Association of Spectral Reflectance Indices with Plant Growth and Lint Yield in Upland Cotton

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ABSTRACT

Canopy reflectance plays an increasingly important role in crop management and yield prediction at large scale. The relationship of four spectral reflectance indices with cotton (*Gossypium hirsutum* L.) biomass, leaf area index (LAI), and crop yield were investigated using three cotton varieties and five N rates in the irrigated low desert in Arizona during the 2009 and 2010 growing seasons. Biomass, LAI, and canopy reflectance indices (normalized difference vegetation index [NDVI], simple ratio [SR], near-infrared index [NIR], and ratio vegetation index [RVI]) were determined at different growth stages. The commonly used NDVI and the other three canopy reflectance indices explained over 87% variation in cotton biomass (all $R^2 > 0.87$) and LAI ($R^2 > 0.93$). Indices SR, NIR, and RVI all had higher coefficients of determination (R^2) compared to NDVI because these indices were not saturated at late growth stages. There was no significant relationship between lint yield and the spectral indices measured at early growth stages. However, the spectral indices determined at peak bloom showed significant correlations with lint yield. Indices SR, NIR, and RVI explained 56, 60, and 58% of variations in cotton lint yield, respectively, while NDVI only explained 47% of variation in lint yield. This study suggests canopy reflectance indices can be used to predict cotton lint yield at peak bloom and the accuracy of yield prediction can be significantly improved when SR, NIR, and RVI are used.

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Abbreviations: LAI, leaf area index; NDVI, normalized difference vegetation index; SR, simple ratio; NIR, near-infrared index; RVI, ratio vegetation index.

Remote sensing techniques have opened new avenues to obtain information on crop growth status and compare canopy density and crop productivity (Wiegand et al., 1991; Araus et al., 2001; Gutierrez et al., 2010). Canopy spectral reflectance can be related to crop growth status such as biomass, leaf area index (LAI), and intercepted radiation (Pinter et al., 1994). In addition to these crop canopy characteristics, spectral indices measured during the growing season can also be used to predict crop yield under different environments, because crop production is correlated with the amount of photosynthetic tissue (Plant et al., 2000; Benedetti and Rossini, 1993; Ma et al., 2001; Li et al., 2001; Zarco-Tejada et al., 2005). While the conventional measurement of agronomic parameters, such as biomass and LAI, is time-consuming and costly, the measurement of spectral indices is fast and nondestructive and could be conducted on a large scale (Eitel et al., 2008).

The normalized difference vegetation index (NDVI) is the most commonly used spectral index calculated from reflectance at wavelengths 900 and 680 nm ($[R_{900} - R_{680}]/[R_{900} + R_{680}]$). It is

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a function of the vegetation cover, LAI, biomass, and leaf chlorophyll (Eitel et al., 2008). Benedetti and Rossini (1993) determined that NDVI correlates with the photosynthetic apparatus capacity and can be employed to predict wheat (*Triticum aestivum* L.) yield in diverse agricultural regions. Wanjura and Hatfield (1987) found that NDVI showed a strong association with crop biomass at high levels of LAI by comparing four row crops (cotton [*Gossypium hirsutum* L.], soybean [*Glycine max* (L.) Merr.], grain sorghum [*Sorghum bicolor* (L.) Moench], and sunflower [*Helianthus annuus* L.]) during periods of vegetative growth. The NDVI also has been used to determine the photosynthetic capacity, N uptake, and grain yield in winter wheat (Solie et al. 1996; Raun et al. 2001). However, when it is used to estimate LAI and chlorophyll, NDVI frequently is insensitive for estimating high biomass, LAI, and chlorophyll concentrations due to its saturation at high vegetation cover (Gitelson and Merzlyak, 1996; Daughtry et al., 2000).

Other vegetation indices and spectral bands have been proposed to estimate biomass, LAI, chlorophyll, and crop N status at diverse canopy densities (Daughtry et al., 2000). Guyot et al. (1988) found that reflectance at 780 nm is highly sensitive to chlorophyll amount in dense canopies and less sensitive at 740 nm. The reflectance at 670 nm is also sensitive at dense canopies and high chlorophyll contents and the combination with reflectance at 780 nm make a simple ratio (SR) index ($SR = R_{780}/R_{670}$), which is sensitive to chlorophyll and biomass (Hatfield et al., 2008; Mistele and Schmidhalter, 2010).

The ratio vegetation index ($RVI = [R_{750} - R_{900}]/[R_{690} - R_{710}]$) has also been proposed to evaluate ground vegetation coverage across a range of canopy types and species (Huete et al., 2002). Biomass was highly correlated with RVI in five grasslands with low and high canopy densities (Shen et al., 2008). Wanjura and Hatfield (1987) reported that the RVI was more sensitive than the NDVI to large amounts of plant biomass and LAI. This index was also reported as more sensitive than NDVI in predicting crop yield in durum wheat [*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.] genotypes (Aparicio et al., 2000).

The reflectance at 810 nm is a spectral waveband related to leaf N accumulation in wheat and rice (*Oryza sativa* L.) and the near-infrared index ($NIR = R_{810}/R_{560}$) has been proposed to estimate leaf N content (Zhu et al., 2007). This index is also associated with biomass, permitting differentiation among rice varieties (Xue et al., 2005; Muller et al., 2008).

In many cases, crop yield is positively correlated with biomass and LAI, but this correlation is more complicated in cotton compared to other crops. This is mainly due to the fact that cotton is a perennial crop but cultivated as an annual and that balanced carbohydrate partitioning between vegetative and reproductive structures (fruiting forms) may be disrupted when rates of fruit shedding are abnormally high. Loss of fruiting structures may result from heat stress, insect pressure, or other environmental factors. This can result in cotton canopies with high levels of biomass but very little lint yield in some cases.

Canopy reflectance has been shown to correlate with shoot N concentration and has been utilized to guide N application and predict lint yield in cotton (Zhao et al., 2010; Bronson et al., 2011; Plant et al., 2000). Plant et al. (2000) investigated the relationships between remotely sensed canopy reflectance and cotton growth and found that NDVI integrated over time showed a significant correlation with lint yield. Cotton yield can be correlated with the amount of photosynthetic tissue, which is highly related to biomass and can be estimated by NDVI (Plant et al., 2000). The relationship between spectral indices and lint yield are found to be growth-stage dependent. For example, Li et al. (2001) found that cotton lint yield and N uptake were related to NDVI measured during the peak bloom. Zarco-Tejada et al. (2005) investigated temporal and spatial relationships between cotton yield variability and many hyperspectral reflectance indices and concluded that the relationships for evaluating lint yield depended on the crop growth stage. Additionally, different indices need to be employed with specific objectives. Bronson et al. (2003) found that green vegetative indices and green normalized difference vegetative indices showed stronger correlations with leaf N but weaker correlations with biomass and lint yield than red vegetative indices and red normalized difference vegetative indices.

The southwestern region of the United States is characterized as semiarid irrigated agriculture where upland cotton (*Gossypium hirsutum* L.) is one of the major crops (Grismer, 2002). Much emphasis has been given to N fertilization due to its significant influence on plant biomass and crop yield (Breitenbeck and Boquet, 1993; Ahmad 2000). While various indices have been developed for estimating crop yield and managing N input in different crops, limited studies have been conducted on the relationships between vegetation indices and cotton lint yield. Therefore, this study used three cotton varieties and five N rates to test if SR, RVI, and NIR may be better than NDVI in estimating crop growth parameters (LAI and biomass) and lint yield in upland cotton.

MATERIALS AND METHODS

Experimental Site and Plot Management

The study was conducted at University of Arizona Maricopa Agricultural Center, (Maricopa, AZ; 33°04′ N 111°58′ W, and 360 m above sea level) during the 2009 and 2010 growing seasons. The experiment was a split-plot design with six replications, where three upland cotton varieties were assigned to the main plots and N fertilizer rates were the subplots. The three varieties were PhytoGen PHY375WRF (PHY375), Stoneville ST4498B2RF (ST4498), and Delta Pine DP164B2RF (DP164) in 2009 and Stoneville ST4288B2RF (ST4288), ST4498, and

DP164 in 2010. The variety change in 2010 was due to lower heat stress tolerance of PHY375 compared to the other two varieties, although there was no yield reduction due to heat stress observed among the three varieties in 2009. Nitrogen fertilizer rates of 45, 90, 135, and 180 kg N ha^{-1} and 0, 45, 90, and 135 kg N ha^{-1}, respectively, were used in 2009 and 2010. The lower N rates were used in 2010 to increase differences among treatments. The N fertilizer was urea ammonium nitrate side-dressed into the beds twice between pinhead square and first bloom. Preplant soil samples indicated that there was about 40 kg N ha^{-1} in the top 20 cm soil. It was estimated that there was about 50 kg N ha^{-1} in the irrigation water in each of the two growing seasons.

Each plot consisted of four planted rows extending 8.2 m in length. Row and in-row spacing was 1.02 m and 8 cm, respectively, with a planting density of 122,000 plants ha^{-1}. Seeds were planted in dry soil on beds during the third week of April in both years and furrow irrigated immediately after planting. The plots were irrigated to ensure there was no drought stress during the growing seasons. The last irrigation was applied in the first week of September in both years. To control insect infestation (i.e., whitefly [*Bemisia tabaci* (Gennadius) Biotype B]), the recommended pesticide pyriproxyfen (700 mL ha^{-1}) was sprayed in mid July and buprofezin (875.7 mL ha^{-1}) sprayed in mid August in both years. Thidiazuron and diuron (877 mL ha^{-1}) was sprayed in the first week of October to defoliate the cotton plants. Ethephon and urea sulfate (4.7 L ha^{-1}) and sodium chlorate (23.4 L ha^{-1}) were applied 2 wk later to open the uppermost bolls before harvest in both years.

Spectral Reflectance Measurements

Canopy spectral reflectance was measured from 350 to 2500 nm in 1.5 nm intervals using a field spectroradiometer (FieldSpec Pro, Analytical Spectral Devices, Boulder, CO). Data were collected during cloud-free days between 1030 and 1400 h after a previous calibration with a white Spectralon plate, which provides maximum reflectance (Labsphere Inc., North Sutton, NH). Four measurements were collected in each plot by positioning a bare fiber optic with a 25° field-of-view at a nadir view angle approximately 1 m above the cotton canopy. Canopy reflectance measurements were collected at five growth stages in the two growing seasons, including pinhead square, first bloom, mid-bloom (2 wk after first bloom), peak bloom, and cut-out (5 nodes above white flower).

About 50 spectral indices were calculated from the canopy reflectance data, including the well-known NDVI ($[R_{900} - R_{680}]/[R_{900} + R_{680}]$) and three other spectral indices that have shown the highest association with cotton growth and yield. These three indices were SR (R_{780}/R_{670}), NIR (R_{810}/R_{560}), and the modified RVI ($[R_{750} - R_{900}]/[R_{690} - R_{710}]$) following the equations described by Jordan (1969), Tucker (1979), Guyot et al. (1988), and Zhu et al. (2007).

Leaf Area Index and Biomass

Leaf area and biomass were measured by collecting 1 m row of cotton plants on the same day as the spectral readings. Leaves were separated from plants and leaf area was measured using a leaf area meter (Licor LI-3100, Lincoln, NE). Leaves and stems were then dried at 65°C with ventilation until a constant weight was reached to record total dry biomass.

Cotton Seed and Lint Yield

Cotton plants in the two center rows of each plot were harvested using a two-row mechanical cotton harvester (Case IH-782 Cotton Picker, Case IH, Racine, WI) in late November in both growing seasons. After harvest, seed cotton samples were ginned in a Mitchell gin (Mitchell Gin Machinery, Dallas, TX) to determine lint yield for each plot.

Statistical Analysis

Since a different variety was used in the second year of the study, data from each growing season was analyzed separately when the treatments were compared for biomass, LAI, and lint yield. However, leaf area, biomass, and lint yield data from the two growing seasons were combined for regression analysis with canopy reflectance because the data in the two growing seasons showed no significant differences. Power functions were used to describe the relationship between cotton biomass and LAI:

$$y = ax^b, \quad [1]$$

where y is biomass (kg ha^{-1}) or LAI (m^2 m^{-2}), x is the value of spectral indices, and a and b are constants determined through the analysis.

For easier description, the above equation was transformed into natural logarithms of biomass and spectral indices:

$$\ln(y) = c + b\ln(x), \quad [2]$$

where $c = \ln(a)$.

Equation [2] was fit to biomass or LAI and spectral readings collected at all growth stages to evaluate the ability of spectral indices to estimate biomass or LAI.

Linear regression equations were fitted to the data with cotton lint yield as the dependent variable and spectral indices at different growth stages as the independent variables to find the growth stages when cotton yield can be best predicted by canopy reflectance indices and to determine the spectral indices that most accurately predict lint yield. The relationships between cotton lint yield and crop biomass at different growth stages were also examined.

To detect if the four spectral indices saturated when biomass and LAI were high, piecewise regression was used according to Ryan and Porth (2007). First, the cut point value (c) was found by a nonlinear regression approach. The cut point occurs where the relationship between biomass or LAI and the spectral index ceases to be linear. In other words, the regression lines for biomass or LAI and the index have different slopes when the index is larger than or smaller than the value at point c. After the cut point was found, two separate regression lines were fitted to the data.

RESULTS

Biomass, Leaf Area, and Cotton Lint Yield

There was no significant interaction between N and variety ($p > 0.65$); the effect of N and variety on cotton biomass, LAI, and lint yield are presented as means for main plot and subplot treatments (Table 1). The N treatments did not affect cotton biomass and leaf area significantly before first bloom in either the 2009 or 2010 growing season. In 2009, cotton biomass in the highest N rate treatment (180 kg ha^{-1}) was higher than other three N treatments at peak bloom and cut-out stages. Leaf area in

Table 1. Cotton biomass and leaf area index (LAI) affected by N rate and variety in 2009 and 2010

			Pinhead square[†]		First bloom		Mid-bloom		Peak bloom		Cut-out	
Year	Factor	Level	Biomass	LAI	Biomass	LAI	Biomass	LAI	Biomass	LAI	Biomass	LAI
			kg^{-1} ha		kg^{-1} ha		kg^{-1} ha		kg^{-1} ha		kg^{-1} ha	
2009	N rate	45	55.8 a[‡]	0.05 a	904 a	0.69 a	–	–	4968 b	1.62 b	10,458 b	4.13 a
		90	53.1 a	0.05 a	877 a	0.71 a	–	–	4319 c	1.51 b	10,444 b	4.10 a
		135	53.9 a	0.04 a	920 a	0.75 a	–	–	5047 b	1.85 ab	10,278 b	4.30 a
		180	50.4 a	0.04 a	915 a	0.68 a	–	–	6497 a	2.14 a	12,227 a	4.38 a
	Variety	PHY375	59.0 a	0.05 a	870 a	0.70 a	–	–	6023 a	1.96 a	10,187 a	3.93 a
		ST4498	57.5 a	0.05 a	949 a	0.74 a	–	–	4879 b	1.80 ab	11,315 a	4.47 a
		DP164	43.5 b	0.03 b	899 a	0.68 a	–	–	4721 b	1.58 b	11,053 a	4.29 a
2010	N rate	0	75.9 a	0.04 a	618 a	0.36 a	1559 b	1.07 a	3519 a	2.02 a	10,442 b	3.97 b
		45	82.6 a	0.05 a	561 a	0.34 a	1626 b	1.09 a	3579 a	2.06 a	11,577 ab	4.74 ab
		90	80.6 a	0.04 a	560 a	0.29 a	1915 a	1.08 a	3523 a	2.07 a	12,137 a	5.08 a
		135	101.3 a	0.05 a	607 a	0.37 a	2002 a	1.24 a	3727 a	2.29 a	12,227 a	4.89 a
	Variety	ST4288	93.5 a	0.05 a	650 a	0.37 a	1972 a	1.25 a	3865 a	2.08 a	11,567 a	4.13 a
		ST4498	103.6 a	0.05 a	669 a	0.40 a	1896 a	1.19 a	3712 ab	2.26 a	11,639 a	4.80 a
		DP164	58.2 b	0.03 b	440 b	0.25 b	1458 b	0.92 b	3183 b	1.99 a	11,581 a	5.07 a

[†] Growing degree days calculated using a base temperature of 12.8°C and a ceiling temperature 30°C were 350 in 2009 and 400 in 2010 at pinhead square, 700 in 2009 and 675 in 2010 at first bloom, 890 in 2010 at mid-bloom, 1198 in 2009 and 1008 in 2010 at peak bloom, and 1548 in 2009 and 1360 in 2010 at cut-out.

[‡] The data in the same factor of the same column followed by different letter are different at the 0.05 probability level.

Table 2. Cotton lint yield affected by N rate and variety in 2009 and 2010.

	2009		2010	
Factor	Level	Cotton lint yield	Level	Cotton lint yield
		kg ha^{-1}		kg ha^{-1}
N rate	45	1893.5 a[†]	0	1513.3 b
	90	1954.9 a	45	1628.1 ab
	135	1965.7 a	90	1650.9 a
	180	1882.3 a	135	1544.3 ab
Variety	PHY375	1679.6 b	ST4288	1553.8 a
	ST4498	2065.7 a	ST4498	1590.7 a
	DP164	2027.0 a	DP164	1608.0 a

[†] The data in the same factor of the same column followed by different letter are different at the 0.05 probability level.

the 180 kg N ha^{-1} treatment was also higher than in the 45 and 90 kg N ha^{-1} treatments. In 2010, the 90 and 135 kg N ha^{-1} treatments increased cotton biomass growth at mid-bloom and cut-out stages compared to the zero N treatment. Cotton leaf area in the zero N treatment was also lower than that of the two high N treatments. There were no significant differences in cotton lint yield among the N treatments in 2009 while the treatment with 90 kg N ha^{-1} increased cotton lint yield by 9.1% compared to the zero N treatment in 2010 (Table 2).

Variety DP164 had lower biomass and leaf area from emergence to peak bloom compared to the other varieties (Table 1). However, there were no significant differences in biomass or leaf area among the varieties at cut-out stage, indicating a higher growth rate for the variety at the late growth stage. Variety DP164 and ST4498 had higher lint yield than PHY375 in 2009, but the differences among the varieties in 2010 were not significant, indicating higher biomass does not always translate into higher cotton lint yield.

Biomass and Leaf Area Index Related with Spectral Indices

The spectral indices showed a power function relationship with biomass during the entire growing season. Therefore, the log-transformed spectral indices and biomass showed a linear relationship (Fig. 1). Among the 50 indices summarized in Li et al. (2001), Chen et al. (2010), and Eitel et al. (2008) and tested in this study, the commonly used NDVI and other three canopy reflectance indices (SR, NIR, and RVI) explained over 87% of variation in cotton biomass (all $R^2 > 0.87$). The SR, NIR, and RVI also showed better correlations with cotton biomass than NDVI. This is due to the fact that NDVI saturated earlier than the other three indices when cotton biomass increased dramatically at peak bloom. The saturation of NDVI due to large amounts of biomass was evident by the low NDVI changes at high biomass content at late growth stages (peak bloom to cut-out) (Fig. 1a). Piecewise regression between NDVI and cotton biomass showed that two regression lines fit the data better than one regression line and that R^2 improved from 0.87 to 0.95, indicating that NDVI saturated at later crop development (Table 3). The NDVI was 0.81 [exp(–0.21)] and biomass was 1664 kg ha^{-1} [exp(8.19 + 3.68 × –0.21)] at the cut point.

The relationship between cotton LAI and spectral indices showed little differences among the four spectral indices (R^2 ranged from 0.93 to 0.94). Similarly, NDVI showed saturation at high LAI values in late growth stages as observed with the biomass relationship (Fig. 2a) and indicated by piecewise regression (Table 3). The NDVI was 0.82 [exp(–0.20)] and LAI was 1.22 [exp(1.00 + 4.02 × –0.20)] at the cut point.

Relationship Between Lint Yield and Spectral Indices

The correlations between lint yield and the spectral indices measured at pinhead square, mid-bloom, peak bloom,

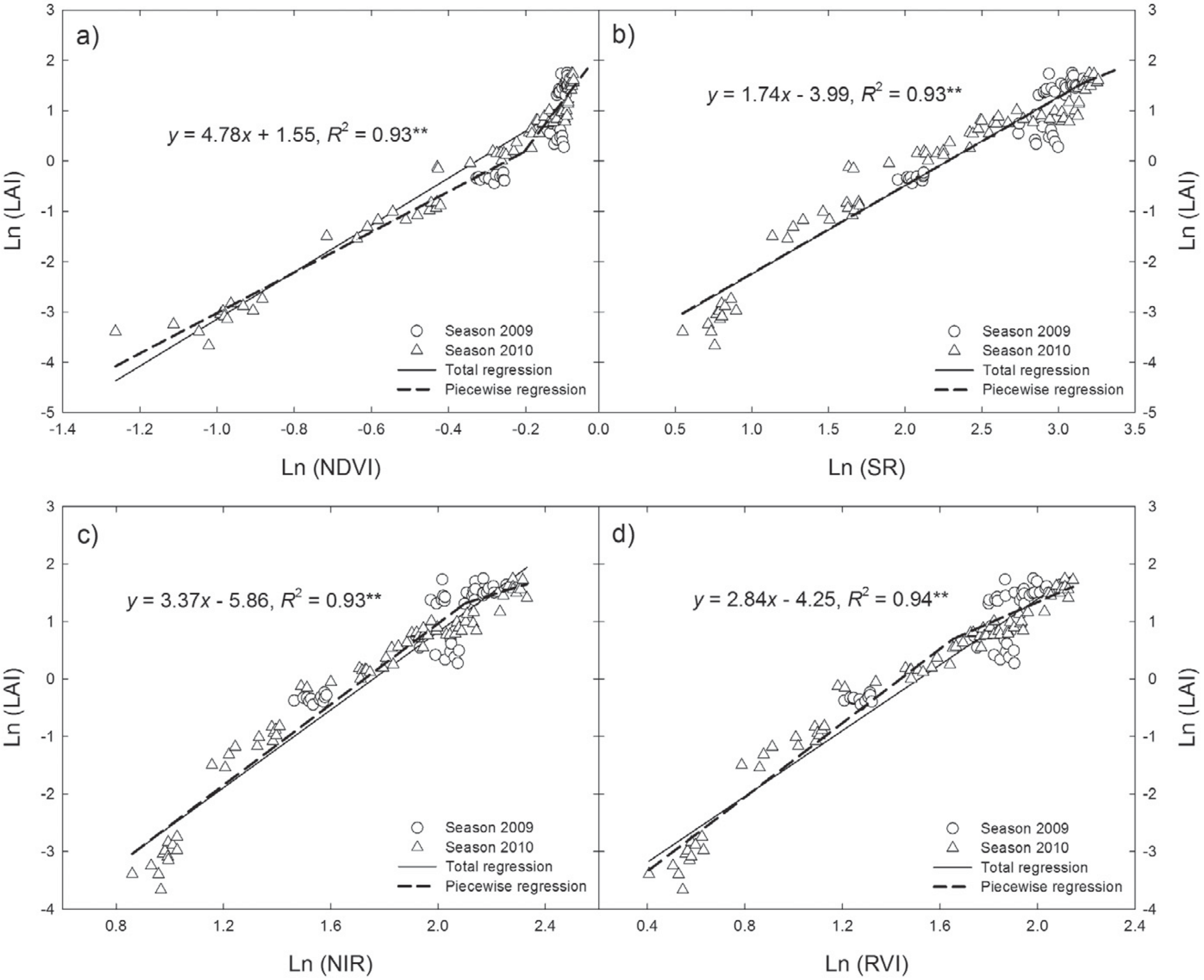

Figure 1. Relationship between spectral indices and cotton biomass measured during crop development in the 2009 and 2010 growing seasons. Regression equations for all data (plain lines) are shown on the graph and regression equations for piecewise lines (dotted) are in Table 3. In the equations, *y* is natural logarithm transformation of cotton biomass (kg ha^{-1}) and *x* is natural logarithm transformation of the spectral index. **, significance probability level of 0.01. NDVI, normalized difference vegetation index; SR, simple ratio; NIR, near-infrared index; RVI, ratio vegetation index.

Table 3. Piecewise regression on biomass or leaf area index (LAI) and spectral indices.

Variable	Spectral indices†	Regression line for all data‡	R^2	Cut point	Piecewise regression line 1	Piecewise regression line 2	Piecewise regression R^2
Biomass	NDVI	$y = 5.25x + 9.34$	0.87	–0.21	$y = 3.68x + 8.19$	$y = 15.41x + 10.68$[§]	0.95
	SR	$y = 1.99x + 3.07$	0.94	3.16	$y = 2.00x + 3.05$	$y = -0.07x + 9.62$	0.94
	NIR	$y = 3.84x + 0.93$	0.94	2.21	$y = 3.95x + 0.79$	$y = -1.03x + 11.77$	0.95
	RVI	$y = 3.24x + 2.79$	0.95	1.65	$y = 3.20x + 2.02$	$y = 3.34x + 2.58$	0.95
LAI	NDVI	$y = 4.78x + 1.55$	0.93	–0.20	$y = 4.02x + 1.00$	$y = 10.05x + 2.23$[§]	0.95
	SR	$y = 1.74x - 3.99$	0.93	3.16	$y = 1.75x - 3.99$	$y = 1.24x - 2.38$	0.93
	NIR	$y = 3.37x - 5.86$	0.93	2.10	$y = 3.51x - 6.06$	$y = 1.43x - 1.69$	0.94
	RVI	$y = 2.84x - 4.25$	0.94	1.65	$y = 3.22x - 4.63$	$y = 1.85x - 2.36$	0.95

[†] NDVI, normalized difference vegetation index; SR, simple ratio; NIR, near-infrared index; RVI, ratio vegetation index.

[‡] In the equations, *y* is natural logarithm transformation of cotton LAI and *x* is natural logarithm transformation of the spectral index.

[§] Slope of the equation is significantly different from 0 and the regression line is significantly different from regression line on all data and piecewise regression line 1 at 0.05 probability level.

or cut-out stages were not significant (Table 4). However, significant correlations between lint yield and the spectral indices were observed at first bloom and peak bloom stages, with higher correlation coefficients at the

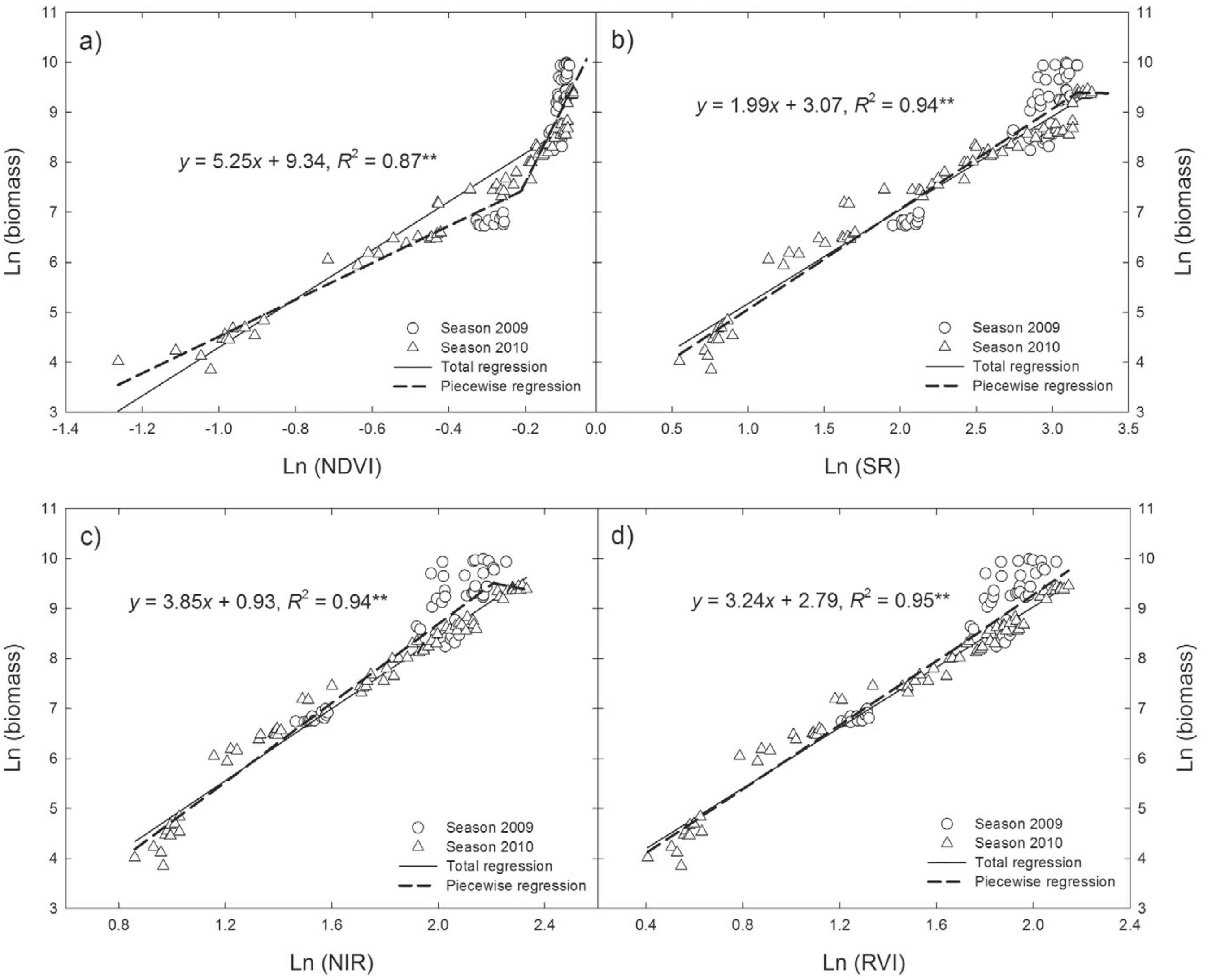

Figure 2. Relationship between spectral indices and cotton leaf area index (LAI) measured during crop development in the 2009 and 2010 growing seasons. Regression equations for all data (plain lines) are shown on the graph and regression equations for piecewise lines (dotted) are in Table 3. In the equations, *y* is natural logarithm transformation of cotton LAI and *x* is natural logarithm transformation of the spectral index. **, significance at probability level of 0.01. NDVI, normalized difference vegetation index; SR, simple ratio; NIR, near-infrared index; RVI, ratio vegetation index.

Table 4. Correlation coefficients between cotton lint yield and spectral indices measured at diverse growth stages in 2009 and 2010 growing seasons.

Growth stage	NDVI†	SR	NIR	RVI
Pinhead square	–0.04	–0.05	–0.04	–0.04
First bloom	0.46**	0.50**	0.48**	0.46**
Mid-bloom‡	0.06	0.08	0.03	0.04
Peak bloom	0.69**	0.75**	0.78**	0.76**
Cut-out	–0.14	–0.12	–0.20	–0.16

**Significant at the 0.01 probability level.

† NDVI, normalized difference vegetation index; SR, simple ratio; NIR, near-infrared index; RVI, ratio vegetation index.

‡ Data were taken in 2010 only at this stage.

peak bloom stage. Similar to biomass and LAI, the NDVI had the lowest correlation with lint yield among the four spectral indices. Regression between cotton lint yield and the four spectral indices showed that SR, NIR, and RVI at peak bloom stage had significantly higher correlations with cotton lint yield (Fig. 3). While NDVI explained 47% of variation in cotton lint yield, SR, NIR, and RVI explained 56, 60, and 58% of variation in lint yield, respectively. This indicates that accuracy of yield prediction at peak bloom can be substantially improved when SR, NIR, and RVI are used.

Relationship Between Lint Yield and Biomass or Leaf Area Index

Since the spectral indices were derived from cotton canopy, the relationship between crop yield and biomass or LAI measured at each growth stage (pinhead square, first bloom, mid-bloom, peak bloom, and cut-out) was examined (Table 5). There were significant correlations between cotton lint yield and cotton biomass or LAI at

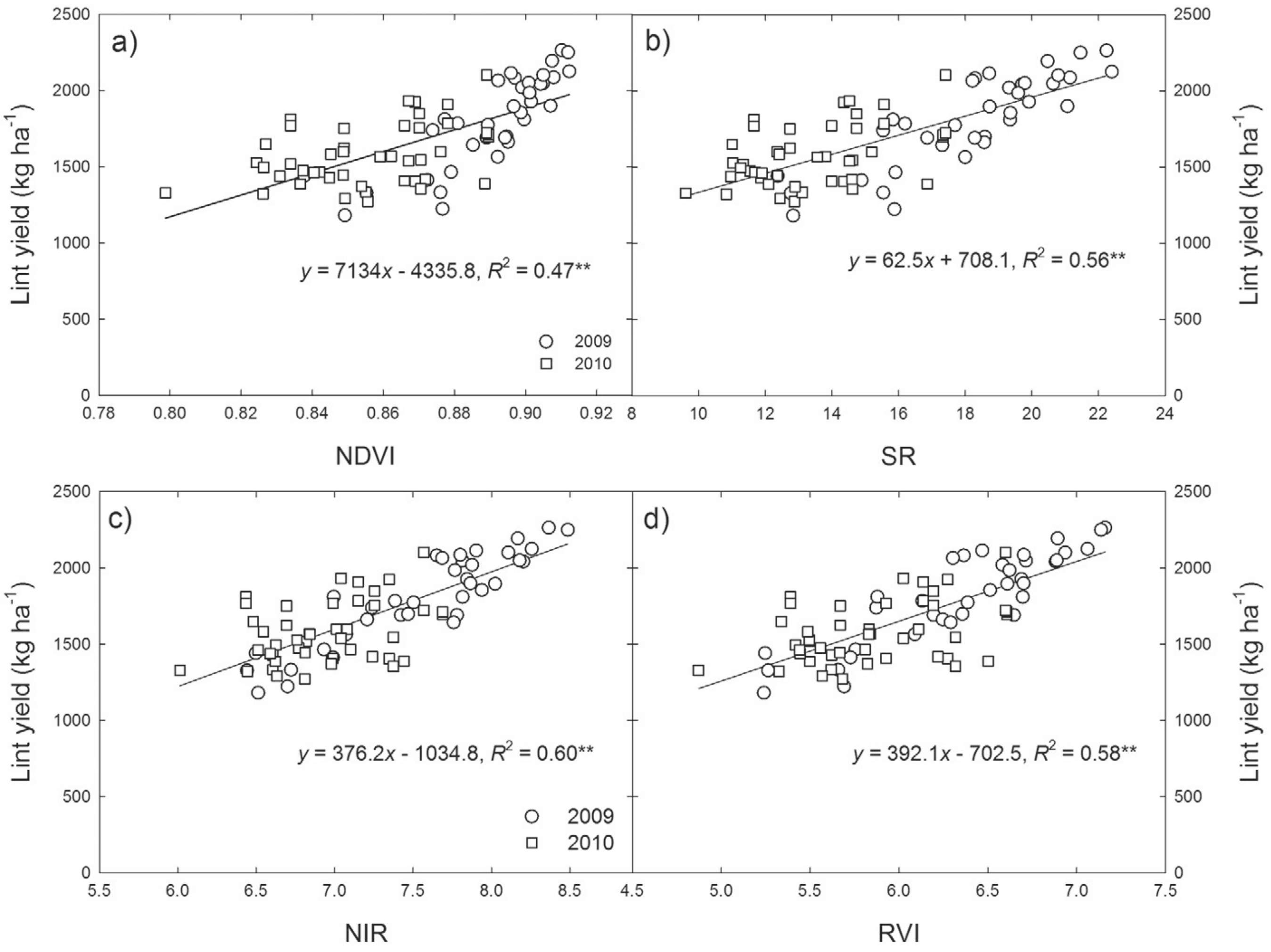

Figure 3. Relationship between spectral indices and cotton lint yield measured at peak bloom in the 2009 and 2010 growing seasons. In the equation, y is cotton lint yield and x is the spectral index measurement. **, significance at probability level of 0.01. NDVI, normalized difference vegetation index; SR, simple ratio; NIR, near-infrared index; RVI, ratio vegetation index.

first bloom and peak bloom. At cut-out stage, lint yield was highly correlated with biomass but not LAI. The high correlations between lint yield and biomass or LAI explain why spectral indices measured at peak bloom had higher correlations with lint yield.

Table 5. Correlation coefficients between cotton lint yield and biomass or leaf area index (LAI) measured at different growth stages in 2009 and 2010 growing seasons.

Growth stage	Biomass	LAI
Pinhead square	−0.44	−0.11
First bloom	0.68**	0.70**
Mid-bloom†	0.32	0.41
Peak bloom	0.75**	0.74**
Cut-out	0.75**	0.26

**Significant at the 0.01 probability level.

†Data were taken in 2010 only at this stage.

DISCUSSION

Leaf Area Index and Biomass Related with Spectral Indices

The four spectral indices used in the study (NDVI, SR, NIR, and RVI) were sensitive to the changes in biomass and LAI from early to late growth stages. The NDVI was the only index among the four indices that showed significant saturation at late growth stages for biomass and LAI. Our study showed that piecewise regression analysis can be a useful tool to identify the biomass or LAI amount at which canopy reflectance indices were saturated. Some studies have reported that NDVI and RVI are saturated at high biomass or LAI in diverse crops and forests (Huete et al., 2002; Gitelson, 2004). However, RVI as well as SR and NIR showed less saturation to high biomass and LAI compared to NDVI in this study. This demonstrates the usefulness of these three spectral indices to estimate cotton growth and crop yield during the cotton growing season, especially at later growth stages. These three indices were the best correlated with crop growth and yield among the 50 published spectral indices that related to biomass, LAI, chlorophyll, and N content in cotton and other crops (data not shown).

Canopy reflectance indices NDVI, SR, NIR, and RVI have been used to assess ground cover, LAI, N status, and crop yield in cotton and other crops (Zhao and Oosterhuis, 2000; Wood et al., 1992; Zhao et al., 2005; Aparicio et al., 2000; Serrano et al., 2000; Zhao et al., 2007; Mistele and Schmidhalter, 2010; Li et al., 2001). Zhao et al. (2007) tested RVI, NDVI, and other spectral indices and found that RVI was one of the most sensitive indices to distinguish N treatments. Gupta (1993) found that the ratio of the NIR provided a better association with the crop growth than NDVI for predicting wheat yield. Results from our study are consistent with the current literature.

Lint Yield Prediction by Spectral Indices

Crop yield prediction using canopy spectral reflectance depends on the sensibility of the spectral index and the growth stage. The peak bloom was the best stage for measuring canopy reflectance to estimate lint yield in our study. The weaker correlation between the spectral indices with lint yield at early growth stages was probably due to lack of sufficient crop biomass and LAI to adequately represent photosynthetic capacity and predict yield. At peak bloom, cotton plants had produced considerable biomass and leaf area that are more closely related to cotton lint yield. Similarly, Aparicio et al. (2000) reported a weak correlation of RVI and NDVI with grain yield in durum wheat when LAI was low. In soybean, Ma et al. (2001) reported that the seed yield predictions at the R2 to R5 reproductive growth stages were satisfactory by using NDVI (Zhao et al., 2007).

When cotton biomass and LAI increased at later growth stages, the overlay of leaves could have caused an underestimation and/or saturation of the spectral indices. Compared to SR, NIR, and RVI, NDVI showed saturation when biomass and LAI were higher, resulting in the three spectral indices being more closely related to lint yield than NDVI. This is probably due to the fact that SR, NIR, and RVI had higher correlations with cotton biomass and LAI compared to NDVI at late growth stages. Our results indicate that these canopy reflectance indices may have advantages over commonly used NDVI in predicting cotton lint yield.

The ability of spectral indices to detect differences in canopy density (biomass and LAI) over the growing season has important implications for yield prediction. These indices can be used to predict crop yield at peak bloom stage when growers can still make the late-season N management decisions (Zhao et al., 2007). Canopy reflectance indices can also be used to determine the canopy structure of high-yielding cotton varieties at peak bloom stage. It should be noted that the conclusions were drawn with three cotton varieties under five different N treatments. Larger number of varieties and more growing environments need to be tested to validate the use of these canopy reflectance indices.

It is also worth noting that the correlation between biomass and lint yield is more complicated for cotton as compared to other crops because it is a perennial crop cultivated as an annual crop. The balance of the vegetative growth (biomass and LAI) and reproductive growth (boll setting) could affect lint yield significantly. Using spectral indices to predict cotton lint yield might not work well in some situations, especially when vegetative growth and reproductive growth are far from the desirable balance.

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