TEMPORAL PATTERNS OF COTTON REFLECTANCE AND NDVI-DAYS LINT YIELD MODELING
Hong Li, Robert J. Lascano, Jill Booker and Kevin F. Bronson
Texas A&M University, Agricultural Research and Extension Center
Lubbock, TX
Edward M. Barnes
USDA-ARS, U.S. Water Conservation Laboratory
Phoenix, AZ
L. Ted Wilson
Texas A&M University, Agricultural Research and Extension Center
Beaumont, TX
Eduardo Segarra
Texas Tech University, Department of Agriculture and Applied Economics
Lubbock, TX

Abstract

Remotely sensed data can be quickly and economically acquired, which is useful for in-season crop management. A multispectral remote sensing study of water and N relations in precision agriculture of cotton (*Gossypium hirsutum* L.) has shown the positive relationships between plant reflectance, spectral index, irrigation amount, soil water content, N uptake, and lint yield, measured in a center pivot irrigated field on the southern High Plains of Texas. In this two-year (1998-1999) study, the treatments consisted of irrigation at 50% and 75% calculated cotton potential evapotranspiration (ET), and N application at rates of 0, 90 and 135 kg ha^{-1} arranged in an incomplete block (ICB) design. The multispectral plant and soil reflectance properties were investigated in eight discrete wavelengths ranging between 447 and 1752 nm. Cotton reflectance in the near infrared (NIR) band and normalized difference vegetative index (NDVI), measured on average twice per week, were related to total N uptake, plant biomass, and lint yield, measured in a 10-day interval during the growing season. The weekly patterns of soil/cotton multispectral reflectance in different spectral bands reflect temporal plant development status across the season. Based on the significant correlations between plant reflectance, NDVI, and lint yield, we attempted to predict cotton lint growth using the NDVI-days concept. The NDVI-days modeling predicts cotton lint yield based on in-season evaluation of NDVI against growing season days. The plant/soil spectral index is useful to determine real-time status of plant development, and to predict crop yield.

Introduction

Cotton plant/soil reflectance investigated for wavelength ranges between 400-2400 nm (Ahlrichs and Bauer, 1983), 400-2500 nm (Bowman, 1989) and 447-1752 nm (Li et al., 2001), and their spectral vegetation indices (Ahlrichs and Bauer, 1983; Bowman, 1989; Wiegand et al., 1994; Maas, 1998, Plant and Munk, 1999, Barnes et al., 2001; Li et al, 2001) have been useful in determining cotton canopy ground cover, plant water and N status, and lint yield related to irrigation and fertilization. Plant reflectance and spectral indices have been used in N deficiency detection for corn canopies (Blackmer et al., 1996), N deficiency and stress for corn with different N and water supplies (Blackmer et al., 1996; Schepers et al., 1996), N and P nutrient status in winter wheat (Sembiring et al., 1998), in forecasting of winter wheat grain yields (Ahlrichs and Bauer, 1983) and cotton lint yields (Plant and Munk, 1999). Plant reflectance, NDVI, and NIR and red ratio responded to water and N stress events, and irrigation and fertilization treatments (Daughtry et al., 1992; Begue, 1993; Wiegand et al., 1994; Blackmer et al., 1996, Barnes et al., 2001). Both water and N stresses altered plant reflectance and lowered NDVI values (Blackmer et al., 1996; Plant and Munk, 1999). Cotton canopy ground cover and remotely sensed scene reflectance measured in Texas and California was linearly correlated (Maas, 1998). Cotton lint yield was significantly correlated to the reflectance in the visible blue, green, red, NIR, and MIR bands (Li et al., 2001), and NIR and red ratio and NDVI (Wiegand et al., 1994; Plant and Munk, 1999, Li et al., 2001). The NDVI-days information obtained by integrating NDVI against time could be used with yield mapping for irrigation management in cotton (Plant and Munk, 1999).

As the correlations between crop reflectance, NDVI, N uptake and lint yield were positive and significant, we hypothesized that this relationship would be useful for further prediction of crop growth against time. Our objectives were to (i) evaluate the temporal patterns of cotton plant reflectance, NDVI, biomass, boll growth, and lint yield with sampling dates, and (ii) model cotton lint growth using the NDVI-days concept.

Materials and Methods

Multispectral Reflectance Measurement

The experimental site is located in a center pivot irrigated field (50 ha) at the Lamesa Agricultural Research Farm (32^{0}46'N, 101^{0}56'W) of Texas A&M University on the southern High Plains of Texas. The soil is classified as an Amarillo sandy loam (mixed, superactive, thermic aridic Paleustalf, Alfisols). The soil physical and chemical characteristics of this soil have been described by Li et al. (2001). The two-year field study started in May 1998. The experimental area was 32 m wide and 700 m long across an altitude between 890.8 and 894.6 m. The experimental treatments consisted of irrigation at 50% and 75% of calculated cotton potential evapotranspiration (ET), and N fertilization at rates of 0, 90 and 135 kg ha^{-1}, respectively, arranged in an incomplete block (ICB) design. Cotton (cv. 'Roundup® Ready 2326') was seeded at a rate of 16.8 kg ha^{-1} on 8 May in 1998 and on 10 May 1999. Irrigation water totaled 242 and 323 mm in 1998, and 190 and 286 mm in 1999 for the 50% ET and 75% ET, respectively. To monitor soil water content (SWC) during the growing season, neutron access tubes (5 cm diameter and 2 m long) were installed 25 m apart along transects located on row 7 and row 14 of each irrigation level. Additional information about irrigation, SWC and leaf area index (LAI) measurements and calculations, soil and plant sampling and analysis, as well as cotton lint harvest of this study is given by Li et al. (2001).

Multispectral plant/soil reflectance was measured in discrete spectral bands (wavelength between 447 and 1752 nm) using a portable MSR16 (8 up- and 8 down-sensors) radiometer (CropScan Inc., Rochester, MN). The specific bands and wavelength were green (G, 546-571 nm), narrow red (Red, 648-674 nm), NIR (NIR, 797-829 nm), and MIR (MIR, 1523-1752 nm). Distance from sensors (looking straight down) to crop canopy top was 2 m. With a 31.1° field of view the sensor viewed an area 1.0 m in diameter. Measurements were taken twice per week within a 15-30° solar zenith angle. A 0.5 x 0.5 m spectralon panel (Labsphere Inc., Orth Sutton, NH) with stable and known reflectance properties was used to calibrate the radiometer. In addition, a dry soil reference was measured on a 0.6 x 0.5 m soil tray to verify the spectralon calibration. Additional information about plant reflectance measurement of this study can be found in Li et al. (2001).

Calculations and NDVI-Days Modeling

The spectral reflectance was expressed as percentage of reflectance, which was a ratio of output in millivolt of down and up sensors times a calibration factor after correction for background voltage. Red reflectance was discriminated in the band between 648 and 674 nm, and NIR reflectance was discriminated in the band between 797 and 829 nm. Plant water stress was related to the MIR reflectance between 1523 and 1752 nm.

The NDVI was determined by the ratio of differencing and combining reflectance measured in NIR and red bands as described by Jackson (1984):

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad [1]$$

We used the concept of NDVI-days (Plant and Munk, 1999) to model cotton lint yield growth in relation to NDVI rate. The NDVI-days was estimated by

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 1:590-594 (2001)
National Cotton Council, Memphis TN

integrating mean NDVI (measured in 1998) against time (t) using the triangulation method:

$$\text{NDVI-days} = \int_0^n f(NDVI)\,dt = \left[F(NDVI)\right]_0^n \qquad [2]$$

where t is time (days from seeding to harvest), dt a time step, and n the number of time step.

There were three steps in the NDVI-days lint yield modeling. First, we used two-year mean NDVI values and a time step of 5 d to integrate the NDVI-days. The n was 26. Second, we determined NDVI-days cotton lint model parameters, and then we predicted lint growth using only the NDVI-days variable (see Eq. [3]-[4] in Result session). Third, the calculated lint yield values by the NDVI-days model were then compared with the two-year lint yield measurements during the growing seasons to validate the model.

Effects of irrigation and N fertilizer on cotton reflectance, plant water content, total N uptake, and cotton lint yield were evaluated using SAS mixed model procedure, and the results are shown in Li et al. (2001). Exponential NDVI-days cotton lint model parameters were determined using nonlinear mixed model procedure (SAS Institute, 1996).

Results and Discussion

Temporal Pattern of Soil and Plant Reflectance and Spectral Index

Weekly patterns of soil/cotton multispectral reflectance in different bands, measured three times per week for the 75% ET irrigation level in 1998, are shown in Fig. 1. At the early vegetative stage, red (637-674 nm) reflectance was as high as 18.9%, which corresponded to a higher percentage of exposed soil surface. As plants grew, red radiance decreased to 6%, 16 weeks after seeding. At the same time, the reflected NIR (797-829 nm) increased linearly from 31.6% to 49.3% and then collapsed (Fig. 1). The weekly pattern of the reflectance at MIR (1523-1752 nm) band was similar to that of the red reflectance (Fig. 1). The MIR reflectance ranged between 24.3 and 38.2% during the growing season. The peak of the NIR reflectance and the bottom of the red and MIR reflectance were measured in mid-August at plant maturity. Mature plants absorbed more blue and red energy, and more strongly reflected NIR energy compared to the younger plants. As a result of plant defoliation, at the boll open stage in September, the red and MIR increased and reflected NIR decreased simultaneously. Furthermore, the reflectance at these bands at harvest was at the same level as at the vegetative stage (Fig. 1). The spectral curves of cotton in this study showed the soil, plant, and water reflectance as a function of wavelength (λ) and plant development (Li et al., 2001), and the reflectance in the visible, NIR, and MIR bands was strongly correlated (r values between - 0.82 and 0.98).

Temporal patterns of NIR/RED ratio, and NDVI, calculated with Eq. [1], are shown in Fig. 2, which can be compared with the NIR temporal pattern given in Fig. 1. As the composite energy reflected highly in the red and increased to the MIR band at the early growing season, both spectral indexes were small. The NIR/RED ratio values were much higher (range of 1.67-8.17) than the NDVI values (range of 0.25-0.80). Both indices increased with increasing NIR reflectance and their peaks were measured 16 weeks after seeding (Fig. 2). The slope of NIR/RED appeared much greater (Fig. 2) than the NIR curve slope (Fig. 1). High NDVI and NIR/RED were a result of an increase in the NIR band and decrease in the red band. Both values were again low at harvest because the composite reflectance was high in the red band. The NDVI was slightly more influenced by red reflectance (r = - 0.89) than NIR reflectance (r = 0.82). The correlation coefficients between NIR/RED and reflectance in the NIR band and red band were 0.81 and - 0.85, respectively.

Temporal Patterns of Cotton Plant NDVI, Biomass and Boll Growth

The temporal patterns of the NDVI and cotton biomass showed followed a S-shaped pattern from vegetative stage to open boll (towards end August) and then collapsed, as demonstrated by the measurements taken in 1999 (Fig. 3). Maximum cotton biomass was 34.5 and 40.6 Mg ha^{-1} in 1998, and 37.1 and 41.3 Mg ha^{-1} in 1999 at the 50% and 75% ET, respectively. The NDVI increased quickly at the vegetative stage, and reached its maximum level before the highest biomass level was measured. Before bloom (6-8 weeks after seeding), total biomass was minimal. From bloom (mid-July) to boll maturity (towards mid Sep.), the biomass increased exponentially and reached the maximum level in early Sep., and then decreased at the beginning of plant defoliation (Fig. 3). The temporal pattern of boll dry matter also followed a S-shaped development (Fig 4.). In 1998, the boll dry matter was 207 and 447 kg ha^{-1} on 26 July, and reached 5587 and 5942 kg ha^{-1} on 15 Sep. on the 50% and 75% ET plots, respectively. About 80% of boll dry matter was composed of the seeds, and 85% of lint yield grew between mid Aug. and mid Sep. The boll and lint growth information should be useful for the irrigation planning.

Relations Between Cotton Plant NDVI and Lint Yield

Mean cotton lint yields were 704 and 962 kg ha^{-1} in 1998, and 819 and 924 kg ha^{-1} in 1999 at 50% and 75% ET irrigation level, respectively. Lint yield was significantly correlated to the reflectance in the blue (r = - 0.80), green (r = - 87), red (r = - 0.83), NIR (r = 0. 40), MIR (r = - 0.86) bands, NDVI (r = 0.80), and NIR/RED ratio (r = 0.79). There was also a significant correlation between N uptake, soil water content, crop surface temperature, blue, green, red, and MIR reflectance, NDVI, and NIR/RED ratio (Li et al., 2001). The analysis of variance with SAS mixed model procedure showed that the fixed effect of irrigation was significant on cotton NIR, red, and MIR reflectance, NDVI, NIR/red ratio, lint yield, and N uptake ($P > 0.0012$-0.0421), and the fixed effect of N fertilizer was significant ($P > 0.0216$) only on lint yield in 1999 (Li et al., 2001). The interaction between irrigation and N fertilization was significant only on reflectance in the near IR band ($P > 0.0162$) in 1998, but the interaction was very significant on red and NIR reflectance as well as NDVI in 1999 (Li et al., 2001). The measured lint yield increased linearly with an increase of NDVI ($R^2 = 0.63$, Fig. 5). Higher lint yield (above the mean of 819 and 924 kg ha^{-1} at 50% and 75% ET respectively) were obtained with a NDVI value ranging between 0.65-0.8. Compared to the NIR/RED ratio, the NDVI better described the correlation between cotton spectral and agronomic characteristics.

NDVI-Days Cotton Lint Yield Models

The two-year mean NDVI values and the NDVI curve showed a S-growth and collapse pathway (Fig. 6a). The NDVI-days, calculated with Eq. [2] by integrating mean NDVI against time t (day) using the triangulation method, is shown in Fig. 6b. The triangulation method calculates the integral by connecting data points with straight lines and computing the integral of the area below the resulting curve (Fig. 6b). The NDVI-days is a spatial and temporal variable since it combines the NDVI and time variables. Unlike the NDVI curve (Fig. 6a), the NDVI-days increased with time and ranged between 0.04 and 55.7 (Fig. 6b).

As the measured 2-year lint yields were on average 762 and 943 kg ha^{-1} for the 50% and 75% ET irrigation, respectively, we assumed that a potential cotton lint yield would be 900 kg ha^{-1} at the 50% ET and 1100 kg ha^{-1} at the 75% ET. These potential lint yield values are 16-18% higher than the measured lint yields. By computing nonlinear mixed model for a logistic cotton growth curve, we obtained the NDVI-days cotton lint yield models at the 50% and 75% ET irrigation levels as follows:

$$\int_o^n Y_{50\%\,ET}(\text{NDVI}-\text{days})\,dt = \frac{900}{1+\dfrac{900-0.162}{0.162e^{-0.2265\,\text{NDVI}-\text{days}}}} \qquad [3]$$

$$\int_{o}^{n} Y_{75\%\,ET}\left(\mathrm{NDVI-days}\right)dt = \frac{1100}{1+\dfrac{1100-0.186}{0.186e^{-0.2349\,\mathrm{NDVI-days}}}} \qquad [4]$$

where Y is cotton lint yield as a function of NDVI-days.

Calculations of cotton lint yield obtained with Eq. [4] and Eq. [5] are compared to the field measurements of lint yields in Fig. 7, where the data are plotted against NDVI-days. Both model calculations and field measurements show a S-sharp pattern. Lint yield increases exponentially while the NDVI-days ranges between 20 and 40 for the both models (Fig. 7ab). Regression analysis with the measured two-year lint yield showed that cotton lint yield was related to NDVI (Fig. 5). Measured lint yields and NDVI-days model calculations (Fig. 7) are strongly correlated ($R^2 = 0.68$). The argument in favor of NDVI-days is that NIR and red reflectance based NDVI has been related to plant growth rate. Our results suggest that real-time reflectance could represent real-time soil and plant conditions, and NDVI-days modeling could promote the further use of remotely sensed data. However, our proposed procedures require further field verification.

Conclusions

The temporal patterns of cotton plant reflectance in visible, NIR and MIR bands, NDVI, and NIR/RED ratio were related to plant development. Cotton NIR reflectance varied primarily as a function of plant biomass. Remote sensing data reflect real-time plant development status, and the spectral index NDVI can be use to forecast crop yield against growing season days. The NDVI-days crop yield modeling is an attempt to promote using the remote sensing data.

Acknowledgments

We thank the Idaho National Engineering Laboratory (INEEL) and Texas Agricultural Experiment Station (TAES) for the funding support.

References

Ahlrichs, J.S., and M.E. Bauer. 1983. Relation of agronomic and multispectral reflectance characteristics of spring wheat canopies. Agron. J. 75:987-993.

Barnes, E.M., T.R. Clarke, P. Colaizzi, J. Haberland, M. Kostrzewski, E. Riley, S. Moran, P. Waller, C. Choi, T. Thompson, S. Richards, R. Lascano, and H. Li. 2001. Coincident detection of crop water stress, nitrogen status and canopy density using ground-based multispectral data. *In* P.C. Robert et al. (ed.) Precision agriculture. Proc. 5th Intern. Conf., ASA-CSSA-SSSAJ, Madison, WI (in press).

Begue, A. 1993. Leaf area index, intercepted photosynthetically active radiation, and spectral vegetation indices: a sensitivity analysis for regular-clumped canopies. Rem. Sens. Environ. 46:45-59.

Blackmer, T.M., J.S. Schepers, G.E. Varvel, and E.A. Walter-Sheashea. 1996. Nitrogen deficiency detection of reflectance shortwave radiation from irrigated corn canopies. Agron. J. 88:1-5.

Bowman, W.D. 1989. The relationship between leaf water status, gas exchange, and spectral reflectance in cotton leaves. Rem. Sens. Environ. 30:249-255.

Daughtry, C.S.T, K.P. Goward, S.D. Prince, and W.P. Kustas. 1992. Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies. Rem. Sens. Environ. 39:141-152.

Jackson, R.D. 1984. Remote sensing of vegetation characteristics for farm management. Rem. Sens. 475:81-96.

Li, H., R.J. Lascano, J. Booker, T.L. Wilson, and K.F. Bronson. 2000. Spectral Reflectance Characteristics of Cotton Related to Soil Water and Topography Variability. *In* P.C. Robert et al. (ed.) Precision agriculture. Proc. 5th Intern. Conf., ASA-CSSA-SSSAJ, Madison, WI (in press).

Maas, S.J. 1998. Estimating cotton canopy ground cover from remotely sensed scene reflectance. Agron. J. 90:384-388.

Plant, R.E., and D.S. Munk. 1999. Application of remote sensing to irrigation management in California Cotton. p. 1511-1522. *In* P.C. Robert et al. (ed.) Precision agriculture. Proc. 4th Intern. Conf., ASA-CSSA-SSSAJ, Madison, WI.

SAS Institute. 1996. SAS system for mixed models. SAS Institute Inc., Cary, NC.

Sembiring, H., W.R. Raun, G.V. Johnson, M.L. Stone, J.B. Solie, and S.B. Phillips. 1998. Detection of nitrogen and phosphorus nutrient status in winter wheat using spectral radiance. J. Plant Nutri. 21:1207-1233.

Schepers, J.S., T.M. Blaclmer, W.W. Wilhelm, and M. Resende. 1996. Transmittance and reflectance measurements of corn leaves from plants with different nitrogen and water supply. J. Plant Physiol. 148:523-529.

Wiegand, C.L., J.D. Rhoades, D.E. Escobar, and J.H. Everitt. 1994. Photographic and videographic observations for determining and mapping the response of cotton to soil salinity. Rem. Sens. Environ. 35:105-119.

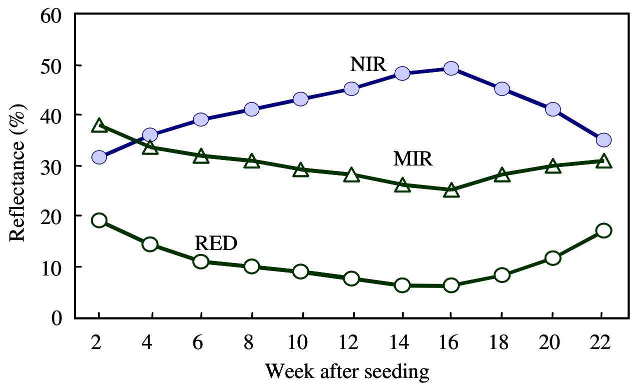

Figure 1. Temporal pattern of visible red, near infrared (NIR), and mid infrared (MIR) reflectance at 75% ET irrigation level, measured in 1998.

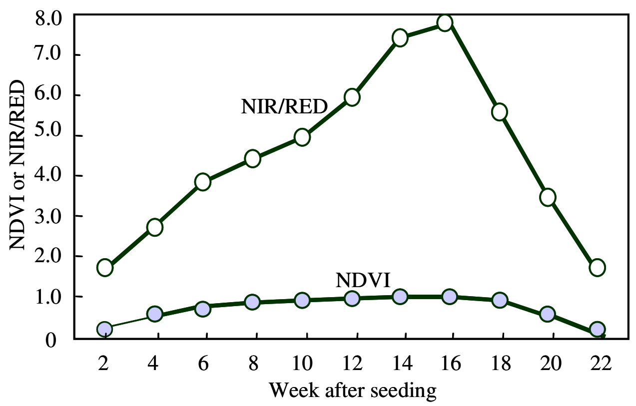

Figure 2. Temporal pattern of NIR/RED ratio, and normalized difference vegetative index (NDVI), measured on the 75% ET plots in 1998.

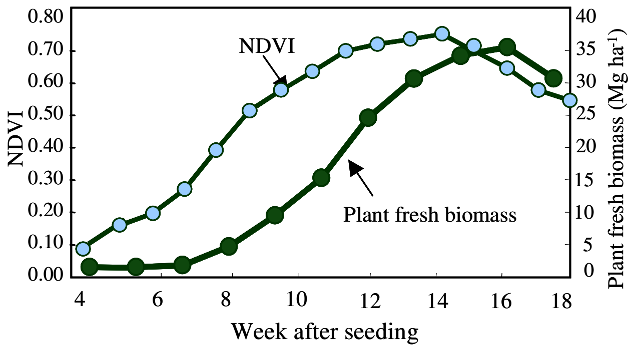

Figure 3. Temporal patterns of plant fresh biomass, and normalized difference vegetative (NDVI) at 50% ET irrigation level, measured in 1999.

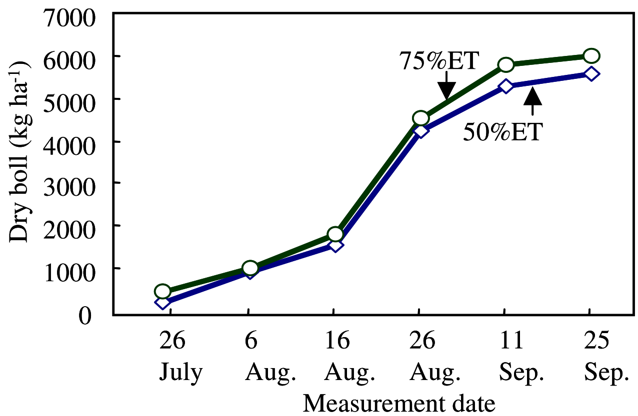

Figure 4. Total dry matter of bolls measured in 1998.

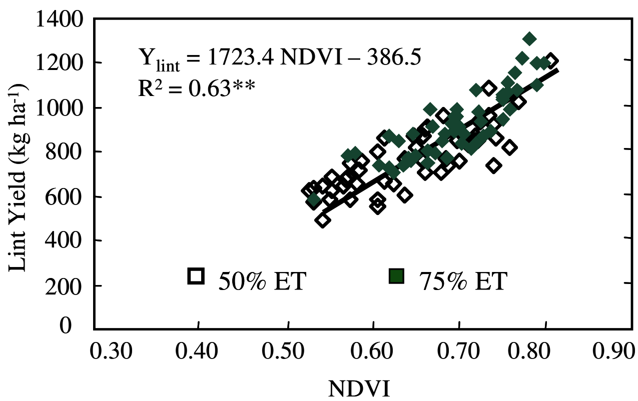

Figure 5. Regression relation between cotton lint yield and normalized difference vegetative index (NDVI), determined in 1999.

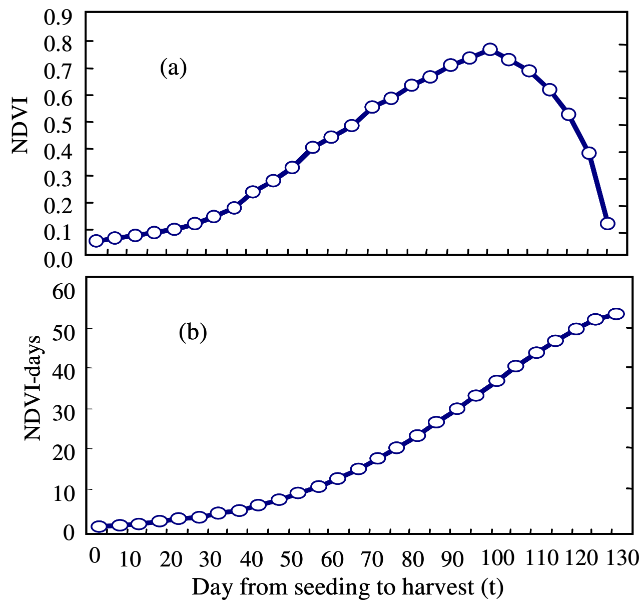

Figure 6. Two-year mean NDVI related to time (a), and the integral of the resulting curve of the NDVI data against time for the NDVI-days (b).

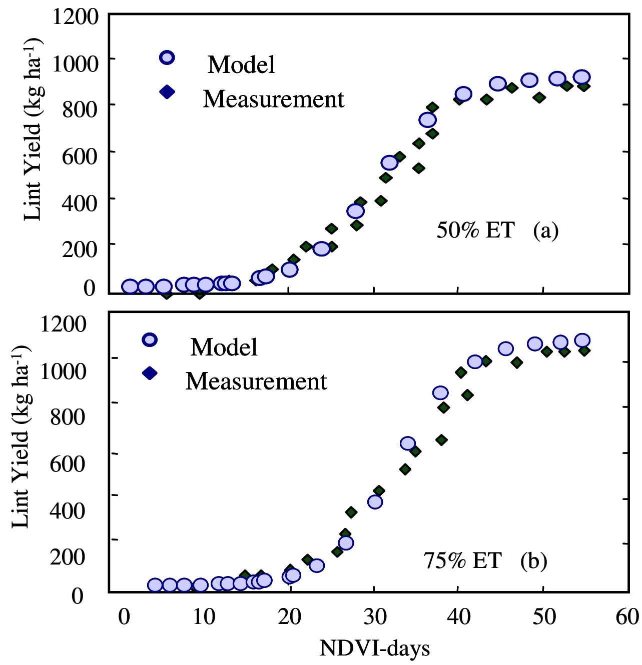

Figure 7. Predictions of the NDVI-days cotton lint yield model related to lint yield (mean of two years) measurements at the 50% ET (a) and 75% ET (b) irrigation levels during the growing seasons.