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RESEARCH

Development of an NDVI-Based Nitrogen Rate Calculator for Cotton

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ABSTRACT

The use and adoption of optical sensors to determine midseason nitrogen (N) application rates in cereal grain production has gained increasing acceptance by producers in the past decade; however, the technology has yet to impact mainstream cotton (*Gossypium hirsutum* L.) production. Overapplication of N in cotton leads to excessive growth and can result in a dramatic yield decrease. This study was designed to develop a sensor-based cotton yield prediction model using normalized difference vegetation index (NDVI) readings from an optical sensor, incorporate the model into an algorithm used to determine midseason N rates, and determine if N response can be predicted using NDVI values collected midseason. A GreenSeeker hand held sensor was used to measure NDVI from seven studies at Lake Carl Blackwell (LCB), Stillwater, OK, and Southwest Research Station (SWR), Altus, OK, from 2006 to 2010. Normalized difference vegetation index readings taken at white flower stage had a good correlation with final yield. Final yield prediction was improved when NDVI was normalized using cumulative growing degree day (CumGDD) measured between planting and sensing. Sorting NDVI by CumGDD to 940 to 1200 and 1400 to 1500 at LCB and SWR sites, respectively, extended the critical sensing window from match-head square to white flower stages. This study showed that yield potential in cotton could be predicted within the season using NDVI, which confirms the potential for using sensor-based N rate recommendations in cotton.

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Abbreviations: CumGDD, cumulative growing degree day; DFP, days from planting; GDD, growing degree day; INSEY, in-season estimate of yield; LCB, Lake Carl Blackwell; NDVI, normalized difference vegetation index; NFOA, N fertilization optimization algorithm; NUE, N use efficiency; RI, response index; $RI_{Harvest}$, response index of grain yield; RI_{NDVI}, response index of NDVI measure midseason; SWR, Southwest Research Station; YP_0, yield potential.

Nitrogen is an essential nutrient in cotton. Nitrogen fertilization of cotton can be challenging and complicated; both underfertilization and overfertilization with N can have negative effects on cotton growth. Nitrogen deficiency can reduce leaf size, number of fruiting nodes, fruit retention, and yield (Hons et al., 2004). On the other hand, excess N fertilization leads to excessive vegetative growth and decreased boll retention, causing reduced yields and lint quality (Hearn, 1986; Singh and Nagwekar, 1989). In addition, overapplication of N increases production cost and presents environmental concerns. Therefore, N fertilization in cotton requires more careful and accurate methods to monitor plant growth and conditions in every production stage.

Precision agriculture technology enables growers to apply the right amount of fertilizers based on the crop's current growth conditions without reducing final yield. In cotton, development of yield-sensing technology (Bronson et al., 2003, 2005; Huang et al., 2013; Raper et al., 2013; Vellidis et al., 2011; 2004; Wilkerson and Hart, 1996; Yang et al., 2001) and soil-fertility mapping (Liakos et al., 2013; Valco et al., 1998) have paved a way for N fertilizer rate determination. In the early 2000s, Oklahoma State University developed an N fertilization optimization

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algorithm (NFOA) that calculates in-season N fertilizer rates in wheat (*Triticum aestivum* L.). The NFOA accounts for variability in spatial yield potential (YP_0), early-season N uptake, and the crop response to additional N fertilizer or response index (RI) (Raun et al., 2002).

Yield potential is the possible attainable grain yield with no addition of N fertilizer (Raun et al., 2002). It can be predicted using an in-season estimate of yield (INSEY), which is calculated by dividing the NDVI by the number of growing degree days (GDDs) from planting to sensing where GDD is >0. Normalized difference vegetation index is a good biomass indicator and also implies total N content (Raper et al., 2013). The INSEY value is related to biomass produced per GDD. Correlation between biomass produced per day and final grain yield has been shown to be highly correlated (Raun et al., 2001).

Response index is described as the response in yield to additional N fertilizer (Johnson and Raun, 2003). It is calculated by dividing the yield of the high-N plot (N-rich strip) by the yield of the zero-N plot or farmer's practice where less preplant N was applied. The RI value calculated using yield is referred to as $RI_{Harvest}$. Response index can also be measured midseason using NDVI values (RI_{NDVI}) collected from the same areas used to determine $RI_{Harvest}$. It has been found that RI_{NDVI} collected midseason is a good predictor of $RI_{Harvest}$ (Hodgen et al., 2005; Mullen et al., 2003).

Raun et al. (2002) reported that the combined use of the RI concept and midseason prediction of INSEY enabled an accurate top-dress N rate to be made in wheat. This is accomplished by predicting yield of the N-rich strip and farmer's practice. Total grain N removed from each area is calculated and the difference between the N-rich and farmer's practice divided by a theoretical efficiency factor, ranging between 0.5 and 0.7, is the prescribed top-dress N recommendation. The combination of these set of calculations is termed as the NFOA (Lukina et al., 2001) and the algorithm is as follows:

$$\text{N rate} = \frac{\left[\left(\text{YP}_0 \times \text{RI}\right) - \text{YP}_0\right] \times \text{percentage N}}{\text{N use efficiency}} \qquad [1]$$

Although the use of N-rich strips, optical sensors, and N rate calculators have been proven successful not only in wheat but in other production systems such as corn (*Zea mays* L.) and canola (*Brassica napus* L.) (Butchee et al., 2011), little information is available if these approaches can be used for cotton production.

The objectives of this study were to determine if NDVI is correlated with yield, to develop a yield potential prediction model using NDVI, and to propose a NFOA for cotton that could be used for the online sensor-based N rate calculator.

Table 1. Field information for all experiments evaluated for predicting cotton lint yield potential at Lake Carl Blackwell, Stillwater OK and Southwest Research Station, Altus OK, 2006 to 2010.

Location†	Experiment	Year	Planting date	N rates used
				kg ha^{-1}
LCB	YP_0	2006	15 May	0, 50, 100, 150, 200
LCB	YP_0	2007	17 May	0, 50, 100, 150, 200
LCB	YP_0	2008	21 May	0, 50, 100, 150, 200
LCB	YP_0	2010	25 May	0, 40, 80, 120, 160
LCB	N rate	2008	21 May	0, 40, 80, 120
LCB	Catch up	2010	25 May	0, 60, 120
SWR	N rate	2007	18 May	0, 40, 80, 120
SWR	N rate	2008	13 May	0, 40, 80, 120
SWR	Catch up	2009	1 May	0, 60, 120
SWR	Catch up	2010	5 May	0, 60, 120
SWR	439 long term	2009	1 May	0, 40, 80, 120, 160, 200
SWR	439 long term	2010	5 May	0, 40, 80, 120, 160, 200

† LCB, Lake Carl Blackwell, near Stillwater, OK; SWR, Southwest Research Station near Altus, OK.

MATERIALS AND METHODS

Yield and NDVI data were collected from four studies located at LCB Agronomy Research Farm near Stillwater, OK, from 2006 to 2010 and from three studies located at SWR near Altus, OK, from 2007 to 2010. The soil at the LCB site was a Pulaski fine sandy loam (mixed, superactive, nonacid, thermic Udic Ustifluvents) and the soil at SWR site was a Hollister silty clay loam (smetitic, thermic Typic Haplusterts). At LCB site, all plots were 3.05 (4 rows) wide and 7.6 m long spaced at 76 cm apart. Preplant N applications were made using urea ammonium nitrate (UAN, 28–0–0) solution banded on the surface and incorporated prior to planting. At SWR site, plot size was 4.1 by 7.6 m for N-Rate and Catch-up studies and 6.1 (6 rows) by 19.8 m for the 439 long-term study. All trials were planted at 102 cm row spacing. A 0.76 m section was removed from each end of the plot immediately before harvest to reduce the end-row effect; thus, the harvested row length at LCB site was 6.1 m and at SWR site were 6.1 m (N-Rate and Catch-up studies) and 18.3 m (439 long-term study). Similar plot sizes were used in on-farm cotton extension projects across the state of Texas (Dr. Randy Boman, personal communication, 2016). Preplant applications were made using urea (46–0–0) broadcast on the surface and incorporated prior to planting. Irrigation systems were sprinkler and furrow in LCB and SWR sites, respectively. Only treatments that received preplant N applications were used for the yield prediction model. Year, planting date, and N rate used for every study at each site are presented in Table 1.

All plots were monitored once a week after the crop reached a height of 45 cm from the two middle rows of each plot. Using a GreenSeeker (NTech Industries) hand-held optical reflectance sensor, NDVI values were collected 70 to 100 cm directly above the crop canopy. The indices of NDVI, which was the value collected by the GreenSeeker sensor, is computed as follows:

$$\text{NDVI} = \frac{\rho\text{NIR} - \rho\text{Red}}{\rho\text{NIR} + \rho\text{Red}} \qquad [2]$$

where ρNIR is the fraction of emitted near-infrared radiation returned from the sensed area (reflectance) and ρRed is the fraction of emitted red radiation returned from the sensed area (reflectance).

At both sites, defoliants and harvest aid were applied each year to facilitate harvesting. All trials were mechanically harvested from the two middle rows using a customized single-row brush roller stripper (commercial two-row stripper cut down to a single-row) mounted on a tractor. In 2006, as a result of a mechanical malfunction of the stripper at LCB site, harvesting was performed through hand picking the two middle rows of each plot. Grab samples were collected from the harvested material in each plot and ginned on small ginning equipment to approximate lint turn out and ginning percentage.

Nonlinear regression models were used to determine the relationships between lint yield and NDVI using the Sigma Plot 13 (Systat Software, 2014). Two methods of calculating INSEY were evaluated as predictive lint yield models: the days from planting (DFP) INSEY, based on days from planting to sensing as outlined by Raun et al. (2002) and Teal et al. (2006), and CumGDD INSEY, based on cumulative GDD as outlined in Teal et al. (2006).

The DFP INSEY was calculated as follows:

$$\text{DFP INSEY} = \frac{\text{NDVI}}{\text{DFP}} \quad [3]$$

The CumGDD INSEY was calculated as follows:

$$\text{CumGDD INSEY} = \frac{\text{NDVI}}{\text{CumGDD}} \quad [4]$$

where CumGDD is cumulative growing degree days from planting to sensing were GDD > 0. The GDD is computed using the optimum-day method by Barger (1969) as follows:

$$\text{GDD} = \frac{T_{\text{max}} + T_{\text{min}}}{2} - T_{\text{base}} \quad [5]$$

where T_{max}, T_{min}, and T_{base} are the maximum temperature, minimum temperature, and base temperature, respectively. For T_{base}, 15.5 (min. threshold) and 38°C (max. threshold) were used in this study.

According to Raun et al. (2005), the model of actual grain yield has the tendency to either under- or overpredict the yield potential at the sensing date since models include data from fields whose yields may have been adversely affected by events subsequent to the date of sensing that could not be predicted. To predict the yield potential more realistically, yield potential or YP_0 + 1 standard deviation is used to fit yields unaffected by adverse conditions from sensing to maturity (Raun et al., 2005; Lukina et al., 2001).

The RI_{NDVI} was calculated by dividing the mean NDVI values of the N-treated plots by the mean NDVI value of the zero-N plots, while $RI_{Harvest}$ was calculated by dividing mean yield of the highest N treatment by the zero N treatment.

RESULTS AND DISCUSSION

Yield Potential

The trend line that best fits the relationship between INSEY and final lint yield was an exponential growth equation similar with other crops where INSEY has been used to predict yield potential midseason (Freeman et al., 2003; Raun et al., 2001). Differences in daily GDD from planting to harvesting were observed at both locations, which may have contributed to site and growth stages as major factors in predicting yield potential for cotton (Fig. 1). Similar to Vellidis et al. (2011), NDVI generally responded to N application rates over time at early stages of cotton growth. When data in all years were combined and the relationship between NDVI readings and final lint yield was examined at both LCB and SWR sites, a very weak correlation (R^2 = 0.0921) was found. When data were regressed by site, exponential relationship improved but was not as strong as when data was presented by site and by stage (data not shown). The best relationship between lint yield and NDVI was achieved at white flower stage (Fig. 2, 3) with R^2 values of 0.48 and 0.69 for LCB and SWR sites, respectively (Table 2). Similar correlation was also observed by Zhao et al. (2007) between relative lint yield and reflectance indices at the early flower stage. However, as the NDVI value approaches 0.8, the relationship between NDVI and lint yield became weak. This may be due to saturation issue of the sensor, which is one of the known limitations of NDVI at crop canopy closure.

Normalizing the NDVI by DFP and CumGDD improved the yield potential prediction model at both sites (Table 2). This indicates that incorporation of environmental component into the model can improve the ability to predict cotton lint yield than using NDVI alone. In this study, the NDVI, DFP INSEY, and CumGDD INSEY were all effective in predicting yield potential; however, given that GDD and NDVI is a measure of temperature and green biomass, respectively, the use of CumGDD INSEY should normalize NDVI more consistently across various field conditions and climates (Teal et al., 2006). Thus, the equation from the CumGDD INSEY relationship at white flower stage can be used to predict cotton yield potential. However, white flower stage allows a narrow range of sensing time (5–10 d depending on weather) before reaching boll formation, which may be a risk of failing to measure NDVI if an inevitable situation, such as bad weather conditions, occurs. To address this concern, sensor measurements were sorted by cumulative GDD (Teal et al., 2006).

In LCB site, the range of 940 to 1200 CumGDD provided a significant exponential relationship with lint yields (P < 0.0001; Fig. 4). This CumGDD range includes data from match-head square to white flower growth stages. The equation for the line is as follows:

$$\text{Cotton lint yield (kg ha}^{-1}) = 42.08e^{4108\times\text{INSEY}}$$

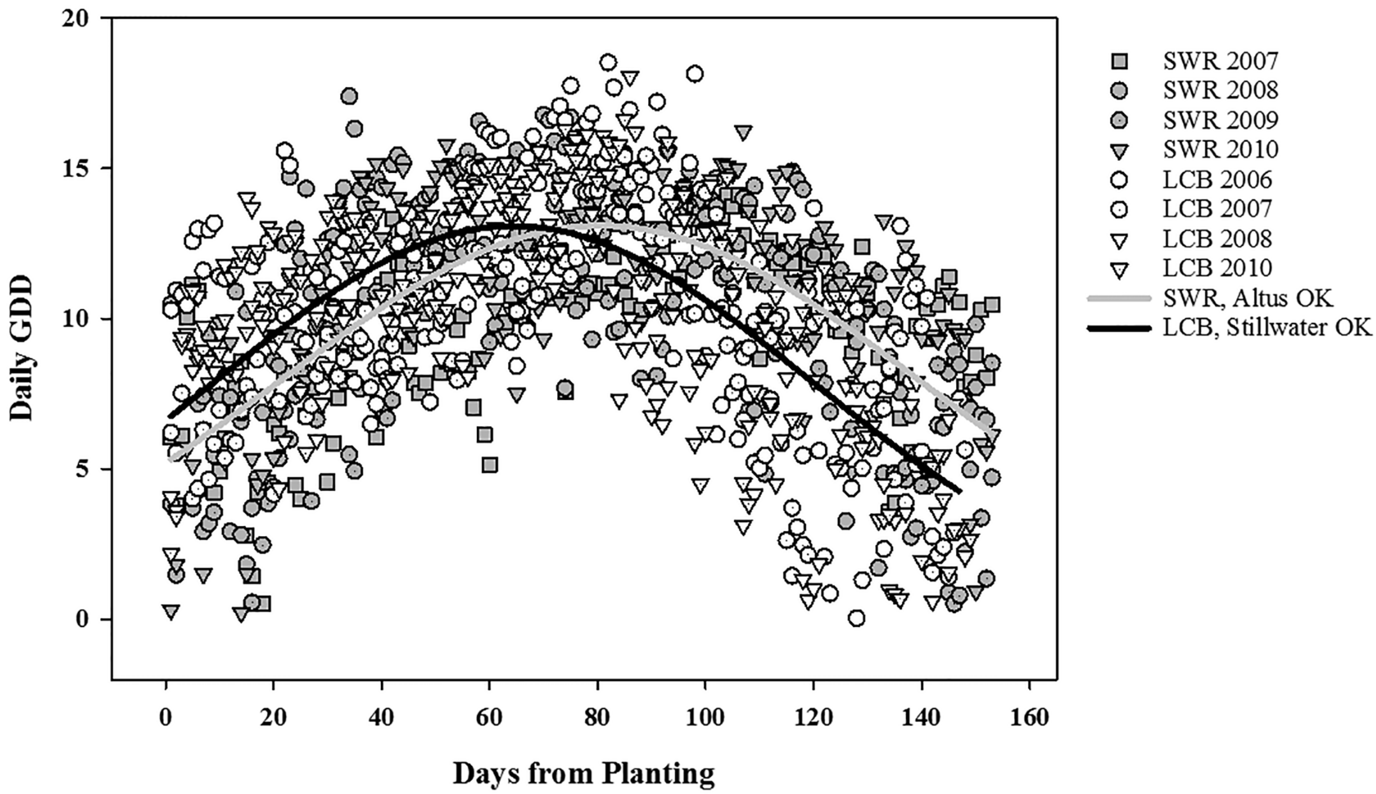

Fig. 1. Daily growing degree days (GDD) at Lake Carl Blackwell, Stillwater, OK, and Southwest Research Station, Altus, OK, from 2006 to 2010.

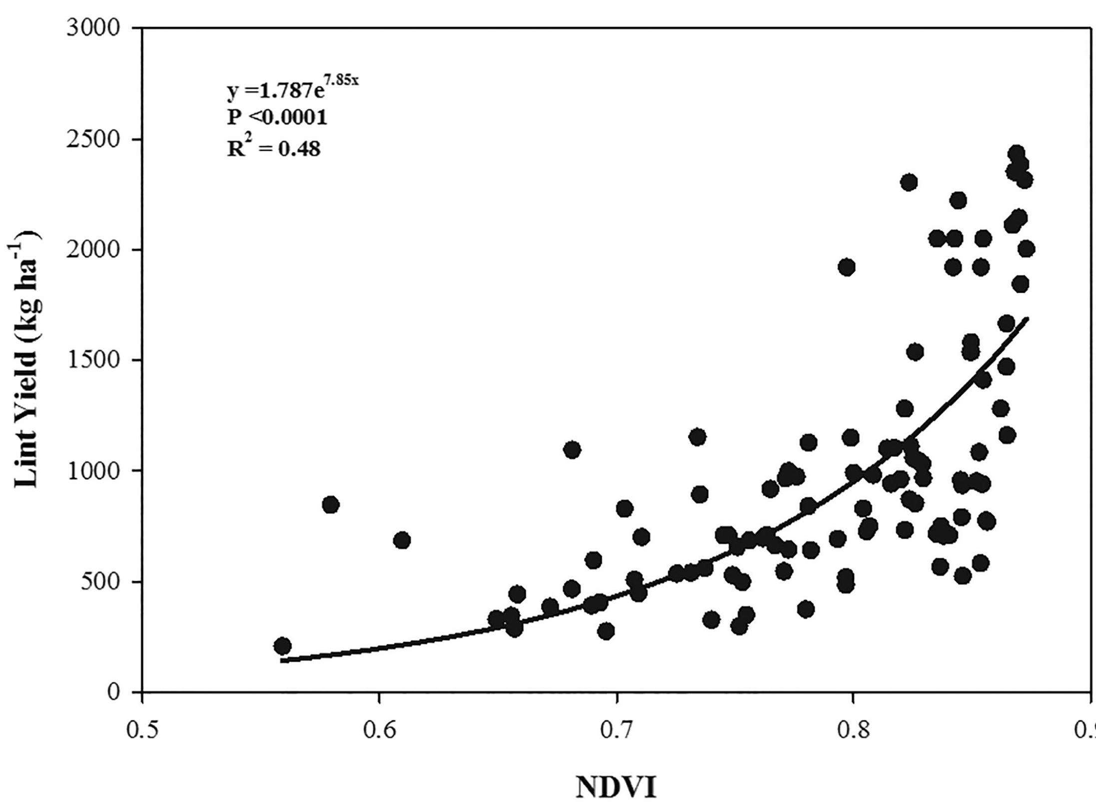

Fig. 2. Relationship between cotton lint yield and normalized difference vegetation index (NDVI) at white flower stage at Lake Carl Blackwell, Stillwater, OK, from 2006 to 2010.

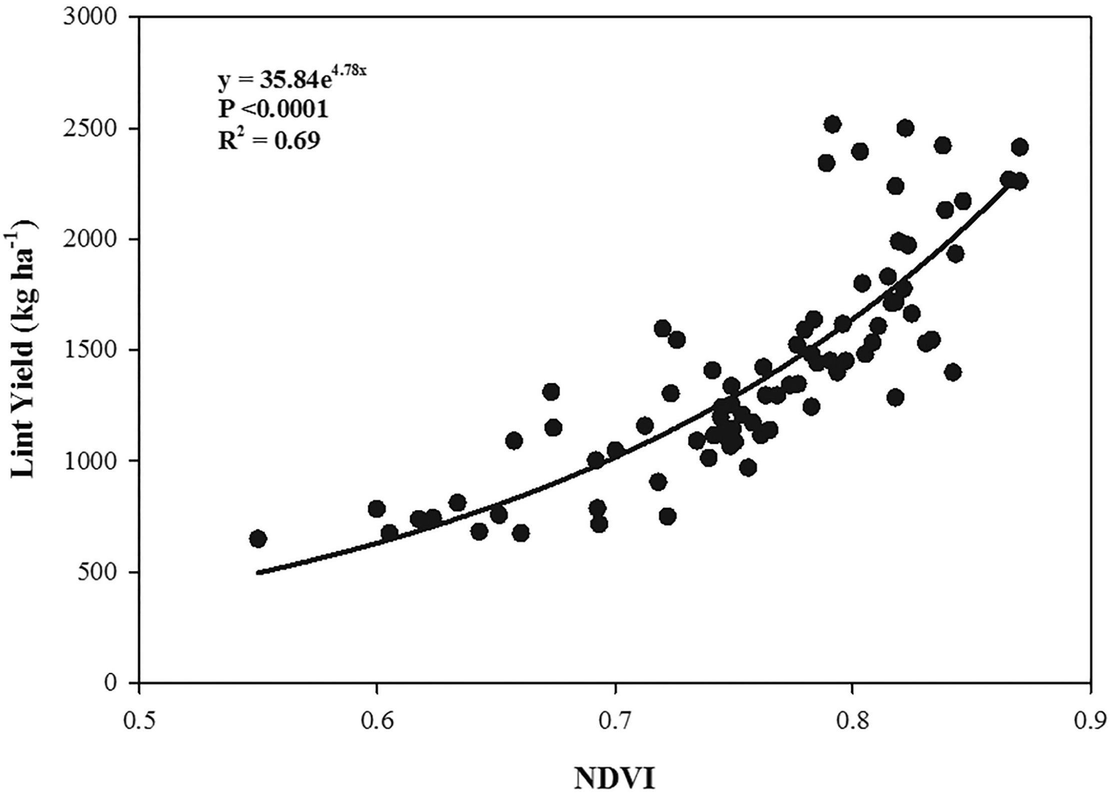

Fig. 3. Relationship between cotton lint yield and normalized difference vegetation index (NDVI) from white flower stage sensor measurements at Southwest Research Station, Altus, OK, from 2007 to 2010.

Table 2. Relationship between lint yield and normalized difference vegetation index (NDVI) fitted to an exponential regression model, 2006 to 2010.

	R^2		
Sites†	NDVI‡	DFP INSEY§	GDD INSEY¶
LCB	0.48	0.79	0.75
SWR	0.69	0.70	0.69

† LCB, Lake Carl Blackwell, near Stillwater, OK; SWR, Southwest Research Station near Altus, OK.

‡ NDVI, (ρNIR − ρRed)/(ρNIR + ρRed), where ρNIR is the fraction of emitted near-infrared radiation returned from the sensed area (reflectance) and ρRed is the fraction of emitted red radiation returned from the sensed area (reflectance).

§ DFP INSEY, days from planting in-season estimate of yield, calculated as NDVI/DFP

¶ GDD INSEY, growing degree day in-season estimate of yield, calculated as NDVI/GDD, where GDD is calculated as [(maximum daily temperature + minimum daily temperature)/2] − 15.5°C, with bases of 15.5 and 38°C for min. and max. temperatures.

In SWR site, CumGDD of 1400 to 1500, which corresponds to stages from match-head square to white flower, also provided a significant exponential relations with lint yields (Fig. 5). The equation for the line in SWR site is as follows:

$$\text{Cotton lint yield (kg ha}^{-1}) = 48.87e^{6200\times \text{INSEY}}$$

To develop an accurate measurement of yield potential, YP_0, the yield potential plus 1 standard deviation method was used (Raun et al., 2005; Lukina et al., 2001). The model used to predict the cotton lint yield for LCB and SWR sites are as follows:

$$\text{LCB: Cotton lint yield potential (kg ha}^{-1}) = 56.39e^{4108\times \text{INSEY}}$$

$$\text{SWR: Cotton lint yield potential (kg ha}^{-1}) = 65.0e^{6200\times \text{INSEY}}$$

Response Index

Aside from the yield potential, the degree to which a crop will respond to additional N is an equally important component in determining N recommendation (Raun et al., 2005). Observed correlations were poor when $RI_{Harvest}$ and RI_{NDVI} was explored by site (for LCB R^2 = 0.21 and for SWR R^2 = 0.32) but was improved when data from LCB and SWR were merged (R^2 = 0.44) (Fig. 6). The best correlation was observed when sensing readings at match-head square to white flower stage were used. This result is similar to Mullen et al. (2003) and Hodgen et al. (2005), wherein the relationship between $RI_{Harvest}$ calculated using lint yield and RI_{NDVI} calculated with NDVI in-season measurements did not result in an equation with an intercept of 0 and a slope of 1. A linear regression model best described the relationship between RI_{NDVI} and $RI_{Harvest}$ expressed as follows:

$$RI_{Harvest} = -2.1858 + (3.25\times RI_{NDVI})$$

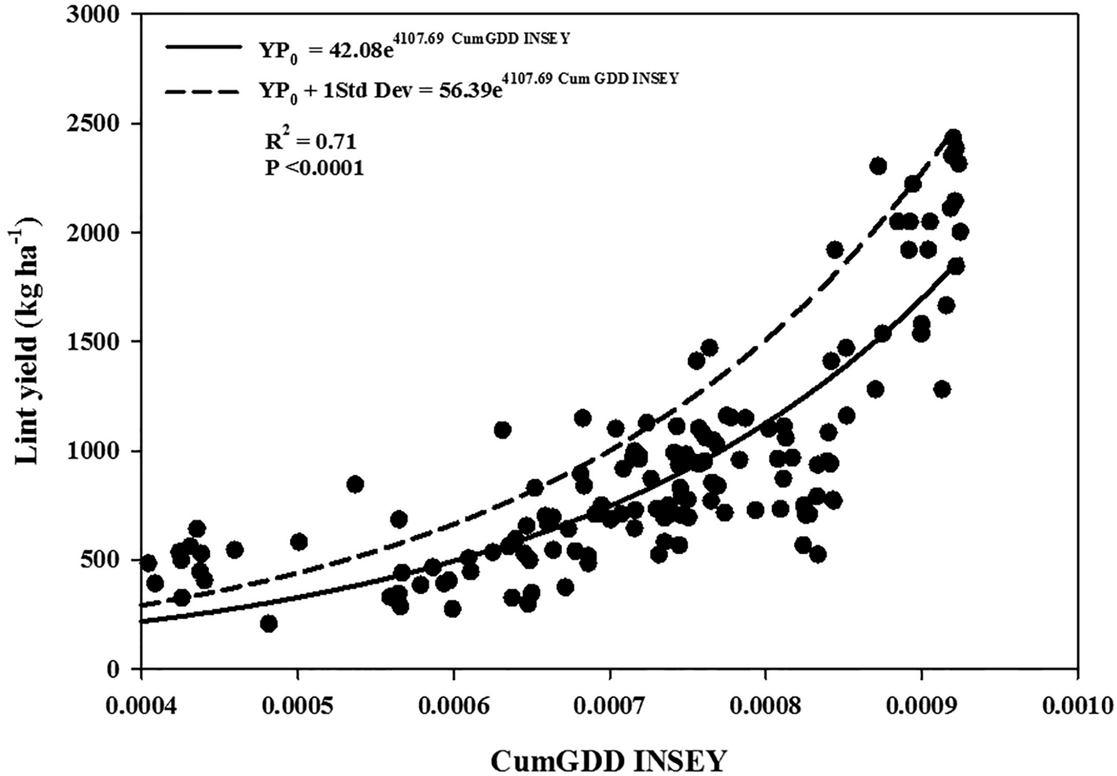

Fig. 4. Relationship between cotton lint yield and the cumulative growing degree day in-season estimate of yield (CumGDD INSEY) from match-head square to white flower stages sensor readings at Lake Carl Blackwell, Stillwater, OK, from 2006 to 2010. YP_0 (yield potential) = mean +1 standard deviation.

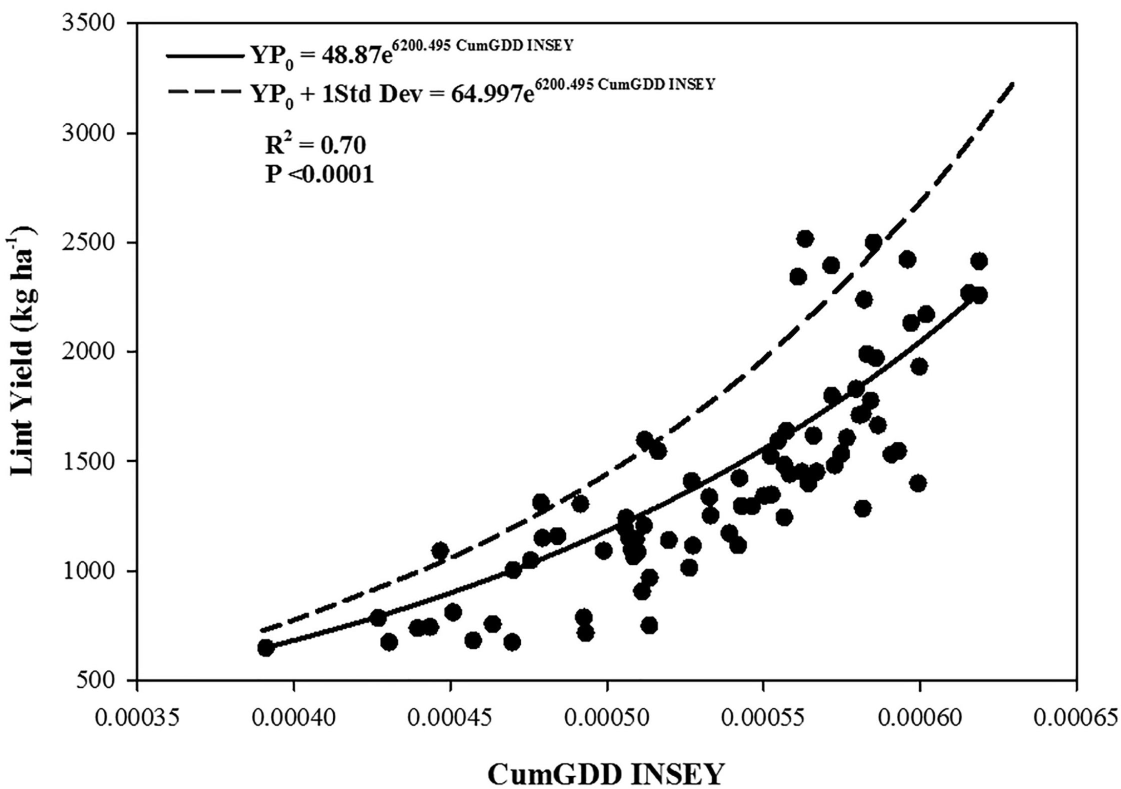

Fig. 5. Relationship between cotton lint yield and the cumulative growing degree day in-season estimate of yield (CumGDD INSEY) from match-head square to white flower stages sensor readings at Southwest Research Station, Altus, OK, from 2006 to 2010. YP_0 (yield potential) = mean +1 standard deviation.

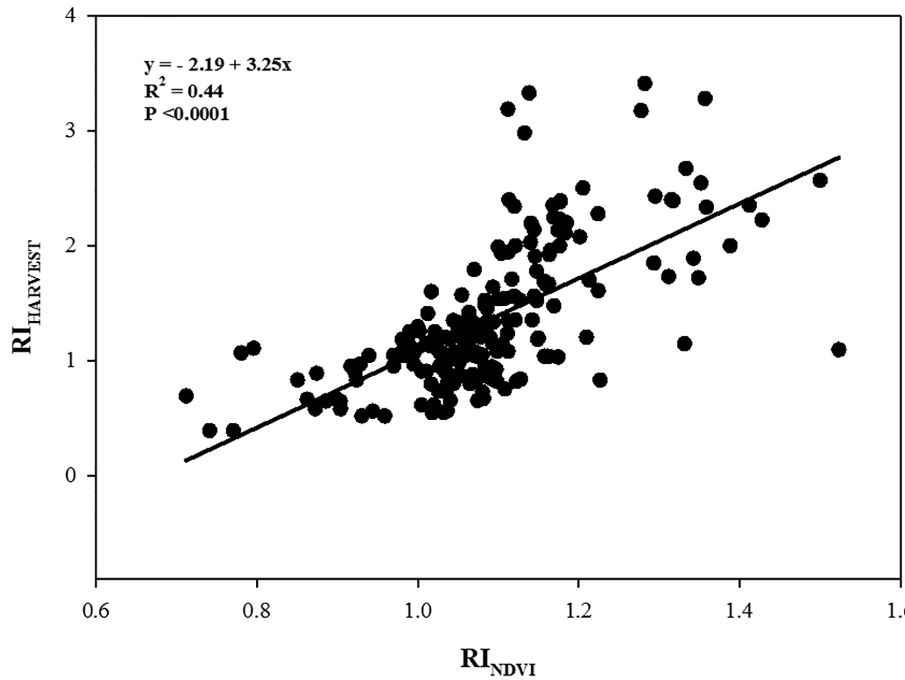

Fig. 6. Relationship between response index $(RI)_{NDVI}$ and $RI_{Harvest}$ at match-head square to white flower stages from Lake Carl Blackwell (LCB) and Southwest Research Station (SWR), OK, 2006 to 2010.

Across two sites, 5 yr, and different environments, RI_{NDVI} was positively and significantly correlated with $RI_{Harvest}$ ($P < 0.0001$; Fig. 6). This result indicates that it is possible to predict the crop responsiveness to added fertilizer. Response index, in combination with predicted yield, allows the prediction of the amount of N that will be removed in fertilized and nonfertilized plots. The difference in projected N uptake between the two is the recommended N rate prior to accounting for N use efficiency (NUE). If a grower uses the full potential of this system, application of preplant N might be reduced, then they can begin to take advantage of years where little or no N is needed to achieve maximum yield (Hodgen et al., 2005). This same approach has worked very well for small grains (Lukina et al., 2001; Mullen et al., 2003; Raun et al., 2005).

Percentage Nitrogen Removal

Using the average N concentration reported (Boquet and Breitenbeck, 2000; Fritschi et al., 2004b; Janat, 2005) in the lint and seed, N removal values were determined. The average N found in seed was calculated to be 42.1 and 3.0 g N kg^{-1} removed in the harvest lint. With an estimated HI of lint to seed in seed cotton set at 33%, the total N removed by the lint and seed for every kilogram of lint is 90 g. Fritschi et al. (2004b) observed that seed and lint make up 59.1% of the total N removed by the crop with the remaining 40.9% being captured in the burs, leaves, and stems. If these plant components (burs, leaves, and stems) will be accounted in the algorithm, this will result to a 146.4 g N kg^{-1} lint. Although, this value is similar to Mullins and Burmester (1990) and Unruh and Silvertooth (1996), it is much higher than the recorded optimum N rates for cotton grown in Oklahoma of 83 g N kg^{-1} lint (Girma et al., 2007). The 90 g N kg^{-1} lint (lint and seed only) closely fit the value that was calculated by Girma et al. (2007). Therefore, for this algorithm, the 90 g N kg^{-1} lint value, will be used instead of 146.4 g N kg^{-1} lint.

Efficiency Factor

There was no consensus within the literature on cotton NUE. It was, however, discussed that soil type and climate play a significant role on expected NUE in cotton. The NUE levels reported in the literature ranged from 25 to 60% (Bassett et al., 1970; Fritschi et al., 2004a,b; Hou et al., 2007; Janat, 2005; Unruh and Silvertooth, 1996). The NUE used for the cotton NFOA will initially be established at 50%. This was chosen because side-dress application of N is expected to be at the higher end of the recorded NUE range. Further research will be needed to refine this value.

Nitrogen Fertilization Optimization Algorithm

Since all the components to establish the NFOA have been discussed, the cotton NFOA is as follows:

$$\text{N rate} = \frac{\left[\left(\text{YP}_0 \times \text{RI}\right) - \text{YP}_0\right] \times \text{percentage grain N}}{\text{NUE}}$$

where

$$\text{YP}_{0(\text{LCB})} = 53.39e^{4108 \times \text{INSEY}}$$

$$\text{YP}_{0(\text{SWR})} = 65.0e^{6200 \times \text{INSEY}}$$

$$RI = -2.1858 + 3.25 \times RI_{NDVI}$$

Percentage grain N = 0.09

NUE = 0.50

The cotton NFOA will evolve over time as more data is collected and theories explored. Several modification and alterations are still necessary to fine-tune the algorithm. At this time, it is unknown if using the N content of the lint and seed is adequate or if it will be essential to include the N contained in burs, leaves, or stems. Also, because the total percentage N removed from the crop as harvested yield is lower in cotton than in grain crops, final estimates of N required needs to be verified. The 50% NUE used in the algorithm requires additional evaluations, since at present, this is a theoretical value because NUE is known to be dependent on the environment. Furthermore, the YP_0 prediction equation will need to be refined with the addition of more sensor data on different cotton varieties. For sensor-based N rate recommendations to be successful, the NFOA approaches and theories involved must be thought as dynamic and therefore changeable and adaptable to the situation and environment.

An additional point hinges around cotton's ability to go into excessive vegetative growth production when N is in excess and the environment is conducive to rapid growth. A potential problem that may be associated with the NFOA is directly related to the need to have reference strips. These high N strips will be the optimum environment for rank growth and the algorithm is using the NDVI values from the optimum area for the N rate recommendation. In this study, the conditions for excessive vegetative growth did not exist. So it will take future research to discover if the NFOA N recommendation will either avoid or create application levels that induce rank growth and if there will be a need to create N rate caps. These caps may be based on NDVI value, maximum yield level, or a maximum N rate.

This work is unique from other research, as this research focuses on proposed procedure that prescribes increased N rates in areas of the cotton field with high yield potential as indicated by CumGDD INSEY and reduced N fertilizer in areas of the field with lower yield potential. In addition, this procedure accounts for the amount of N in cotton, at the time of sensing, and adjusts for need accordingly. Compared with previous methods for developing N rate recommendation, which have often relied on a yield-goal approach (Stanford and Legg, 1984), this approach incorporates in-season environmental condition from planting to sensing. It recognizes the role environment plays in supplying a portion of the crops' N requirement by adjusting N recommendations. Furthermore, this approach addresses the issue of year-to-year variability in environmental conditions, as these can cause considerable year-to-year variation in soil N supply as well as crop N requirements (Shanahan et al., 2008). The NFOA could replace N fertilization rates determined using production history (i.e., yield goals), provided that the production system allows for in-season application of fertilizer N. Application of this procedure should increase NUE when the production system allows for in-season application of fertilizer N (Raun et al., 2002).

CONCLUSION

The development of an NFOA will allow for more accurate top-dress N rate recommendations to provide an alternative to applying all N preplant and ultimately reducing the risk of applying too much or too little N. Normalized difference vegetation index readings taken at white flower provided good correlation with final yield. Sorting sensor data by GDD extended the critical sensing window from match-head square to white flower growth stages. Normalizing the NDVI by DFP and CumGDD improved the yield potential prediction model with the understanding that CumGDD normalize NDVI more consistently across various field conditions and climates. The application of the correct N rate will not only benefit the producer and environment by reducing excessive N use but also reduce the need for additional chemical application that helps the producer control the growth and more easily harvest the crop.

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References

Barger, G. L. 1969. Total growing degree days. Weekly Weather Crop Bull. 56:10.

Bassett, D.M., W.D. Anderson, and C.H.E. Werkhoven. 1970. Dry matter production and nutrient uptake in irrigated cotton (*Gossypium hirsutum*). Agron. J. 62:299–303. doi:10.2134/agronj1970.00021962006200020037x

Boquet, D.J., and G.A. Breitenbeck. 2000. Nitrogen rate effect on partitioning of nitrogen and dry matter by cotton. Crop Sci. 40:1685–1693. doi:10.2135/cropsci2000.4061685x

Bronson, K.F., J.D. Booker, J.W. Keeling, R.K. Boman, T.A. Wheeler, R.J. Lascano, and R.L. Nichols. 2005. Cotton canopy reflectance at landscape scale as affected by nitrogen fertilization. Agron. J. 97:654–660. doi:10.2134/agronj2004.0093

Bronson, K.F., T.T. Chua, J.D. Booker, J.W. Keeling, and R.L. Lascano. 2003. In-season nitrogen status sensing in irrigated cotton: II. Leaf nitrogen and biomass. Soil Sci. Soc. Am. J. 67:1439–1448. doi:10.2136/sssaj2003.1439

Butchee, K.S., J. May, and B. Arnall. 2011. Sensor based nitrogen management reduced nitrogen and maintained yield. Crop Manage. 10. doi:10.1094/CM-2011-0725-01-RS

Freeman, K.W., W.R. Raun, G.V. Johnson, R.W. Mullen, M.L. Stone, and J.B. Solie. 2003. Late-season prediction of wheat grain yield and grain protein. Commun. Soil Sci. Plant Anal. 34:1837–1852. doi:10.1081/CSS-120023219

Fritschi, F.B., B.A. Roberts, D.W. Rains, R.L. Travis, and R.B. Hutmacher. 2004a. Fate of nitrogen-15 applied to irrigated acala and pima cotton. Agron. J. 96:646–655. doi:10.2134/agronj2004.0646

Fritschi, F.B., B.A. Roberts, R.L. Travis, D.W. Rains, and R.B. Hutmacher. 2004b. Seasonal nitrogen concentration, uptake, and partitioning pattern of irrigated acala and pima cotton as influenced by nitrogen fertility level. Crop Sci. 44:516–527. doi:10.2135/cropsci2004.5160

Girma, K., K.W. Freeman, R.K. Teal, R.K. Boman, and W.R. Raun. 2007. Cotton lint yield and quality as affected by applications of N, P, and K fertilizers. J. Cotton Sci. 11:12–19.

Hearn, A.B. 1986. Effect of preceding crop on the nitrogen requirements of irrigated cotton (*Gossypium hirsutum* L.) on a vertisol. Field Crops Res. 13:159–175. doi:10.1016/0378-4290(86)90018-3

Hodgen, P.J., W.R. Raun, G.V. Johnson, R.K. Teal, K.W. Freeman, K.B. Brixey, K.L. Martin, J.B. Solie, and M.L. Stone. 2005. Relationship between response indices measured in-season and at harvest in winter wheat. J. Plant Nutr. 28:221–235. doi:10.1081/PLN-200047605

Hons, F.M., M.L. McFarland, R.G. Lemon, R.L. Nichols, R.K. Boman, and V.A. Saladina. F. J. J. Mazac, R. L. Jahn, and J. R. Stapper. 2004. Managing nitrogen fertilizer in cotton. Texas Coop Ext. Texas A&M Univ., TX. http://www.cottoninc.com/fiber/AgriculturalDisciplines/Agronomy/NitrogenFertilizer/ManagingNitrogenFertilizationInCotton.pdf (accessed 5 Nov. 2015).

Hou, Z., P. Li, B. Li, J. Gong, and Y. Wang. 2007. Effects of fertigation scheme on N uptake and N use efficiency in cotton. Plant Soil 290:115–126. doi:10.1007/s11104-006-9140-1

Huang, Y., R. Sui, S. J. Thomson, and D. K. Fisher. 2013. Estimation of cotton yield with varied irrigation and nitrogen treatments using aerial multispectral imagery. Int. J. Agric. Biol. Eng. 6:37–41.

Janat, M. 2005. Assessment of nitrogen content, uptake, partitioning, and recovery by cotton crop grown under surface irrigation and drip fertigation by using isotopic technique. Commun. Soil Sci. Plant Anal. 35:2515–2535. doi:10.1081/LCSS-200030355

Johnson, G.V., and W.R. Raun. 2003. Nitrogen response index as a guide to fertilizer management. J. Plant Nutr. 26:249–262. doi:10.1081/PLN-120017134

Liakos, V., G. Vellidis, G. Harris, R. Hill, and H. Henry. 2013. Variable rate application of side-dress nitrogen on cotton in Georgia, USA. Precis. Agric. 13:435–442.

Lukina, E.V., K.W. Freeman, K.J. Wynn, W.E. Thomason, R.W. Mullen, M.L. Stone, J.B. Solie, A.R. Klatt, G.V. Johnson, R.L. Elliott, and W.R. Raun. 2001. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. J. Plant Nutr. 24:885–898. doi:10.1081/PLN-100103780

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347–351. doi:10.2134/agronj2003.0347

Mullins, G.L., and C.H. Burmester. 1990. Dry matter, nitrogen, phosphorus, and potassium accumulation by four cotton varieties. Agron. J. 82:729–736. doi:10.2134/agronj1990.00021962008200040017x

Raper, T.B., J.J. Varco, and K.J. Hubbard. 2013. Canopy-based normalized difference vegetation index sensors for monitoring cotton nitrogen status. Agron. J. 105:1345–1354. doi:10.2134/agronj2013.0080

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131–138. doi:10.2134/agronj2001.931131x

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820. doi:10.2134/agronj2002.8150

Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen, H. Zhang, J.S. Schepers, and G.V. Johnson. 2005. Optical sensor-based algorithm for crop nitrogen fertilization. Commun. Soil Sci. Plant Anal. 36:2759–2781. doi:10.1080/00103620500303988

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008. Responsive in-season nitrogen management for cereals. Comput. Electron. Agric. 61:51–62. doi:10.1016/j.compag.2007.06.006

Singh, V., and S.N. Nagwekar. 1989. Effect of weed control and nitrogen levels on quality characters in cotton. J. Indian Soc. Cotton Imp. 14:60–64.

Stanford, G., and J.O. Legg. 1984. Nitrogen and yield potential. In: R.D. Hauck, editor, Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI. p. 263–272.

Systat Software. 2014. SigmaPlot version 13.0. Systat Software, San Jose, CA.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488–1494. doi:10.2134/agronj2006.0103

Unruh, B.L., and J.C. Silvertooth. 1996. Comparisons between an upland and a Pima cotton cultivar: II. Nutrient uptake and partitioning. Agron. J. 88:589–595. doi:10.2134/agronj1996.00021962008800040016x

Valco, T.D., R.L. Nichols, and W.F. Lalor. 1998. Adopting precision farming technology for cotton nutrition. In: Proc. Beltwide Cotton Conf., San Diego, CA. 5–9 Jan. 1998. Natl. Cotton Counc., and the Cotton Foundation, Memphis, TN. p. 627–629.

Vellidis, G., H. Savelle, R.G. Richie, G. Harris, R. Hill, and H. Henry. 2011. NDVI response of cotton to nitrogen application rates in Georgia, USA. In: J.V. Stafford, editor, Precision agriculture 2011: Proc. 8th European Conf. on Precision Agric. (8ECPA), Prague, Czech Republic, p. 358–368.

Vellidis, G., M.A. Tucker, C.D. Perry, D.L. Thomas, N. Wells, and C.K. Kvien. 2004. Predicting cotton lint yield maps from aerial photographs. Precis. Agric. 5:547–564. doi:10.1007/s11119-004-6342-5

Wilkerson, J.B., and W.E. Hart. 1996. Yield sensing technology in cotton harvest applications. In: Proc. Beltwide Cotton Conf., Nashville, TN. 9–12 Jan. 1996. Natl. Cotton Counc., and the Cotton Foundation, Memphis, TN. p. 184–186.

Yang, C., J.M. Bradford, and C.L. Wiegand. 2001. Airborne multispectral imagery for mapping variable growing conditions and yields of cotton, grain sorghum, and corn. Trans. ASAE 44:1983–1994. doi:10.13031/2013.6997

Zhao, D., K.R. Reddy, V.G. Kakani, J.J. Read, and S. Koti. 2007. Canopy reflectance in cotton for growth assessment and lint yield prediction. Eur. J. Agron. 26:335–344. doi:10.1016/j.eja.2006.12.001