International Journal of Remote Sensing
Vol. 26, No. 24, 20 December 2005, 5525–5534

Taylor & Francis
Taylor & Francis Group

Use of remote sensing for drought stress monitoring, yield prediction and varietal evaluation in castor beans (*Ricinus communis* L.)

P. VIJAYA KUMAR*†, Y. S. RAMAKRISHNA†, D. V. BHASKARA RAO‡, G. SRIDHAR†, G. SRINIVASA RAO† and G. G. S. N. RAO†

†Central Research Institute for Dryland Agriculture, Santoshnagar, Saidabad (PO), Hyderabad—500 059, India

‡Meteorology and Oceanography Department, Andhra University, Vishakapatnam, India

(*Received 30 November 2004; in final form 22 July 2005*)

The current study was taken up to investigate the utility of remote sensing tools like infrared thermometer and spectral radiometer for screening of germplasm, stress monitoring and yield prediction in castor beans (*Ricinus communis* L.). The study was carried out through field experiments conducted for six years (1994–1999) at Hayatnagar Research Farm, Hyderabad, India. In each year, four cultivars of castor beans, viz. VP-1, 48-1, GCH-4 and Aruna, were planted on two different dates maintaining an interval of 6–8 weeks so as to expose the crop to different environments. The infrared thermometric observations like canopy–air temperature differential (T_c–T_a) explained 50–60% variation in soil moisture status and showed a significant relationship with soil moisture. Yield of castor beans exhibited significant inverse relationship with T_c–T_a, which explained 59% of variation in yield. The hybrid GCH-4, registering comparatively lesser mean T_c–T_a over the entire growing period, established itself as a better cultivar. The spectrometer observations also proved GCH-4 to be a superior genotype in view of its higher reflectance in near-infrared region of the spectrum. The significant negative relationship of T_c–T_a of GCH-4 with saturation vapour pressure deficit brought out its drought tolerance trait over the other genotypes studied. These findings at field level can be extended to wider spatial level using satellite imageries.

1. Introduction

In dryland agriculture, crop water stress during the growing period of long duration crops like castor beans is a recurring phenomenon. Monitoring of plant-water status thus becomes essential for understanding the effect of moisture stress. Soil moisture has long been used as an indicator of plant-water stress before the advent of remote sensing tools like infrared thermometers and spectral radiometers. With these techniques the emphasis in recent years has shifted from using soil as a plant-water status indicator, to plant itself, for monitoring of soil moisture. Consequently, infrared thermometry research has been increasingly used to relate either plant-water status or soil moisture to canopy temperature (Ehrler *et al.* 1978, Jackson *et al.* 1981, Hatfield 1983, Khera *et al.* 1992, Stanghellini and Lorenzi 1994, Vijaya Kumar *et al.* 1999, Patel *et al.* 2001). Yield prediction using remote sensing, through

*Corresponding author. Email: pvkumar@crida.ernet.in

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2005 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160500285258

establishment of a relationship between yield and T_c–T_a, i.e. the difference between canopy temperature and air temperature, or predicting yield using T_c–T_a were reported in other crops by Idso *et al.* (1977), Jackson *et al.* (1981), Singh and Kanemasu (1983), McKinney *et al.* (1989), Das *et al.* (1992), Patel *et al.* (2001) and Baweja (2002). However, such relationships between yield and T_c–T_a have not been reported in castor beans, a drought-hardy dryland crop of tropics and semi-arid tropics.

For more than two decades, infrared thermometry has been used for screening genotypes for yield and drought tolerance in crops (Blum *et al.* 1982, McKinney *et al.* 1989, Rashid *et al.* 1999). No such effort, however, has been made in castor beans, which are mostly grown in drought prone areas.

Spectral reflectance and related indices are being used in agriculture for variety of studies like water stress estimation (Inoue *et al.* 1993, Mogensen *et al.* 1996), evaluation of crops and crop varieties (Reddy *et al.* 2001, Schmidt and Skidmore 2001, Rajapakse *et al.* 2002), salinity and irrigation effects (Wang *et al.* 2002), growth parameters and yield (Pinter *et al.* 1981, Coubey and Choubey 1999, Hajare *et al.* 2001, Srinivasa Rao and Shekh 2001) and prediction of drought (Liu and Negron Juarez 2001). Varietal evaluation using spectral reflection has not yet been attempted in castor beans. Spectral reflectance and related indices are being used for estimation of water stress in many crops (Inoue *et al.* 1993, Mogensen *et al.* 1996) and for studying crop growth and yield (Sumer Singh 1997, Raj Singh *et al.* 2001). Though leaf–air temperature difference measured by infrared thermometry was identified as a potential trait for screening of genotypes (Blum *et al.* 1982) in wheat, the technique was unsuccessful in rice (Turner *et al.* 1986). In sorghum, the drought resistant varieties showed lower canopy temperature compared to drought susceptible varieties (Blum *et al.* 1989), similar to the result obtained in this work. In wheat also, Rashid *et al.* (1999), screened varieties for drought tolerance based on the differences in mean canopy temperature. More research work is thus needed in castor beans grown under dryland conditions, before considering leaf water status measured by infrared thermometry as a desirable trait. Moreover, canopy temperature data from irrigated experiments were more accurate in varietal evaluation than data from non-irrigated environments because environmental stress on plants reduced genetic variability (McKinney *et al.* 1989). The objective of the present study was to monitor moisture stress, estimate yield and evaluate the varieties of castor beans using infrared thermometer and spectral radiometer techniques.

2. Materials and methods

2.1 *Site and climate*

The study was conducted in alfisols of Hayatnagar Research Farm of the Central Research Institute for Dryland Agriculture, Hyderabad, India (latitude 17°20′ N, longitude 78°35′ E). Hyderabad is located in the semi-arid tropical region of peninsular India. Nearly 70% of the total annual precipitation, i.e. 767 mm, is received during the monsoon season (June–September) and 18% during the post-monsoon season (October–November).

The soils of the experimental site are red, shallow, loamy sands with topsoil depth varying from 0.05–0.3 m. Moisture storage in the profile at field capacity (0.03 MPa) and permanent wilting point (1.5 MPa) is 14.5% and 4.5% by volume, respectively.

2.2 *Experimental design*

The remote sensing studies in castor beans were conducted on cultivars VP-1, 48-1, GCH-4 and Aruna during 1994–1999. The crop was planted on two different dates at an interval of 6–8 weeks so as to expose the crop to different weather conditions (table 1).

The experimental design was split plot with two dates of sowing as main treatments and cultivars as sub-treatments. All the treatments were replicated four times. The crop was raised under rain-fed condition by adopting a recommended package of practices like optimum row spacing, fertilizer doses, pest control, etc. Seeds were hand dribbled at an intra-row spacing of 30 cm and inter-row spacing of 60 cm so as to maintain optimum plant density of 70 000 plants ha^{-1}.

2.3 *Canopy temperature observations*

Canopy temperatures (T_c) were measured between 1100 and 1230 h IST (Indian Standard Time) on selected days using infrared thermometer (Teletemp AG-42, Teletemp Corp., 351 S Raymond Avenue, Fullerton, CA 92631, USA). Canopy temperature and canopy air temperature differential measurements were taken from three general locations of the subplot (two ends and centre). Both canopy temperature and canopy air temperature differential are obtained as direct output from the infrared thermometer. The specific area measured was selected randomly inside the three areas. At each observation site, canopy temperature was recorded by viewing the canopy from two opposite directions. Thus, six observations on canopy temperature were recorded in each subplot containing each genotype. T_c of each subplot was taken as the average of six observations. Canopy temperatures were taken after the canopy was fully developed, so as to avoid infrared emissions from the soil. These data were recorded by viewing the canopy at an angle of 30° from horizontal level. T_c of the plots of the same planting date treatments was averaged over four replications on a particular day to represent T_c of that day. In these experiments, the canopy–air temperature differentials, i.e. T_c–T_a values, were obtained as a direct output from infrared thermometer. Dry bulb and wet bulb temperatures inside and above the canopy were monitored on selected days using Assman's psychrometer. The T_c–T_a were normalized for saturation vapour pressure deficit (SVPD) by dividing T_c–T_a by SVPD (Vijaya Kumar *et al.* 1999).

Table 1. Date of sowings of castor beans in each year.

Year	Date of sowing	Sowing date (Julian days)
1994	Early (first date)	169
	Late (second date)	228
1995	Early (first date)	175
	Late (second date)	217
1996	Early (first date)	177
	Late (second date)	221
1997	Early (first date)	185
	Late (second date)	244
1998	Early (first date)	174
	Late (second date)	220
1999	Early (first date)	177
	Late (second date)	217

The T_c–T_a obtained over main treatments (two dates of sowing) were consolidated in all the years of experimentation for obtaining results. The idea behind combining or consolidating the T_c–T_a and other data is to get a greater number of data points sufficient for attempting statistical relations and also to have a wider range of weather conditions during the period of observation of T_c–T_a values.

2.4 *Spectral radiation*

Reflectance of the solar radiation by four genotypes of castor in different bands of solar spectrum—red (660–680 nm), near-infrared (NIR; 750–1000 nm) and total (300–1100 nm)—were monitored on selected days using a spectral radiometer (Licor LI-1600, Licor Inc./Licor Ltd, Box 4425, Lincoln, NE 668504, USA). Besides measuring reflected (outgoing) radiation in different spectral bands, incoming radiation in red, infrared and visible regions of the spectrum were also monitored. The ratio of reflected (outgoing) and incoming radiation was calculated to obtain spectral reflectance.

3. Results and discussion

3.1 *Soil moisture and stress degree days*

Though there is a lot of scatter in the relationship between soil moisture status and T_c–T_a (figure 1), T_c–T_a have enabled 53% of variation in soil moisture to be explained. When the T_c–T_a were normalized for saturation vapour deficit by dividing T_c–T_a values by vapour pressure deficit, the predictability of soil moisture increased slightly by 6% only (figure 2). Normalization of T_c–T_a was done by dividing them by vapour pressure deficit on the day of observation. Similar results of improved relationship between plant extractable soil water and normalized T_c–T_a were observed by Vijaya Kumar *et al.* (1999) in a single castor genotype. A similar inverse relationship between soil water and T_c–T_a related indices was observed in other crops also (Stricevic and Caki 1997, Carcova *et al.* 1998).

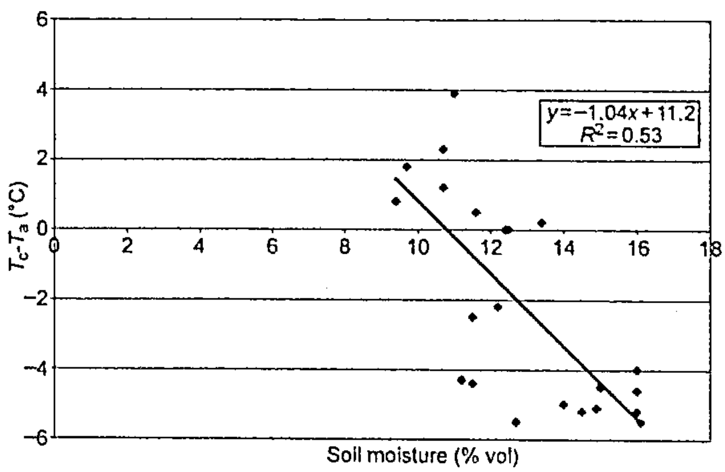

Figure 1. Relationship between T_c–T_a and soil moisture in castor.

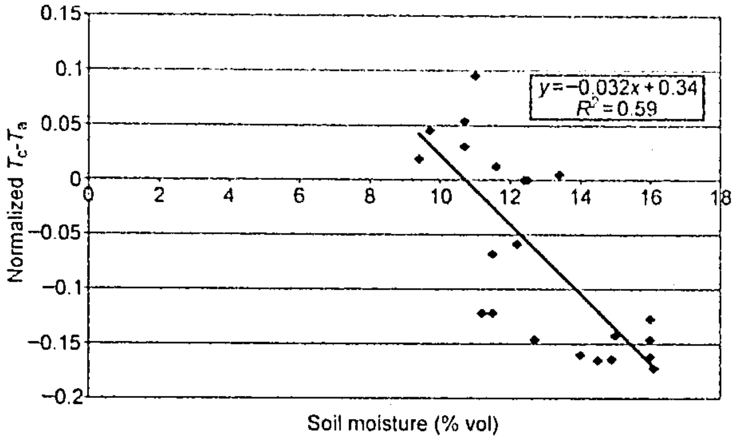

Figure 2. Relationship beween normalized T_c-T_a and soil moisture.

3.2 T_c–T_a values and varietal evaluation

Canopy–air temperature differential (T_c–T_a) values, which indicate crop water status, were utilized to identify the castor variety that showed less water stress compared to other genotypes under similar weather conditions. These studies showed that the mean canopy–air temperature differential during the crop-growing period (averaged over dates of observations and years) of variety GCH-4 was comparatively less than other genotypes (table 2). However, the difference in T_c–T_a between GCH-4 and other cultivars was not statistically significant. The lower (T_c–T_a) value indicated that a slightly better water status was maintained by GCH-4 than the other varieties.

3.3 T_c–T_a values and yield

The mean T_c–T_a, i.e. the canopy air-temperature differentials of the genotypes averaged over the growing season, in different years were related with the yield of respective genotypes in those years (figure 3) to understand yield and T_c–T_a relationship. The results showed that yield was inversely and significantly related with T_c–T_a in castor beans crop. The results further revealed that the higher the

Table 2. Mean canopy–air temperature differentials (°C) of early sown castor genotypes in different years.

	T_c–T_a in castor genotypes			
Year	VP-1	48-1	GCH-4	Aruna
1994	−3.0	−3.6	−3.7	−3.4
1995	−5.5	−5.9	−5.9	−6.1
1996	−1.8	−1.4	−2.0	−1.6
1997	−0.4	−0.2	−0.3	−0.4
Mean	−2.7	−2.8	−3.0	−2.9
t-Value[a]	1.48	1.54	–	0.80
(P-level)	(0.12)	(0.11)		(0.24)

[a]To test the significance of differences in T_c–T_a of GCH-4 with other cultivars. The number of observations (n) is 14, range of VPD is 0.2–2.2 kPa.

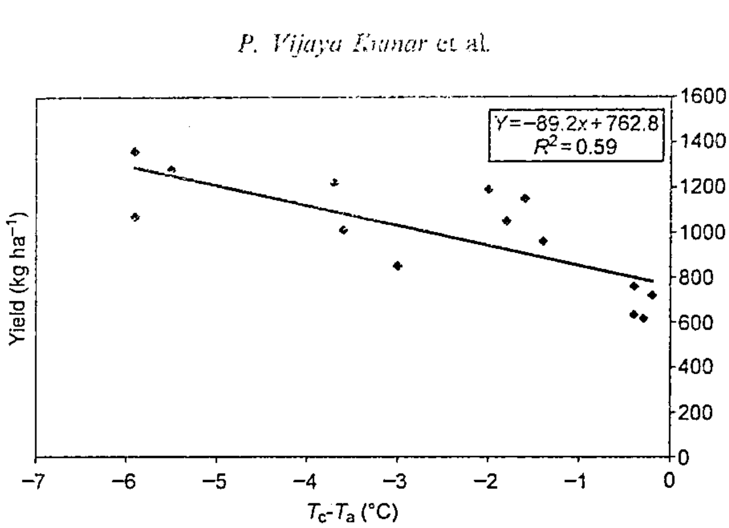

Figure 3. Relationship between yield and T_c–T_a in castor.

canopy–air temperature differential, the lower the yield and vice versa. Similar relationships between yield of different crops and T_c–T_a were reported by Idso *et al.* (1977), Jackson *et al.* (1981), Singh and Kanemasu (1983), McKinney *et al.* (1989), Singh *et al.* (1991), Das *et al.* (1992), Patel *et al.* (2001) and Baweja (2002).

3.4 *Drought tolerance of genotypes*

The genotypes capable of maintaining a negative relationship between their T_c–T_a and high evaporative demand are usually considered as drought tolerant. McKinney *et al.* (1989) made comparisons of the slopes of regression between T_c–T_a and VPD among the soybean lines to identify drought tolerant genotypes. A similar approach was adopted to identify drought tolerance in this study. The slopes of the regression equations between T_c–T_a and saturated VPD (table 3) showed that among the genotypes, GCH–4 was the only cultivar showing a significant negative relationship and higher drought tolerance. The cultivar VP-1 showed positive slope, which is not possible and has not been reported in any crop. This might be due to the dwarf nature of the cultivar (whose height is 25 cm) in comparison to other cultivars (height more than 70 cm). As reported by Feldhake *et al.* (1997), the crop canopy temperatures may not be valid and may be influenced by the soil thermal environment when the crop height is less than 50 cm. The positive relationship between T_c–T_a and VPD in cultivar VP-1 may be ignored. The T_c–T_a of the other two genotypes did not respond to changes in VPD. These results showed that indirect selection of drought tolerance using canopy temperature might be effective in castor beans also.

Table 3. Response of T_c–T_a in castor genotypes to vapour pressure deficit on selected days in which the soil profile was fully saturated.

Genotype	Regression equation	R^2
VP-1	$y=-6.9+0.37x$	0.68 NS
48-1	$y=-2.8-0.19x$	0.17 NS
GCH-4	$y=-0.6-0.43x$	0.85[a]
Aruna	$y=-2.0-0.24x$	0.43 NS

[a]Significant at 0.05 probability level.

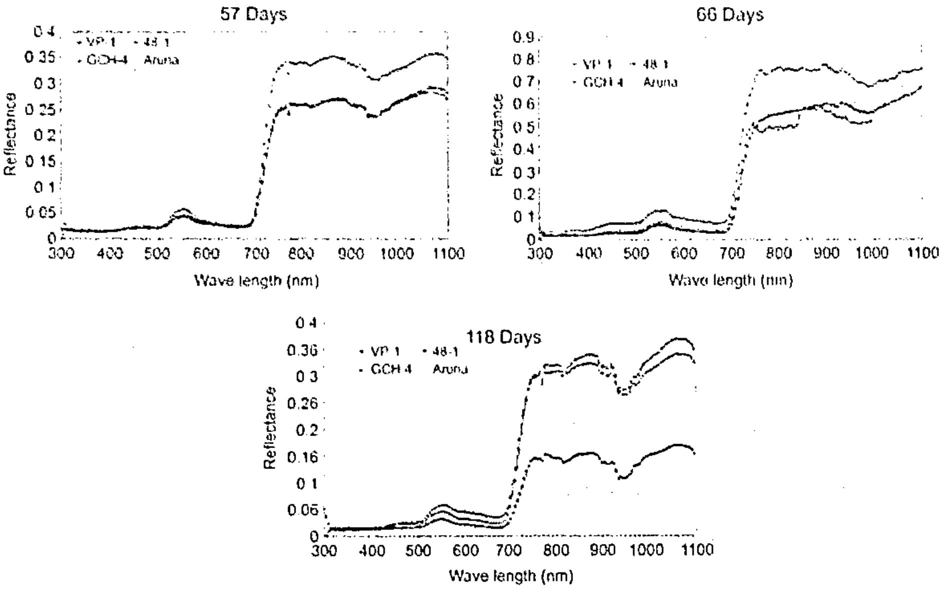

Figure 4. Spectral reflectance of different genotypes at different growth stages.

3.5 *Spectral characters of castor genotypes*

An attempt to screen the varieties using spectral reflectance at different growth stages, viz. 57, 66 and 118 days (figure 4), and the spectral difference averaged over the entire growing period (figure 5) showed that genetic variability is very well reflected through spectral characteristics. All the four cultivars exhibited a smaller peak of reflectance around the green region (550 nm) and a major peak in the NIR region (750–900 nm), which is characteristic of vegetation. Though the spectral reflectance patterns at 57 and 66 days and averaged over the season are similar, the

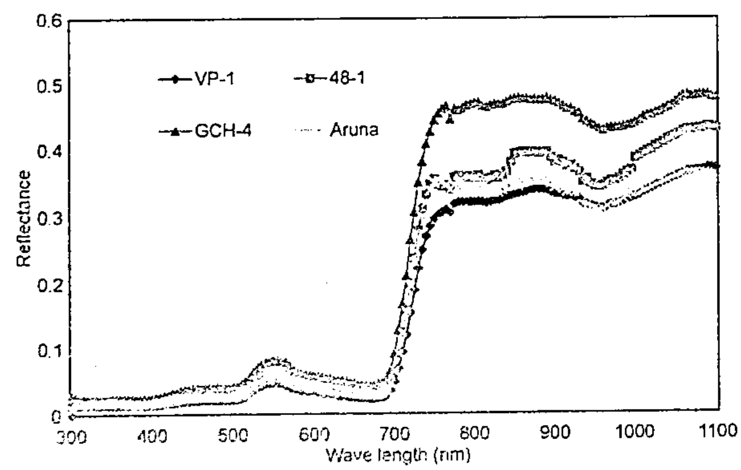

Figure 5. Spectral reflectance of different genotypes average over different observation dates.

spectral reflectance pattern at 118 days appears to be different and spurious in the case of varieties VP-1 and Aruna. The reason for the same may be due to their early senescence and lower leaf area index (LAI) (1.06 and 1.17 in VP-1 and Aruna, respectively) when compared to other cultivars 48-1 (LAI = 1.77) and GCH-4 (LAI = 1.73). Though the water absorption band at around 970 nm is prominent in all the cultivars, due to early senescence of these cultivars, which have reached their late reproductive period, decrease in LAI and ground cover resulted in unusual spectral signatures. On an average, the hybrid GCH-4 had higher reflectance, in all the wave bands of the solar spectrum and more so in the NIR. Higher reflectance in the NIR region, which is indicative of highest intercellular water content and greenness of the crop, can be considered as one of the traits for indirect selection of genotypes. The yield superiority of the hybrid GCH-4 over other varieties was also reflected in the higher reflectance in NIR by GCH-4. Statistically significant differences in the spectral reflectance between grass species, similar to this study, were reported by Schmidt and Skidmore (2001). In another study of spectral reflectance (Rajapakse *et al.* 2002), different tea clones showed unique spectral characteristics. Importance of canopy reflectance in NIR wave band for studying healthiness of crop was also reported (Wang *et al.* 2002) in soybean canopy based on reflectancy measured by multispectral radiometer.

4. Conclusion

The present study was undertaken to test the utility of remote sensing tools like infrared thermometer and spectral radiometer for stress monitoring, yield prediction and varietal evaluation in castor beans crop. The important results of the study are as follows.

(1) Canopy–air temperature differential (T_c–T_a) showed significant negative relationship with soil moisture and explained 50–60% variation in soil moisture.
(2) The hybrid GCH-4 registered a comparatively smaller mean T_c–T_a during the crop-growing period than the other three genotypes, thus proving it to be a better genotype.
(3) Yield of castor beans was inversely and significantly related with the T_c–T_a.
(4) The hybrid GCH-4 was identified as the most drought tolerant genotype in view of the negative relationship of its T_c–T_a with saturation vapour pressure deficit during the crop-growing period.
(5) The higher reflectance of GCH-4 in NIR of the spectrum proved it to be superior over other genotypes.

References

BAWEJA, P.K., 2002, Predicting grain yield in maize: canopy temperature based regression indices. *Journal of Agrometeorology*, 4(2), pp. 177–179.

BLUM, A., MAYER, J. and GOLAN, G., 1982, Infrared thermal sensing of plant canopies as a screening technique for dehydration avoidance in wheat. *Field Crops Research*, 5, pp. 137–146.

BLUM, A., MAYER, J. and GOLAN, G., 1989, Agronomic and physiological assessments of genotypic variation for drought resistance in sorghum. *Australian Journal of Agricultural Research*, 40(1), pp. 49–61.

CARCOVA, J., MADDONNI, G.A. and GHERSA, C.M., 1998, Crop water stress index of three maize hybrids grown in soils with different quality. *Field Crops Research*, **55**, pp. 165–174.

COUBEY, V.K. and CHOUBEY, R., 1999, Spectral reflectance, growth and chlorophyll relationships for rice crop in a semiarid region of India. *Water Resource Management*, **13**(2), pp. 73–84.

DAS, D.K., MISHRA, K.K. and KALRA, N., 1992, Modelling growth and yield of wheat using remotely sensed canopy temperature and spectral indices. *Proceedings of International Conference on Remote Sensing and GIS*, JNTU, Hyderabad, 26–28 February, pp. 1–6.

EHRLER, W.L., IDSO, S.B., JACKSON, R.D. and REGINATO, R.J., 1978, Wheat canopy temperatures: relation to plant water potential. *Agronomy Journal*, **70**, pp. 251–256.

FELDHAKE, C.M., GLENN, D.M., EDWARDS, W.M. and PETERSON, D.L., 1997, Quantifying drought for humid, temperate pastures using Crop Water Stress Index (CWSI). *New Zealand Journal of Agricultural Research*, **40**, pp. 17–23.

HAJARE, T.N., NALAMWAR, R.V., VERMA, K.S. and SAXENA, R.K., 2001, Evaluation of safflower productivity using spectral indices under varying management in shrink swell soils. In *Spatial Information Technology Remote Sensing and Geographical Information Systems*, I.V. Murali Krishna (Ed.), pp. 257–261 (New Delhi: B.S. Publications).

HATFIELD, J.L., 1983, The utilization of thermal infrared radiation measurements from grain sorghum crop as a method of assessing their irrigation requirements. *Irrigation Science*, **3**, pp. 259–268.

IDSO, S.B., JACKSON, R.D. and REGINATO, R.J., 1977, Remote sensing of crop yields. *Science*, **196**, pp. 19–25.

INOUE, Y., MORINAGA, S. and SHIBAYAME, M., 1993, Non-destructive estimation of water status on intact crop leaves based on spectral reflectance measurements. *Japan Journal of Crop Science*, **62**, pp. 462–469.

JACKSON, R.D., IDSO, S.B., REGINATO, R.J. and PINTER, P.J., 1981, Canopy temperatures as a crop water stress indicator. *Water Resource Research*, **17**, pp. 1133–1138.

KHERA, K.L., SANDHU, B.S., SINGH, C.B. and KUMAR, K., 1992, Water stress, radiation and plant temperature relationship in maize grown in subtropical region of northern India. *Tropical Ecology*, 33(1), pp. 63–71.

LIU, W.T. and NEGRON JUAREZ, R.I., 2001, ENSO drought onset prediction in north-east Brazil using NDVI. *International Journal of Remote Sensing*, **22**, pp. 3483–3501.

MCKINNEY, N.V., SCHAPAUGH, W.T. Jr and KANEMASU, E.T., 1989, Canopy temperature, seed yield and vapour pressure deficit relationship in soybean. *Crop Science*, **29**, pp. 1038–1041.

MOGENSEN, V.O., JENSEN, C.R., MORTENSEN, G., THAGE, J.H., KORIBIDIS, J. and AHMED, A., 1996, Spectral reflectance index as an indicator of drought of field grown oil seed rape (*Brassica napus* L.). *European Journal of Agronomy*, **5**, pp. 125–135.

PATEL, N.R., MEHTA, A.N. and SHEKH, A.M., 2001, Canopy temperature and water stress quantification in rainfed pigeonpea (*Cajanus cajan* L.). *Agriculture and Forest Meteorology*, **109**, pp. 614–621.

PINTER, P.J., JACKSON, R.D., IDSO, S.B. and REGINATO, R.J., 1981, Multidate spectral reflectance as predictors of yield in a water stressed wheat and barley. *International Journal of Remote Sensing*, **2**, pp. 43–48.

RAJ SINGH, RAO, V.U.M., SINGH, D. and SRINIVASA RAO, G., 2001, On spectral reflectance characteristics of *Brassica* spp. In *Spatial Information Technology Remote Sensing and Geographical Information Systems*, I.V. Murali Krishna (Ed.), pp. 244–256 (New Delhi: B.S. Publications).

RAJAPAKSE, R.M.S.S., TRIPATHI, N.K. and HONDA, K., 2002, Spectral characterization and LAI modelling for the tea (*Camellia sinensis* (L.) O. Kuntze) canopy. *International Journal of Remote Sensing*, **23**, pp. 3569–3577.

RASHID, A., STARK, J.C., JANVEER, A. and MUSTAFA, T., 1999, Use of canopy temperature measurements as a screening tool for drought tolerance in spring wheat. *Journal of Agronomy Crop Science*, **192**, pp. 231–237.

REDDY, S.G., NARASHIMHA RAO, C.L., VENKATARATANAM, L. and KRISHNA RAO, P.V., 2001, Influence of plant pigments on spectral reflectance of maize, groundnut and soybean grown in semi-arid environments. *International Journal of Remote Sensing*, **22**, pp. 3373–3380.

SCHMIDT, K.S. and SKIDMORE, A.K., 2001, Exploring spectral discrimination of grass species in African rangelands. *International Journal of Remote Sensing*, **22**, pp. 3421–3434.

SINGH, P. and KANEMASU, E.T., 1983, Leaf and canopy temperatures of pearl millet genotypes under irrigated and no irrigated conditions. *Agronomy Journal*, **75**, pp. 64–72.

SINGH, R., TRIPATHI, R.P. and SINGH, R., 1991, Production function: as valuable tools in crop planning and measurements of rice. *New Agriculturist*, **2**, pp. 141–144.

SRINIVASA RAO, G. and SHEKH, A.M., 2001, Studies on potato crop growth performance and yield prediction using spectral indices and agrometeorological parameters. In *Spatial Information Technology Remote Sensing and Geographical Information Systems*, I.V. Murali Krishna (Ed.), pp. 226–235 (New Delhi: B.S. Publications).

STANGHELLINI, C. and LORENZI, F.D., 1994, A comparison of soil and canopy temperature based methods for the early detecting of water stress in a simulated patch of pasture. *Irrigation Science*, **14**, pp. 141–146.

STRICEVIC, R. and CAKI, E., 1997, Relationship between available soil water and indicators of plant water status of sweet sorghum to be applied in irrigation scheduling. *Irrigation Science*, **18**, pp. 17–21.

SUMER SINGH, 1997, Study on growth and yield of *Brassica* spp. in relation to spectral indices under different environments. MSc thesis, CCSHAU, Hisar, India.

TURNER, N.C., O'TOOLE, J.C., CRUZ, R.T., NAMUCO, O.S. and AHMED, S., 1986, Response of seven diverse rice cultivars to water deficits. 1. Stress development, canopy temperature, leaf rolling and growth. *Field Crops Research*, **13**, pp. 257–271.

VIJAYA KUMAR, P., RAMAKRISHNA, Y.S., RAMANA RAO, B.V., KHANDGONDA, I.R., VICTOR, U.S., SRIVASTAVA, N.N. and RAO, G.G.S.N., 1999, Assessment of plant-extractable soil water in castor beans (*Ricinus communis* L.) using infrared thermometry. *Agricultural Water Management*, **39**, pp. 69–83.

WANG, D., WILSON, C. and SHANNON, M.C., 2002, Interpretation of salinity and irrigation effects on soybean canopy reflectance in visible and near-infrared spectrum domain. *International Journal of Remote Sensing*, **23**, pp. 811–842.