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USING REMOTE SENSING AND SOIL PHYSICAL PROPERTIES FOR PREDICTING THE SPATIAL DISTRIBUTION OF COTTON LINT YIELD

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ABSTRACT

This field crop research study addresses the potential of image based remote sensing to provide spatially and temporally distributed information on timely basis for site-specific cotton crop management. Universal applicability of site specific crop management is hampered by lack of timely distributed and economically feasible information on soils and crop conditions in the field and their interaction. The objectives of this study were to demonstrate (1) how site-specific lint yield and associated soil physical properties in a cotton (*Gossypium hirsutum L.*) production field are related to changes in NDVI across the growing season, and (2) when multispectral images should be collected to optimize the cost and efficiency of remote sensing as a tool for site-specific management of the cotton crop. Temporal multispectral images data acquired comprised 10 dates (1998) and 17 dates (1999) during growing seasons, respectively with analysis focused on 24 areas of interest (AOI) (each 2 x 8 m) located in two transects on a 162-ha farm field. Along each transect, soil textural classification ranged from sandy loam to silt loam. At an early growth stage [~300-600 degree days (DDs) after emergence], low NDVI and plant density were associated with soils having low saturated hydraulic conductivity (k_s) and characterized as drainage ways. Among the AOI's, maximal NDVI was reached at approximately 1565 DD in 1998 and 1350 DD in 1999. A strong range of Pearson correlation (r^2=0.65 – 0.83) between lint yield and NDVI during flowering stage (~800-1500 DDs) supports the utility of NDVI maps for site-specific application. However, values for NDVI did not correlate well with lint yields beyond 1500 DDs [fruit (boll) opening stage] and decreased sharply on sites with sandy soil texture. Visual separation of seasonal trends in the NDVI vs. DD relationship was also related to sandy soil vs. silt loam soil texture and seasonal rainfall difference between years. Based on the statistical relationship between NDVI vs. DD it was concluded that acquisition of a single imagery during peak bloom period would be sufficient for predicting the spatial distribution of lint yield and will also be economically feasible. Results of this study indicate that spatial variability in soil physical properties induced variability in crop growth and yield. Similar methodology could be adopted for site-specific management of other crops.

Keywords Alluvial soils; Degree days; Precision agriculture, Soil texture; Volumetric water content

INTRODUCTION

Farm profitability depends on proper management on timely basis of inputs, such as fertilizers, crop varieties, pesticides, and irrigation. The site specific crop management system is designed to target crop and soil inputs according to within field spatial variability/requirements to optimize profitability and reduce the environmental impact (Shaver et al., 2011; Hochman et al., 2013). Geoinformatic techniques (remote sensing & GIS) can meet many of the data requirements in precision agriculture, because it appears to provide a means to timely assess field-level spatial variability in crop and soil conditions (Hatfield et al., 2008). To encourage the adoption of remote sensing techniques to be utilized by growers/consultants, agricultural scientists should define a timeline for acquiring imagery specific to major field crops for specific crop inputs/management. Due to the indeterminate growth habit of cotton, timely information regarding crop vigor and yield assessment is particularly important for the management of production inputs.

The reflectance spectra of a vegetation canopy is affected by plant chemical composition and canopy level architecture, that is, the arrangement and/or density of leaves, flowers, stems, and their shadows against a soil background (Wiegand, et al. 1991; Wall et al., 2008). Two reflectance indices, the near infrared (NIR) to red ratio (NIR/R) and the normalized difference vegetation index

(NDVI), have been widely used for assessment of crop biophysical conditions, such as, water and nutrient status, leaf nitrogen concentration, leaf area index (LAI) and above ground biomass (Basso et al., 2012; Lofton et al., 2012). The principle is that chlorophyll and carotenoid pigments have major effects on canopy reflectance in the visible wavelengths; whereas, changes in reflectance in the near-infrared (NIR) region of the spectra are related to differences in leaf structure and canopy development (Shaver et al., 2011). In this sense, the ability of NDVI to capture changes in crop development over time has made it a useful parameter for predicting tiller development in wheat (*Triticum aestivum* L.) (Flowers et al., 2001; Duchemin et al., 2006), improving models that simulate crop phenology (Boken et al., 2005), and large-scale forecasting of crop yields (Kastens et al., 2005).

Reflectance measurements in cotton have been related to changes in N status (Winterhalter et al., 2011; Zhang et al., 2012), lint yield (Yang et al., 2004; Zhao et al., 2007) and yield-limiting insect populations (Zhang et al., 2012). In a Mississippi study with Upland cotton, Zhao et al. (2007) reported final lint yield correlated well with NDVI measurements based on a hand-held spectroradiometer. In a California study, Plant et al. (2000) reported significant correlation between lint yield and NDVI values integrated over the growing season. They found the spatial-temporal pattern of NDVI tends to indicate the presence of N stress and were closely coincident with the onset of plant water stress. Additionally, the relative nitrogen vegetation index was not superior to NDVI as an indicator of N stress. Similarly, Li et al. (2001) established significant cross correlation of cotton reflectance in red, NIR and NDVI with soil water and the percentage of sand and clay at different locations within a production field. They further suggested variable-rate N applications could be based upon spatial variability of crop and soil reflectance characteristics. Ritchie and Bednarz, (2005) proposed a spectrometric method for quantifying cotton defoliation (a chemical treatment to remove leaves prior to mechanical harvest), based on the relationship between narrow-waveband NDVI values and leaf area index. They suggested reflectance indices based on red edge (705 nm to 720 nm) measurements and argued that it can offer accurate and consistent estimates of when to use chemical defoliants in cotton production, which could potentially increase defoliation efficiency and decrease costs.

The practice of acquiring weekly or biweekly remote sensing imagery data for research purposes may be economically feasible but may not be economically practical for growers. Since the bottom line for the farmer is profitability. Therefore, the objectives of this study were to (1) resolute when multispectral imagery should be collected to minimize the cost and optimize the efficiency of remote sensing data as a tool for site-specific management of the cotton crop and (2) demonstrate how site-specific lint yield and associated soil physical properties in a cotton production field are related to changes in NDVI across the growing the seasons.

MATERIALS AND METHODS

Study Site Description

The field study was conducted at a private farm (34º 00' 41" N, 90º 55' 39" W) located near the Mississippi River on the northern edge of Bolivar County, MS, USA (Fig. 1). The study site was a 162 ha, cotton production field, having a 2-m elevation range and irrigated with central-pivot system. Climatic data for the site were recorded using an automatic weather station (Fig. 2). A soil survey was conducted to identify the major soil types in the field. The soils in Mississippi Delta are alluvial in nature. Three major soil types were found in the study area i.e. Commerce silt loam (fine-silty, mixed, superactive, nonacid, thermic Aeric Fluvaquents); Robinsonville sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Udifluvents); and Souva silt loam (very fine, smectitic, thermic choromic Epiaquents). Commerce silt loams are characterized as somewhat poorly drained, moderately slow in water permeability, medium in runoff with 1% slope, and typically water-saturated in layers below 0.5 to 1.2 m during the months of December-April. Robinsonville sandy loam soils are characterized as well drained, slow to medium in runoff with water table fluctuates between 1.2 - 1.8 m during the months of January-April. Souva silt loam soils are somewhat poorly drained. These soils are usually found in the depressions & drainage ways of the fields and water table usually fluctuate within 1-2 m (USDA-NRCS, 1951).

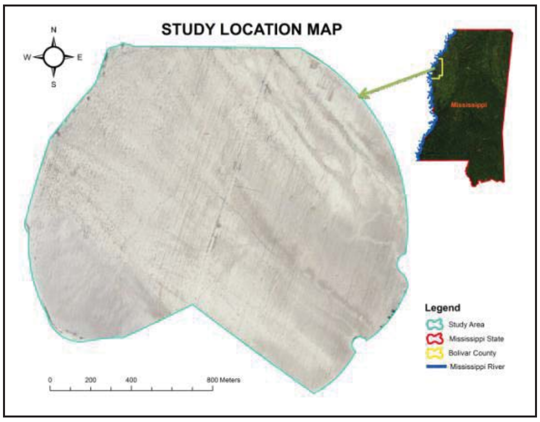

Fig. 1. Study area location map.

Soil Data Analysis

In previous studies (Iqbal et al., 2005) reported on spatial variability of soil physical properties by sampling 209 soil profiles (Fig. 3) in 18 parallel transects to a depth of 1.0 m based on a 91.4 m interval. The present study reports results for two of these field transects located on the west (T_3) and east side (T_{14}) of the field (Fig.3). These two transects were selected because it approximately represent 97 % of the soil-mapping units of the field. The geographic coordinates of each site were recorded using an eight-channel, differential Global Positioning System (GPS) receiver (March-II-E, CMT Inc., Corvallis, OR).

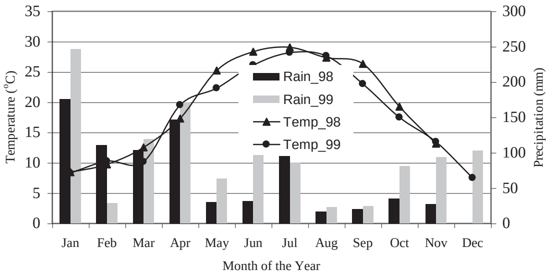

Figure 2. Monthly precipitation and average daily temperature during the experimental period.

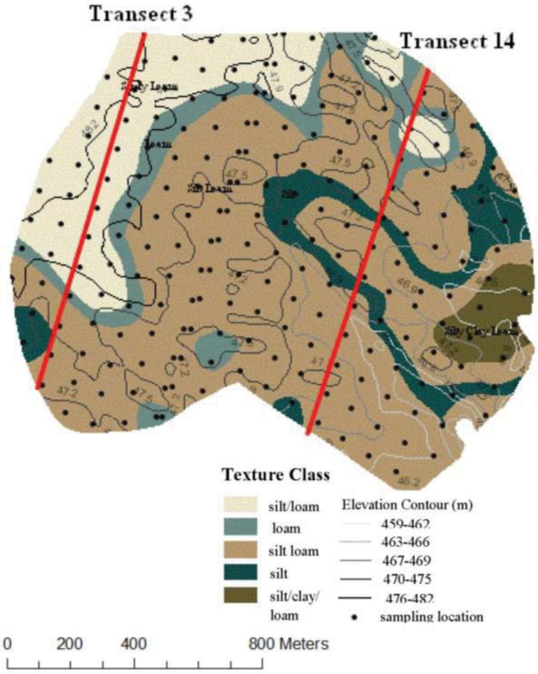

Fig. 3. Field boundary map and the location of 12 sampling sites, at a spacing of approximately 91 m, within each of two transect.

At each location, a tractor-mounted hydraulic soil sampling machine (Giddings no. 10-T Model GST, Giddings Machine Co. Inc., Fort Collins, CO) was used to collect undisturbed, soil profiles to a depth of 1 m as described by Iqbal et al. (2005). The profile was removed from the sampling tube and the depth of each horizon was recorded based on soil morphological characteristics. The different soil profile horizons were excised, mixed separately, and a subsample placed in a waxed, cardboard box. Soil horizon samples were air dried, crushed, sieved (2 mm), and analyzed for particle size distribution using the hydrometer method (Gee and Bauder, 1986) and organic C content using dry combustion method (Rabenhorst, 1988). Additionally, two cores were collected to 1-m depth near the first profile core using the Giddings probe equipped with either a 7.62-cm by 7.62-cm (diameter by depth) or a 7.62- by 1-cm sampling rings. Undisturbed soil cores were obtained from depths representative of a surface, subsurface, and deep soil horizon depths. Soil cores were transported to the laboratory for determination of bulk density, saturated soil hydraulic conductivity, and volumetric soil water content. The 7.62- x 1-cm soil cores were used to determine soil volumetric water content at seven pressure heads of 1, 10, 33, 67, 100, 500, and 1500 kPa using a pressure plate apparatus (Klute, 1986). The data was used to construct a soil moisture release curve, which describes the relationship between soil water tension and moisture content and is influenced largely by soil texture. The saturated soil hydraulic conductivity for each undisturbed soil profile core/depth was determined using the falling head method (Klute and Dirksen, 1986). Soil available water content of coarse-textured soils was expressed as the difference between volumetric soil water content at field capacity (-10 kPa) and water available at permanent wilting point (-1500 kPa); whereas, for fine-textured soils it was expressed as the difference between soil water content at -33 kPa and -1500 kPa (Jury et al., 1991).

Conventional crop management practices were applied by the grower during the two growing seasons (1998 and 1999). Cotton (cv NuCotn 33B) was planted in 1-m row spacing on April 1, 1998 and April 30, 1999. The seeding rate was 11-13 kg ha^{-1}, which would produce a final population of approximately 98,500 plants ha^{-1} (40,000 acre^{-1}). Split applications of fertilizer N were side-dressed as urea ammonium nitrate solution [Ensol: 32% N in NH_4NO_3 $CO(NH_2)$] using an 8-row applicator in late May (72 kg N ha^{-1}) and early July (62 kg N ha^{-1}). Cotton was harvested on September 8, 1998 and September 22, 1999 using a four-row picker equipped with a GPS and field-calibrated yield monitor (± 2%). To ensure accuracy at the 12 sampling sites within each field transect, the picker was maneuvered to precise locations in order to harvest a 16-m section of the rows centered on each site (4-m width x 16-m length). Once the seed cotton was harvested, it was transferred to a weigh wagon and the biomass determined. A subsample (~1000 kg) was ginned using a 10-saw gin to determine lint percentage (lint weight/seed cotton weight), which was used to estimate lint yield on a site-by-site basis. Lint percentage ranged from 38 to 41% across the 24 field locations.

Analysis of Cotton Crop Remote Sensing Data

The NASA commercial remote sensing program acquired imagery at 7-10 d intervals during the growing season, April to September. A three-band digital camera system mounted in the belly of a fixed wing aircraft operated at an average speed of 204 km h^{-1} (110 knots) obtained the multispectral imagery from an altitude of 1824 m above ground level, which rendered a 1 m^2 spatial resolution per pixel. The three bands were centered at 540 nm (green, chlorophyll reflectance), 695 nm (red, chlorophyll absorption), and 840 nm (near-infrared – NIR tissue reflectance) with a 10 nm spectral resolution.

Imagery data comprised 10 acquisition dates in 1998 and 17 acquisition dates in 1999. Image pixel values were extracted from a 2 by 8 m rectangular area of interest (AOI) centered on each of the 24 study sites using

ERDAS IMAGINE (ERDAS, 1997). Each AOI was oriented at an angle of 164° to align with the crop rows. Sample sites and AOI's were at the same locations each year. The average DN value of each AOI (n=16) was used to derive the site-specific normalized difference vegetation index (NDVI) using the formula:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR}_{840} - \mathrm{Red}_{695})}{(\mathrm{NIR}_{840} + \mathrm{Red}_{695})}$$

The concept of degree days (DD, daily heat units) was used to relate potential plant growth to the temporal pattern of NDVI for each AOI. The DD concept can be used to better predict the physiological development, growth stages and maturity of a crop than calendar date, and is calculated as follows:

$$\mathrm{DD} = \frac{T_{max} - T_{min}}{2} - \mathrm{T}_{\mathrm{base}}$$

where, T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature, and T_{base} is the base temperature of 15.6 ºC (Vories et al., 2011). The principle is that starting at 15.6 ºC (60 ºF), cotton doubles its growth rate for every 10 ºC (18 ºF) increase in ambient temperature. Degree days were accumulated daily from the date of plant emergence to determine plant growth stages, which is crucial for making management decisions in cotton production.

To compare the spatial distribution of plant growth between two growing seasons, 1998 and 1999, imagery data of NDVI were overlaid on a three-dimensional map of elevation for the 162-ha field. Additionally, the elevation data were analyzed using ArcView GIS software (ESRI, 1998) in order to derive natural pattern of water flow across the field landscape. Once this 'hydrology network' was derived, the results were overlaid on the three-dimensional NDVI map in order to visualize its relationship to main drainage areas and channels in the field.

RESULTS AND DISCUSSION

During the growing season, April – September, approximately 36% less rainfall was recorded in 1998 (376 mm) than 1999 (594 mm) (Fig. 2). In 1998, relatively low rainfall during May and June resulted in a 150 mm rainfall deficit for the period. Water plays a crucial role in controlling cotton crop development to achieve a favorable balance between vegetative growth and reproductive development. During this period the plant is flowering and a number of young bolls are establishing. These young bolls, if successful, will have a high contribution to final yield. However, it is during this stage that they are highly sensitive to moisture stress. Turner et al (1986) showed that water deficits influence photosynthesis, leaf expansion, the retention of flowers and bolls, and ultimately the yield of cotton.

Additionally, ambient air temperatures during the May-August period were somewhat warmer in 1998 than 1999. Because cotton is typically at pre-bloom (flowering) stage of development in early July (~450 DDs), decreased soil water potential during this critical period may cause transpiration to fall below the potential evaporation rate, could likely cause stress and reduce crop biomass. Based on site-specific NDVI measurements in July, relatively low rainfall in 1998 apparently led to increased variability in NDVI, as compared to 1999 when rainfall was similar to the long-term average (Figs. 2 and 4).

Remote Sensing of Cotton Crop

Variability in site-specific NDVI was evident in both years which were in agreement with Plant et al. (2000). NDVI profile during July readily captured differences in cotton growth and development both across the two years and among the 12 sampling sites (Fig. 4). Beginning in July, the cotton crop usually grows vigorously and develops a relatively high leaf area index. Site-specific NDVI values in July ranged from 0.33 to 0.52 in 1998 (mean = 0.44 ± 0.05), and from 0.53 to 0.62 in 1999 (mean = 0.60 ± 0.02), with higher NDVI typically observed in Transect 3, as compared to Transect 14. Five of the twelve sites in Transect 3 have soils with sandy loam texture class with relatively high saturated hydraulic conductivity (Fig.4 and Table 1).

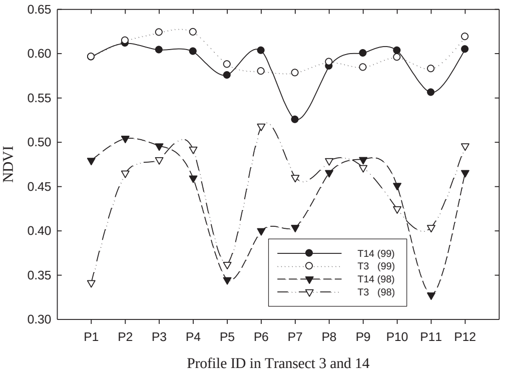

Fig. 4. Normalized difference vegetation index (NDVI, based on digital number values) of cotton on July 18, 1998 and July 29, 1999 at 12 sampling sites (P1 – P12) for soil physical properties in each of two transects, 'T3' and 'T14'.

Unlike Transect 3, nine of the twelve sites in Transect 14 have soils with silt loam soil texture class, which had relatively low values for soil saturated hydraulic conductivity, suggesting relatively low soil available water content at lower depths. Consistent with these observations, remote sensing imagery in July indicated relatively low NDVI for sites 7 and 11 in Transect 14 in 1999, and for sites 5, 7, and 11 in both of the transects in 1998 (Fig. 4). The sites in Transect 3 having low NDVI were associated with sandy-loam and silt-loam soil textures; whereas, the sites in Transect 14 were associated with silt-loam textures of the surface soil (Table 1). The Robinsonville soil series (sandy loam soils) was found in 7 of the 12 sites in Transect 3 and were characterized by high sand content (40 to 70 %), high hydraulic conductivity (15 to 80 cm day^{-1}) and low volumetric water content at plant wilting point (generally < 17%) (Table1). By comparison, surface soils along Transect 14 were dominated by Commerce and Souva soil series (silt loam to silt clay loam) that were characterized by high clay content (12to 20 %), low hydraulic conductivity (0.14 to 7.0 cm day^{-1}) and high volumetric water content at the wilting point (generally 20 to 26%).

Table 1. Surface soil (0-30 cm depth) bulk density (BD), saturated hydraulic conductivity (K_{sat}), clay content, sand content, textural classification, organic matter (OM), volumetric water content at field capacity (FC), volumetric water content at wilting point (WP) and soil available water content (SAWC) at 24 sampling sites in two field transects in Livingston Field, Perthshire Farm, Mississippi.

Soil type^a	Site	BD g cm^{-3}	Ksat cm day^{-1}	Clay %	Sand %	Texture	OM %	Volumetric water (%)^b		
								FC	WP	SAWC
						Transect 3				
So	P01	1.16	37.37	24.4	18.5	silt loam	1.42	19.69	8.97	10.72
So	P02	1.16	42.55	21.5	16.5	silt loam	1.66	15.70	9.89	5.81
So	P03	1.01	26.49	14.0	11.8	silt loam	1.42	14.04	6.75	7.28
Cc	P04	1.23	62.54	12.7	36.5	silt loam	1.10	32.57	22.19	10.37
Ra	P05	1.19	79.10	7.5	70.4	sandy loam	0.51	42.82	15.90	26.92
Rl	P06	1.28	8.41	10.1	49.7	loam	0.90	34.50	23.25	11.25
Cl	P07	1.24	11.05	10.1	45.1	loam	0.90	24.24	13.69	10.55
Ra	P08	1.35	8.10	17.8	58.4	sandy loam	0.77	30.72	18.82	11.91
Ra	P09	1.19	16.48	15.5	58.9	sandy loam	0.86	41.91	26.62	15.29
Ra	P10	1.21	72.95	6.3	58.8	sandy loam	0.66	18.14	7.06	11.07
Rl	P11	1.41	77.30	10.1	42.7	loam	0.86	28.44	13.22	15.22
Ra	P12	1.28	18.66	8.8	57.0	sandy loam	0.82	28.79	17.08	11.71
						Transect 14				
Cs	P01	1.28	0.06	1.9	10.2	silt	1.47	14.69	6.56	8.14
Cc	P02	1.14	32.03	3.2	26.9	silt loam	1.00	17.04	7.32	9.71
Cc	P03	1.09	7.58	1.3	33.6	silt loam	1.18	25.26	15.38	9.88
Cc	P04	1.21	104.17	2.2	27.9	silt loam	1.12	16.46	9.30	7.16
So	P05	1.11	3.42	19.4	4.5	silt loam	1.29	42.00	32.99	9.01
Cc	P06	1.19	0.14	21.1	10.1	silt loam	1.36	32.19	24.00	8.19
Cc	P07	1.07	0.33	25.1	2.5	silt loam	1.92	36.36	20.68	15.68
Cc	P08	1.17	0.46	8.3	14.8	silt loam	1.12	26.98	11.78	15.21
Cc	P09	1.17	165.65	2.2	32.0	silt loam	1.20	37.96	26.14	11.82
Cc	P10	1.08	7.00	12.8	19.4	silt loam	1.41	36.16	21.32	14.85
Ra	P11	1.16	22.28	4.4	74.6	loamy sand	0.47	30.59	21.26	9.34
Cl	P12	1.11	2.76	8.8	43.9	loam	0.87	30.71	24.53	6.18

[a] Soils comprise three types (or series), a Commerce silt loam (Cc), a Robinsonville sandy loam (Ra), and a Souva silt loam (So). Sub types were identified due to difference in the surface-soil texture and included Robinsonville loam (Rl), Commerce silt (Cs), Commerce loam (Cl).

[b] Field capacity is the amount of soil water content held by the soil after excess water has drained (which is equivalent to the water content at -33 kPa pressure head); the wilting point can be defined as the soil water content at which plants wilt, when transpiration exceeds the rate of water uptake by roots (which is equivalent to the water content at -1500 pressure head); and soil available water content is the portion of water content that can be readily absorbed by plant roots (which is equivalent to the difference in water content between pressure heads of -33 and -1500 kPa).

Seasonal curves of the relationship between site-specific NDVI values and DDs were used as surrogates of crop canopy development (Fig. 5). Difference between years in the NDVI response curves illustrate difference in crop vigor due to annual rainfall, as well as difference in leaf area development, as the field was planted approximately 30 days earlier in 1998 than 1999. Negative, but progressively increasing NDVI values were observed until approximately 875 DDs in 1998 (~ June 17) and approximately 750 DDs in 1999 (~ July 2). In 1998, distinctive NDVI curves were evident between 300 and 600 DDs, when cotton is typically in pre-bloom (or squaring) stage of plant development (Reddy et al., 1993). Low NDVI at pre-bloom stage was probably due to low plant density, plants of lower vigor or growth between years, or both of these effects. Relatively low rainfall in May-June 1998 probably also contributed to site-specific difference in NDVI during the pre-bloom growth stage. Among the 12 AOI’s, visually separation of the seasonal trends in the NDVI vs. DD relationship was more obvious across Transect 3, where the soils were sandy in texture, as compared to Transect 14, where the soils were silt loam in texture (Table 1). With regard to the potential effects of soil attributes on NDVI, most of the sites located on sandy soils in Transect 3 had low NDVI and a more abrupt decline in NDVI values was observed as the plants matured (beyond ~1500 DDs), as compared to sites on silt-loam soils in Transect 14. Low water holding capacity of sandy soils in Transect 3 apparently limited plant growth and development at some sites, leading to earlier termination of flowering (cut-out), which led to early crop maturity. In a Texas study on the relationship between cotton lint yield and narrow wavebands (3.6 nm bandwidth) of red and NIR reflectance (centered at 630 and 830 nm, respectively), images for two fields in mid-June after peak vegetative development revealed plants in areas with high sandy soil texture had low NDVI, low plant density and low canopy cover (Yang et al., 2004). These results and those from related field studies (Li et al., 2001; Bronson et al., 2005) suggest that low water- and nutrient-holding capacity of the surface soils (0-30 cm depth) with sandy loam soil texture may cause the observed spatial distribution of growth and yield development in this cotton production field. Apparently, yield was reduced because irrigation provided by the center pivot was less than plant transpiration.

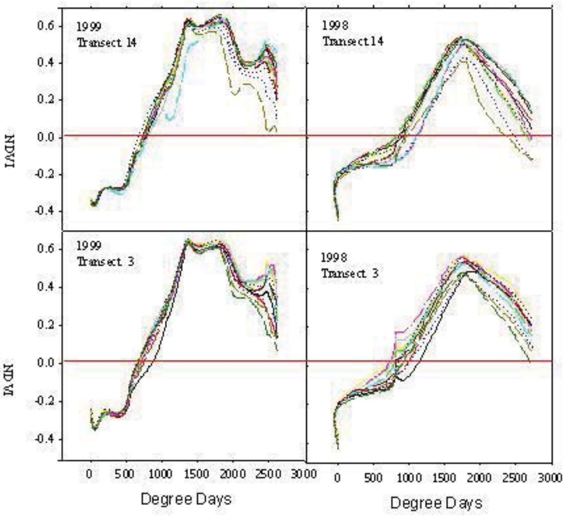

Fig. 5. Relationship between normalized difference vegetation index (NDVI) and growing degree days (DD, 15°C base temp) at 12 sampling sites in 1998 and 1999, where multispectral imagery data was used to calculate NDVI with 1-m resolution for each 2 x 8 m area of interest. Note the distinctive pattern for NDVI curves between 300 and 600 DD.

NDVI for Crop Management on Different Soils

Strong Pearson correlation coefficients between NDVI and final lint yield were obtained across 24 AOI's at peak-bloom, corresponding to image acquisition dates of 18 July 1998 and 29 July 1999 (Fig. 6). In 1998, NDVI values reached a maximum at ~1565 DDs (July 18) and explained approximately 83% of the variability in final lint yield (r^2 = 0.83; p < 0.001). A decreasing trend in NDVI beyond approximately 1565 DDs (Fig. 5) was associated with a decreasing trend in the correlation between NDVI and yield (Fig. 6). In sugarcane (*Saccharum officinarum* L.), Guérif and Duke (2000) used reflectance data to calibrate the 'SUCROS' model and improve its relationship with final biomass yield. They concluded that yield estimation was dependent on stage of plant development (i.e., the timing of remote sensing data) and the best relationship was obtained when the data covered the whole period of leaf area development, including the maximal leaf area index.

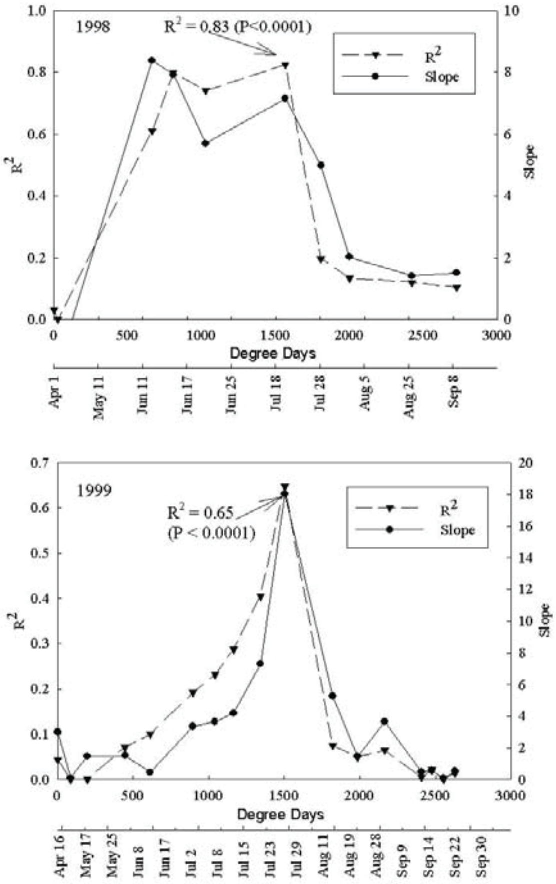

Fig. 6. Changes in R^2 and slope of the linear relationship between normalized difference vegetation index (NDVI) and lint yield across 24 sampling sites as a function of degree days (DD, 15 °C base temp) in 1998 (a) and 1999 (b).

In 1999, final yield and NDVI were related linearly on 29 July (r^2 = 0.65; p < 0.001), when the slope of the relationship was maximal at approximately 18 NDVI units per degree day.

Similarly, Li et al. (2001) reported proximal measurements of broad-band NDVI (26-32 nm bandwidth) in August, when leaf area and NDVI were maximal and explained approximately 64% of the variation in final lint yield. The relationship between NDVI and lint yield varied in different studies. In a remote sensing study of two production fields (16-22 ha), Yang et al. (2004) used hyperspectral reflectance observations in June after the crop achieved its maximum canopy cover. They rectified NDVI and final yield on a 8-m grid and also aggregated 102 hyperspectral bands (3.63 nm bandwidth) to mimic four broad bands of the Landsat ETM+ sensor, (blue, 450–515 nm; green, 525–605 nm; red, 630–690 nm;, and NIR, 775–900 nm). In that study, broad-band NDVI explained 30% and 38% of the variability in yield for the two fields, respectively, and similar Pearson correlation was obtained between yield and narrow-band NDVI. Additionally, Yang et al. (2004) reported stepwise regression models based on several significant narrow-waveband NDVIs explained 61 to 69% of lint yield variability. While these results agree with other studies that accuracy of yield estimation in cotton increases as plants mature (Plant et al., 2000; Zhao et al., 2007) and NDVI can have broader uses other than just yield prediction since different management decisions occur at different times of the season.

Figure 7 illustrates areas of the 162-ha field with low NDVI highlighted with ‘grey’ to ‘yellow’ pixels and encircled in red. These areas were also low in plant density and associated with a main drainage way with inclined topography (a channel produced by the flow of surface runoff). Additionally, these and other low NDVI areas of the field were observed in both the main and tertiary drainage ways. Low yields were recorded in 1999 at sampling sites located in the main drainage ways and areas adjacent to drainage ways. Apparently, decreased crop performance in or around the drainage ways that were transected by Transect 14 profiles 5 and 11 were related to a thinning of the fertile surface soil and exposure of the subsurface soil, which is relatively hard and impervious to water. Because percolation is impeded in this area’s soil, water is not retained and generates more as surface runoff, particularly during heavy rainfall or irrigation events which also removes applied N and ultimately create nutrients deficiency in those impermeable drainage ways. Lower NDVI values of N-deficient cotton are associated with lower plant biomass relative to cotton with sufficient N (Li et al., 2001). To mitigate excessive runoff losses, this area of the field would need to be leveled and sub-soiled in order to improve hydraulic conductivity of the soil.

By combining degree days with knowledge of the NDVI vs. lint yield relationship it is possible to characterize cotton growth stage(s) when the NDVI utility might be the most profitable in agronomic management decisions (Reddy et al., 1993; Hatfield et al., 2008). Results for this relationship at multiple crop growth stages suggest remote sensing to encompass the ‘first-square’ growth stage (typically around 550 DDs), may aid in decisions concerning fertilizer or irrigation management, particularly under low rainfall conditions i.e. from emergence to flowering stage of growth, leaf area and vegetative structures that will then support future reproductive growth. Multispectral imagery to encompass the ‘mid-bloom’ (flowering) growth stage (between approximately 1000 and 1500 DDs), would be useful for estimation of cotton lint yield. Such a remote sensing temporal studies may help to determine the need and/or timing of harvest aides (e.g., chemical defoliants) (Ritchie and Bednarz, 2005), as well as areas of field that should be harvested first. Flowers et al. (2001) reported a significant simple correlation (r = 0.88) between tiller density and NIR digital counts in wheat during tillering phase (Zadoks growth stage 25) and suggested that the relationship could be used to direct N fertilizer applications on a site-by-site basis. In either case, site-specific NDVI appeared to provide timely information regarding the spatial distribution of soil properties in the field. These results agree with studies in the Canadian Prairies of Saskatchewan that compared yield estimates for wheat based on either NDVI from 16 years of NOAA AVHRR satellite data (between 1987 and 2002) or the Cumulative Moisture Index, a land-based weather-related measurement (Wall et al. (2008). Those authors found NDVI possessed explanatory power four weeks earlier in the growing season, as compared to the Cumulative Moisture Index.

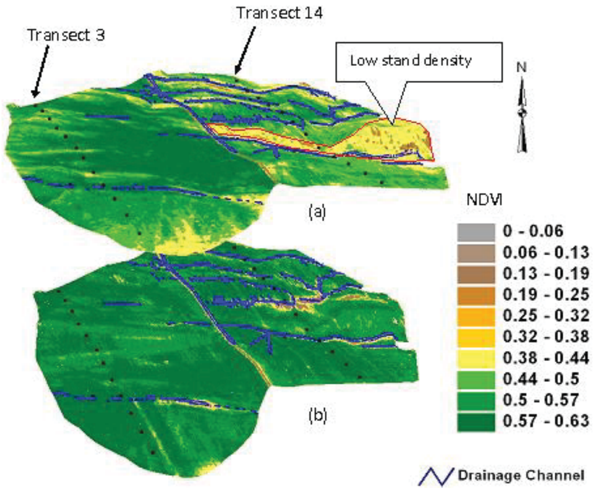

Fig. 7 Three-dimensional map of normalized difference vegetation index (NDVI) for the field on July 28, 1998 (a) and July 29, 1999 (b). Values for NDVI were draped over an elevation map that was produced using a GPS-equipped cotton yield monitor and used to delineate major drainage ways in the field. The area encircled in ‘red’, which had low NDVI values in 1998 due to low plant density, corresponds to one of the largest drainage ways.

CONCLUSIONS

This 2-yr field study demonstrated an association between the spatial distribution of crop NDVI and point estimates of several soil physical properties, some of which had influenced cotton growth and yield. Additionally, differences between years in NDVI patterns across field could be attributed to differences in seasonal rainfall coupled with inherent spatial variability in soil physical properties. Optimal timing of airborne remote sensing data acquisition for agronomic management was identified by the occurrence of significant correlation during the growth season between lint yield and NDVI across 24 sampling sites. The observation of strong yield vs. NDVI correlation in imagery during July, with low values confined chiefly to the main drainage ways, suggest two to three multispectral images acquired at flowering stage of plant development would be optimal for assessing spatial variability in lint yield on alluvial flood plain soils common in the Mississippi Delta region. Acquisition of multispectral remote sensing data earlier in the growth season may be useful for directing site-specific applications of N fertilizer or plant growth regulators.

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