

The results of the regression analysis show that $\mathrm{RI}_{\mathrm{NDVI}}$, 4 wk after N fertilization, had a significant linear relationship with

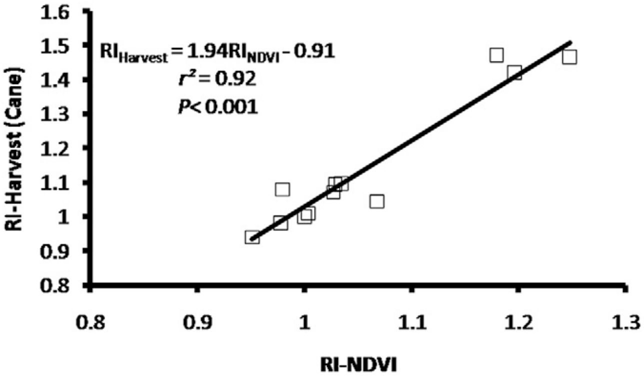

Fig. 3. Relationship between response index calculated using normalized difference vegetative index and response index calculated at harvest for cane tonnage 4 wk after fertilization in Louisiana.

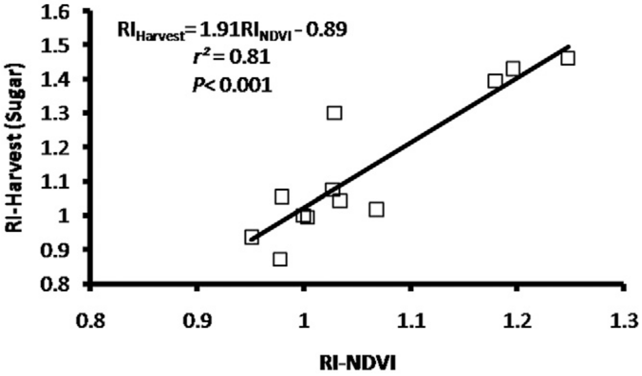

Fig. 4. Relationship between a response index calculated using normalized difference vegetative index and response index calculated at harvest for sugar yield 4 wk after fertilization in Louisiana.

Table 3. Equation, coefficient of determination (r^2), and *P* value for relationships of response index normalized difference vegetative index (RI_{NDVI}) and modified RI_{NDVI} with response index at harvest ($RI_{Harvest}$) at different weeks after fertilization.

Week after fertilization	Cane tonnage			Sugar yield		
	Equation	r^2	*P* value†	Equation	r^2	*P* value†
			RI_{NDVI} and $RI_{Harvest}$			
3	0.09x + 0.87	0.02	0.56	0.09x + 0.796	0.47	0.62
4	1.94x – 0.91	0.92	<0.001	1.91x –0.89	0.81	<0.001
5	1.67x – 0.63	0.81	0.012	1.57x – 0.532	0.70	<0.001
			Modified RI_{NDVI} and $RI_{Harvest}$			
3	0.57x + 0.52	0.21	0.025	0.16x + 0.904	0.02	0.59
4	2.01x – 0.99	0.85	<0.001	2.06x – 1.06	0.81	<0.001
5	1.7x – 0.68	0.83	<0.001	1.69x – 0.66	0.77	<0.001

† Designated *P* values are for overall model components.

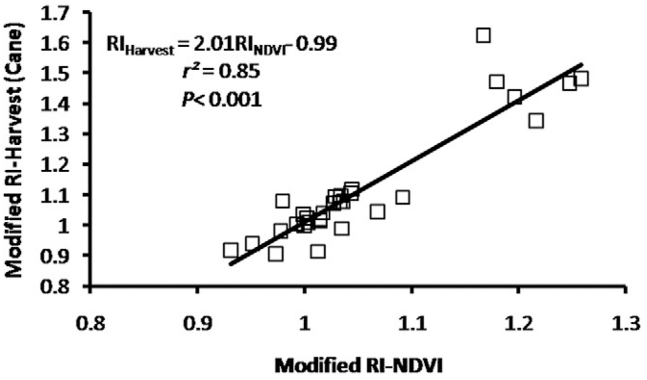

Fig. 5. Relationship between a response index calculated using normalized difference vegetative index using all N rates and a response index calculated at harvest using all N rates for cane tonnage 4 wk after fertilization in Louisiana.

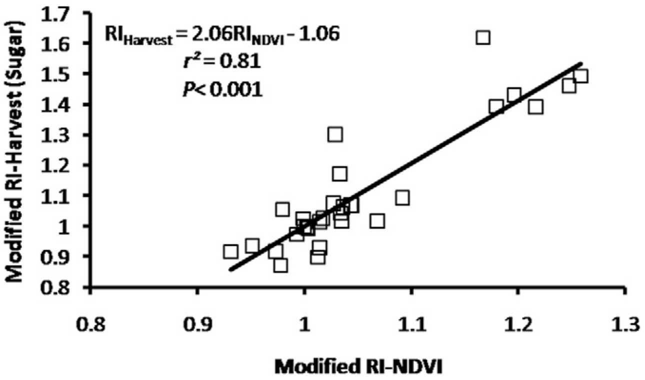

Fig. 6. Relationship between a response index calculated using normalized difference vegetative index using all N rates and a response index calculated at harvest using all N rates for sugar yields 4 wk after fertilization in Louisiana.

cane tonnage $RI_{Harvest}$ with r^2 of 0.92 (Fig. 3). Similarly, the linear relationship between RI_{NDVI} and sugar yield $RI_{Harvest}$ was significant with r^2 of 0.81 (Fig. 4). These findings suggest that RI_{NDVI} can be used to estimate the actual response of sugarcane to applied N in-season using the equations in Fig. 3 for cane tonnage and Fig. 4 for sugar yield.

Sugarcane, as with crops in general, does not positively respond to applied N rates above optimum level, showing either small, nonsignificant increases in yield or yield reduction. Several reports suggest that sugarcane yield was reduced when supplied with high, nonlimiting rates of N fertilizer (Wiedenfeld, 1995; Muchow et al., 1996; Kwong et al., 1996; Keating et al., 1997). Das (1936) reported that excess N fertilization can lead to increased lodging, which can decrease cane tonnage and sugar yield due to problems associated with harvesting the sugarcane. Numerous studies have also reported reductions in sugar content per harvested unit of sugarcane if excess N was applied (Wiedenfeld, 1995; Muchow et al., 1996; Kwong et al., 1996). Thorburn et al. (2003) also found that cane yield, crop biomass N, and juice amino acid N decreased with higher N rates (>100 kg N ha^{-1}). In this study, the increase in cane tonnage and sugar yield did not proportionately increase with increasing N rates (Table 2). For example, in a few of the experiments, the 135 kg N ha^{-1} rate plots yielded less cane tonnage and sugar yield than plots which received lower N rates. With the aforementioned observations, further analysis and processing of data were conducted to determine the relationship between RI_{NDVI} and $RI_{Harvest}$, where RIs were computed for all individual applied N rates to the check plot. By performing this modification, the relationship between RI_{NDVI} and $RI_{Harvest}$ included sugarcane response across N rates (Fig. 5 and 6). The modified RI compared all applied N rates to the check plot for both RI_{NDVI} and $RI_{Harvest}$ by the following equations:

$$RI_{45} = (45 \text{ kg N ha}^{-1} \text{ plot})/(\text{check plot})$$

$$RI_{90} = (90 \text{ kg N ha}^{-1} \text{ plot})/(\text{check plot})$$

$$RI_{135} = (135 \text{ kg N ha}^{-1} \text{ plot})/(\text{check plot})$$

There was a strong relationship between the RI_{NDVI} and the $RI_{Harvest}$ when the modified method of calculating RI was implemented ($r^2 = 0.85$ for cane tonnage and 0.81 for sugar yield) (Fig. 5 and 6). While there was a slight reduction in the linear relationship between RI_{NDVI} and cane tonnage $RI_{Harvest}$, when compared to using only nonlimiting N rate (r^2 values, 0.92 vs. 0.85), the accuracy (slope) and precision (r^2) of predictive model was not compromised. This also applies for sugar yield $RI_{Harvest}$. The slight difference between RI_{NDVI} and $RI_{Harvest}$ was expected for this study as sugarcane may have encountered growing conditions that can potentially alter yield post sensing. This is similar to the report provided by Mullen et al. (2003) for corn.

The outcome of this procedure suggests that both methods of computing RI (traditional and modified) were able to establish models that can be used to predict cane tonnage and sugar yield response to applied N using NDVI readings. The benefits of determining RI for multiple N rates (modified RI procedure) are evident when the application of high N rates does not achieve the greatest cane tonnage and sugar yield response. While the establishment of N reference plots with multiple rates may be more time consuming, it provides a better understanding of both cane tonnage and sugar yield response to N compared to using a single high N rate.

Optimum Timing for Response Index Estimation

Identifying the optimum timing for RI estimation using NDVI has an implication in terms of the feasibility of using an in-season N monitoring using remote sensor in producers' fields. The NDVI readings were collected at 3, 4, and 5 wk after N fertilization. Later sampling dates were not pursued since the existing time frame of spring N fertilization for sugarcane production in Louisiana is narrow. This means that the usefulness of in-season N monitoring is confined within the time period closest to current spring N fertilization schedule. According to Legendre et al. (2000), current spring N fertilization is commonly scheduled by sugarcane growers between 1 and 30 April. While there is no documentation on the negative impacts of delaying N fertilization into May on sugarcane growth, the feasibility of May N fertilization is limited by the ability of equipment to cross the field without incurring physical damage to the sugarcane plants.

Table 3 summarizes the relationships between $\mathrm{RI}_{\mathrm{NDVI}}$ and $\mathrm{RI}_{\mathrm{Harvest}}$ for both methods as a function of time. At 3 wk after N fertilization, $\mathrm{RI}_{\mathrm{NDVI}}$ was not able to establish a good relationship with $\mathrm{RI}_{\mathrm{Harvest}}$ for both cane tonnage and sugar yield. At this period, it is possible that the effects of N which was applied 3 wk prior have not affected the canopy and leaf variables for the sensor to discriminate. Using the modified method, the $\mathrm{RI}_{\mathrm{NDVI}}$ at 4 and 5 wk after N fertilization obtained significant ($P < 0.05$) linear relationships with $\mathrm{RI}_{\mathrm{Harvest}}$ (Fig. 5 and 6). The r^2 values 4 wk after fertilization were 0.85 and 0.81 for cane tonnage and sugar yield, respectively. Even with the traditional method of calculating RI, both $\mathrm{RI}_{\mathrm{NVDI}}$ at 4 and 5 wk were able to establish strong relationships with $\mathrm{RI}_{\mathrm{Harvest}}$ (with r^2 values, 4 wk after fertilization, of 0.92 and 0.81 for cane tonnage and sugar yield, respectively). Results obtained by Chung et al. (2010) in winter wheat showed a similar trend. They reported that the relationship between $\mathrm{RI}_{\mathrm{NDVI}}$ and $\mathrm{RI}_{\mathrm{Harvest}}$ became stronger throughout the growing season until Feekes 7, at which point the relationship stabilized.

An N management program that uses in-season RI will allow producers to determine the possibility of achieving an N response at harvest. An RI value is an estimation of the percent increase in yield that can be expected in conjunction with a particular N rate. Therefore, RI cannot exclusively be used to determine N rate recommendations. However, it is a vital component of an in-season N decision tool that has shown to be successful in many crops (Mullen et al., 2003; Hodgen et al., 2005; Teal et al., 2006; Tubana et al., 2008; Raun et al., 2011). Raun et al. (2011) illustrated that the two vital components of this N management tool are independent which means that a high RI does not indicate high yield potential and vice versa. Therefore, RI estimate for sugarcane can be established and calculated separately, and in combination with estimate of yield potential, can be used to determine an accurate in-season N fertilization recommendation. The implementation of in-season N decision tool requires establishment of an N reference strip within each management zone. Based on the findings of this study, to achieve full potential, an N reference strip either a single high N rate (traditional RI) or multiple increasing N rates (modified RI) should be established at least 4 wk before the proposed N fertilization. By using the latter method, producers can take advantage of years in which optimum yield can be achieved with minimal or no N fertilizer.

CONCLUSIONS

This study demonstrated that sugarcane yield response to applied N can be estimated using NDVI readings. Both traditional and modified methods of determining $\mathrm{RI}_{\mathrm{NDVI}}$ provided a good estimation of $\mathrm{RI}_{\mathrm{Harvest}}$. The benefit of the modified RI is it allows for estimation of the highest sugarcane yield response, which may not coincide with the highest N rate. The ability to use an N management scheme which incorporates an in-season estimation of sugarcane yield response would allow producers to take into account variability of the current growing conditions associated with different weather patterns and growth limiting factors. While the use of an in-season estimation of sugarcane yield response appears beneficial, it is imperative that this technology can be used within the narrow time frame of spring N fertilization. The strongest relationship between $\mathrm{RI}_{\mathrm{NDVI}}$ and $\mathrm{RI}_{\mathrm{Harvest}}$ occurred 4 wk after N fertilization. Therefore, N reference strips would need to be implemented approximately 1 mo before the proposed spring N fertilization. Further research is needed to determine the effects of a wider array of fertilization timings, including early March to as late as the end of May, on the relationship between $\mathrm{RI}_{\mathrm{NDVI}}$ and $\mathrm{RI}_{\mathrm{Harvest}}$ in anticipation to any future research on the potential of split and delayed N spring fertilization in Louisiana sugarcane production.

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