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Sun-angle and canopy-architecture effects on the spectral reflectance of six wheat cultivars

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Abstract. Canopy spectral reflectances were measured over six cultivars of spring wheat (*Triticum aestivum* L.) grown at Phoenix, Arizona. Data were collected at 30–45 min intervals on 9 March 1983 using two ground-based radiometers with bandpass characteristics similar to those of the Multispectral Scanner and Thematic Mapper on LANDSAT-4 and -5. Major differences in reflectance were observed among cultivars at every time period despite their apparent similarities in green leaf area and green biomass. Single-leaf spectra measured in the laboratory with a spectrophotometer revealed no cultivar-related differences and supported the contention that the reflectances were strongly influenced by canopy architectural features. The diurnal patterns of reflectance reinforced this conclusion with planophile canopies exhibiting the least amount of variability due to changes in Sun angle and erectophile canopies showing the most. These data underscore the complexities of interpreting remotely sensed multispectral data and suggest that multiple Sun-angle data acquisitions may be required to extract desired information.

1. Introduction

The diurnal patterns of crop spectral reflectance have an important bearing on the use of remotely sensed information for agricultural resource management purposes. Changes in the direction of solar irradiance and its interaction with canopy biomass, cover, height and row orientation are significant in determining the nature of these patterns (Fuchs *et al.* 1972, Jackson *et al.* 1979 a, b, Kirchner *et al.* 1982, Kollenkark *et al.* 1982, Curran 1983, Kimes 1983). However, even when these canopy parameters are held constant, the three-dimensional distribution of differentially reflective elements within the canopy plays an equally important role in governing the magnitude of reflectance and also the manner in which it changes throughout the day. Intensive modelling efforts have been directed towards a better understanding of these effects (Suits 1972, 1983, Chance and LeMaster 1978, Kimes *et al.* 1980, Verhoef and Bunnik 1981, Bunnik 1984, Kimes 1984) but experimental verification of the sensitivity of reflectance to subtle architectural dissimilarities is limited.

The vertical distribution of elements within the canopy also affects the daily

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patterns of reflectance. Thus, Pinter *et al.* (1983) found that their ability to accurately discriminate different green leaf area index (GLAI) levels in wheat depended on the time of day when reflectance measurements were taken. At certain times, reflectances were ambiguous with respect to measured GLAI because the distribution of green elements within the canopies was affected by growth stage and drought-induced leaf senescence. Apparently, relatively minor changes in the orientation of canopy leaves can also produce a similar effect on the reflectance-GLAI function (Bunnik 1978). Schutt *et al.* (1984) contend that the observed decrease in red reflectance of a wheat canopy during heading may stem from a corresponding shift in flag leaf orientation from a vertical to horizontal position and a difference in the reflective properties of abaxial and adaxial leaf surfaces.

Architectural characteristics can also express themselves quite differently depending upon the cultivar involved. Hatfield (1981), for example, found that the variability in reflectance among 82 wheat cultivars grown at Davis, California, increased during grain filling and precluded their use in predicting final yields. Dissimilarities in canopy architecture may have been responsible for this variability but differential susceptibility of the cultivars to grain shattering and disease as well as different phenological ages of the crops complicated the analysis. Duggin (1977) noted major differences in the diurnal reflectance behaviour of seven wheat cultivars in Australia. However, it was not clear whether these canopies were similar in their gross agronomic characteristics, and thus it was not possible to determine if canopy structural differences were responsible for his results.

In this report, we use ground-based radiometers and intensive multitemporal sampling to measure the canopy reflectances of six wheat cultivars which were very similar in green leaf area, biomass and stage of growth but differed in their architectural arrangement. We examine the diurnal patterns of canopy reflectance for each cultivar to demonstrate the effect of canopy architectural differences on spectral reflectance measurements. Canopy reflectances are then compared with single-leaf reflectances measured in the laboratory with a spectrophotometer equipped with a reflectance attachment.

2. Experimental methods and conditions

2.1. *Field site*

Spring wheat (*Triticum aestivum* L.) was planted during mid-December, 1982 at Phoenix, Arizona (33° 26′N, 112° 01′W). Six cultivars ('Ciano 79', 'Genaro 81', 'Pavon 76', 'Seri 82', 'Siete Cerros 66' and 'Yecora 70') were obtained from Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) in Ciudad Obregon, Sonora, Mexico. Each represented a line that was selected for disease resistance and high-yield potential under limited water conditions. Seed from each cultivar was sown in separate 12 m × 25 m flood irrigation basins. Rows were oriented in a north–south direction and were spaced at 0·18 m. The soil was an Avondale loam (a fine, loamy, mixed (calcareous), hyperthermic, Antropic Torrifluvent). Plants were grown under non-limiting water and nutrient conditions.

2.2. *Plant measurements*

Agronomic parameters were determined from five twice-weekly destructive plant samples centred around 9 March 1983, the date spectral measurements were taken. Green biomass levels were estimated from 12 plants of each cultivar selected at random on each sampling date. All green above-ground plant parts were oven-dried at 70°C for at least 48 hours. GLAI was measured with an optically integrating leaf area meter on a three median-sized plant subsample of the plants chosen in the biomass sample. Plant densities and grain yields (on a dry weight basis) were determined for each cultivar during final harvest in June.

2.3. *Spectral measurements*

2.3.1. *Field measurements of canopy reflectance*

Observations were made using two different radiometers (table 1). Each was equipped with a 15° field of view aperture and deployed in a nadir orientation so that they viewed approximately the same target areas. The first, an Exotech Model 100A†, had spectral bandpass filters similar to the two visible and two near-infrared (IR) channels of the LANDSAT Multispectral Scanner (MSS). Its light weight made it possible to hold this instrument in the hand over the canopy and soil targets. The spectral characteristics of the second radiometer, a Barnes Modular Multiband Radiometer (MMR) (Robinson *et al.* 1979), were similar to those of the Thematic Mapper (TM) deployed on LANDSAT-4 and -5. In addition to the three visible, one near-IR, two mid-IR and one thermal channels of the TM, the MMR also monitored a second near-IR waveband (1·15–1·30 μm) which does not have an equivalent on the TM. A backpack transport system was devised to suspend the MMR off to one side and slightly above the operator's shoulder level. This imparted portability to a radiometer which, because of its heavier weight, is normally boom mounted in ground-based operations. Access to the field plots was provided by east–west boardwalks running just to the north of the spectral target areas and elevated approximately 20 cm above the soil surface. With this system, the operator was able to take numerous spectral measurements over adjacent field plots in rapid succession.

Analogue signals from both radiometers were recorded on Polycorder data-collection devices which time-stamped each set of measurements for later Sun-angle

Table 1. Spectral band specifications of the Exotech Model 100A and Barnes Modular Multiband Radiometers (MMR). Both radiometers were equipped with 15° field of view apertures.

Radiometer band	LANDSAT band	Wavelength interval (μm)	Detector type	Range
Exotech 1	MSS 4	0·5–0·6	Silicon	Green
2	MSS 5	0·6–0·7	Silicon	Red
3	MSS 6	0·7–0·8	Silicon	Near-IR
4	MSS 7	0·8–1·1	Silicon	Near-IR
Barnes MMR 1	TM 1	0·45–0·52	Silicon	Blue
MMR 2	TM 2	0·52–0·60	Silicon	Green
MMR 3	TM 3	0·63–0·69	Silicon	Red
MMR 4	TM4	0·76–0·90	Silicon	Near-IR
MMR 5	No equiv.	1·15–1·30	PbS	Near-IR
MMR 6	TM 5	1·55–1·75	PbS	Mid-IR
MMR 7	TM 6	2·08–2·35	PbS	Mid-IR
MMR 8	TM 7	10·4–12·5	LiTaO3	Thermal

†Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

calculations. Reflectances were calculated as the ratio of radiances measured over each soil or vegetation target to irradiances inferred from observations of a 0·6 m × 0·6 m, horizontally positioned, painted $BaSO_4$ reflectance panel. The latter data were obtained at the start, midpoint and finish of each measurement sequence and a time-based linear interpolation was used to estimate irradiance when individual targets were measured. Correction factors were applied to the $BASO_4$ data to compensate for non-Lambertian properties of the panel (Robinson and Biehl 1979, Kimes and Kirchner 1982). Additional factors were applied to MMR bands 5, 6 and 7 to correct the PbS detectors for ambient temperature sensitivity (Jackson and Robinson 1985). Data from the MMR thermal channel (band 8) are not reported in this paper.

Data collection began at 07·45 hours (M.S.T) and continued at 30–45 min intervals throughout the day. Each data set required about 8–10 min to complete. Nineteen such data sets were collected using the Exotech radiometer and 16 sets were collected with the MMR. Six 'scans' of each radiometer's wavebands were taken within each of two previously designated, 1 m × 3 m targets within each border. This resulted in 12 measurements which were then combined to yield an average reflectance for each cultivar.

2.3.2. *Laboratory measurement of single-leaf spectra*

Two weeks after the field measurements were made, four fully expanded upper leaves were collected from plants of each plot. The leaves were sealed within plastic bags and placed in an insulated container with ice to limit leaf dehydration. Within 24 hours, the reflectance from the upper surface of each leaf was measured in 10 nm increments over the range of 0·4–2·5 μm using a Beckman Model UV 5240 laboratory spectrophotometer equipped with an integrating sphere reflectance attachment. The output was ratioed against a $BaSO_4$ standard, recorded as reflectance versus wavelength on a strip chart recorder and later digitized. Interpolated values for each wavelength were multiplied by response functions for each of the MMR reflective bands as described by Jackson (1984), resulting in single-leaf reflectance values that were comparable to the MMR measured field reflectances.

2.4. *Weather and Sun conditions*

Cloud-free sky conditions prevailed during the diurnal reflectance measurements on 9 March 1983. Haze levels remained low to moderate and winds were generally light from an easterly direction with occasional calm periods. The soil surfaces in all plots remained wet throughout the day, a result of three rains totalling 6·25 cm the previous week and 10 cm of irrigation on 22 and 23 February.

Sunrise occurred at 06·52 hours, solar noon at 12·39 hours and sunset at 18·25 hours (M.S.T.) Solar zenith angles varied from about 78° during the first set of measurements to 38° at midday and 75° during the last set of Exotech readings. Solar azimuth angles changed from 104 to 249° over this interval. The spectral distribution of irradiance as inferred from radiometric measurement of the calibrated reference panel with the Exotech radiometer is shown in figure 1. It revealed a symmetrical pattern about solar noon, which is typical for cloudless-sky conditions at Phoenix during March.

2.5. *Dew conditions*

Moderately high dew densities of 0·4–0·8 kg/m³ were present on all cultivars during the early morning measurement period. Dew dissipated rapidly from 08·30 hours until

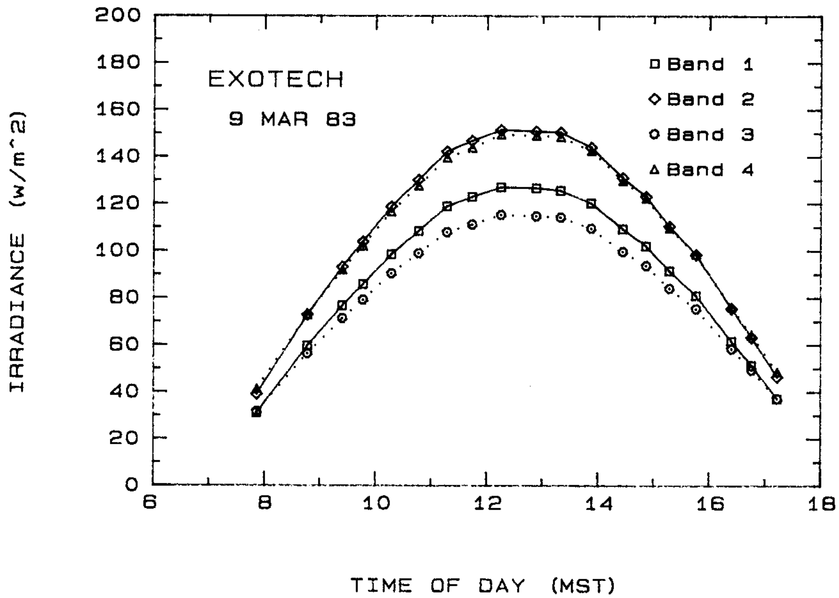

Figure 1. Spectral irradiance during 9 March 1983 in the two visible and two near-IR wavebands of the Exotech radiometer.

10·00 hours. An hour later most visual signs of dew were absent from each cultivar. The relationship between dew density on wheat and spectral reflectance is discussed further by Pinter and Jackson (1982).

2.6. *Agronomic parameters*

By 9 March, each wheat cultivar was growing vigorously and had reached complete canopy cover. Table 2 lists pertinent agronomic information. Less than 1 week's development separated the phenological growth stages of the six cultivars. Yecora, Pavon and Seri were the most advanced: each had the second node formed on the main stem, and the next to the last leaf was just visible. The first node of the main stem was evident in Siete Cerros, but it could not be discerned in either Ciano or Genaro. Canopy height ranged from 38–47 cm. Green leaf areas and biomass levels were similar for all cultivars.

Table 2. Agronomic characteristics of six wheat cultivars on 9 March 1983 and their final grain yields at harvest.

Plot	Variety	Growth stage		Field height (cm)	Green LAI	Dry green biomass (mg/ha)	Grain yield (mg/ha)
		Zadoks	Feekes				
1B	Yecora	32	7	46	4·5	2·57	7·12
2B	Siete Cerros	31	6	46	4·7	2·38	7·12
3B	Ciano	23	2	44	4·5	2·48	6·96
4B	Pavon	32	7	46	4·4	2·56	6·89
5B	Genaro	26	3	38	4·2	2·57	7·49
6B	Seri	32	7	47	3·5	2·87	7·10

2.7. *Canopy architecture*

The architectural structure of the canopies varied among cultivars. Figure 2 depicts the leaf arrangement observed for Yecora, a moderately planophile canopy, and Ciano, an erectophile canopy. Note that Yecora (figure 2 (*a*)) displayed broad leaves with a floppy behaviour which imparted a horizontal orientation to the upper canopy elements. Pavon and Seri (not shown in figure 2) were also somewhat planophile, but their narrower leaves resulted in a more complex vertical structure. Ciano (figure 2 (*b*)) had narrow leaves and the most erectophile canopy of the six cultivars we studied. Relatively few leaves in the upper portion of the Ciano canopy were oriented horizontally. This more open structure permitted some direct beam radiation to reach the soil surface at midday.

3. Results and discussion

3.1. *Diurnal patterns in canopy spectral reflectance*

Canopy reflectances are shown as a function of time-of-day for the Barnes and Exotech radiometers in figures 3 and 4. Each data point in those figures represents an average of 12 reflectance measurements per cultivar, six from each of two separate 1 m × 3 m target areas. We found that within-target variability in spectral reflectance was small, but it was influenced by the Sun angle at the time measurements were taken. For example, the standard errors were 6–7 per cent of the mean target reflectance during early morning and late afternoon. This was because low angles of illumination resulted in patchy shadows on the top of the canopy that were large relative to the area viewed by a shoulder-level instrument. During midday, however, the pattern of shadows had a finer texture and the standard errors declined to 3 or 4 per cent of the mean reflectance value.

Differences in spectral reflectances between the two targets in a given cultivar were several times larger than the target variability. Target reflectances were averaged for the purposes of this report because the differences were consistent throughout the day and small relative to differences observed between cultivars.

Although each cultivar had similar green leaf area and biomass, we observed large differences in their reflectances. These differences appeared to be a result of cultivar characteristics in plant architecture. Data points for the most planophile cultivar (Yecora) and most erectophile cultivar (Ciano) are joined by solid lines to emphasize the reflectance patterns shown by canopy extremes in leaf angle orientation. Notice that Yecora, with broad horizontal leaf elements near the top of the canopy, had the highest light reflectance in all wavebands throughout the day. Conversely, Ciano with its vertical leaf structure, usually reflected the least amount of energy towards the nadir-oriented radiometer.

3.1.1. *Visible radiation*

The daily trajectories exhibited by planophile and erectophile canopies were also quite different. In all visible wavebands (Exotech bands 1 and 2, MMR 1, 2, and 3) Yecora displayed a relatively flat spectral response throughout the day, while Ciano and several of the other cultivars had a pronounced midday rise in reflectance. The more vertical structure of these erectophile canopies permitted more direct beam insolation to reach the soil at times near solar noon, thereby effecting an increase in the reflectance of visible light.

The diurnal patterns of reflectance in Exotech bands 1 and 2 can be compared with their narrower, more selective bandwidth counterparts, represented by MMR bands 2

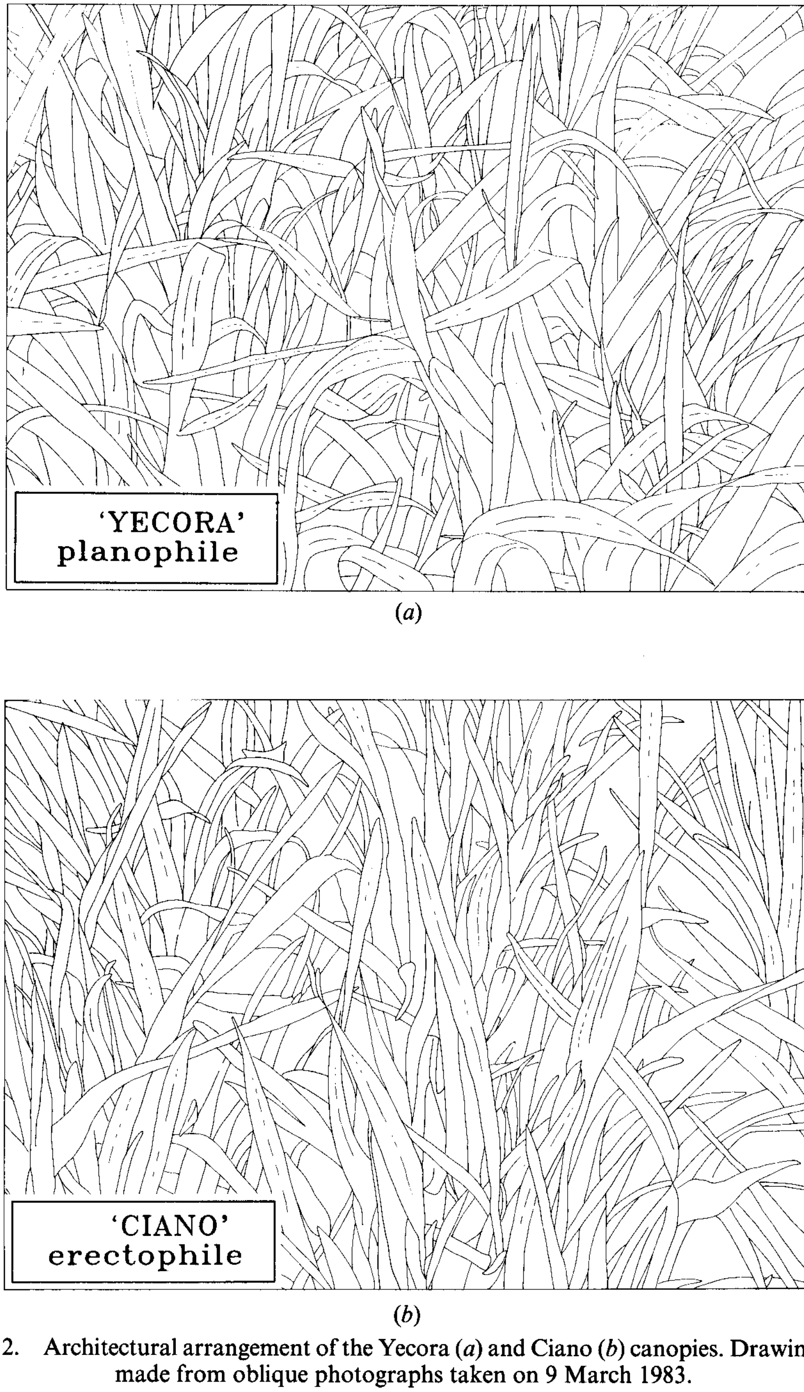

Figure 2. Architectural arrangement of the Yecora (*a*) and Ciano (*b*) canopies. Drawings were made from oblique photographs taken on 9 March 1983.

and 3, respectively. Component bands within each pair ranked the cultivars similarly in order of reflectance. However, midday reflectances in the red waveband of the MMR (band 3) more clearly differentiated between the Yecora canopy and that of Siete Cerros and Seri. The broad red wavelength interval of Exotech band 2 did not discriminate among those three canopies at low solar zeniths. This indicates that the narrower spectral window of the TM red band may provide information on canopy charcteristics which could not be obtained with the MSS.

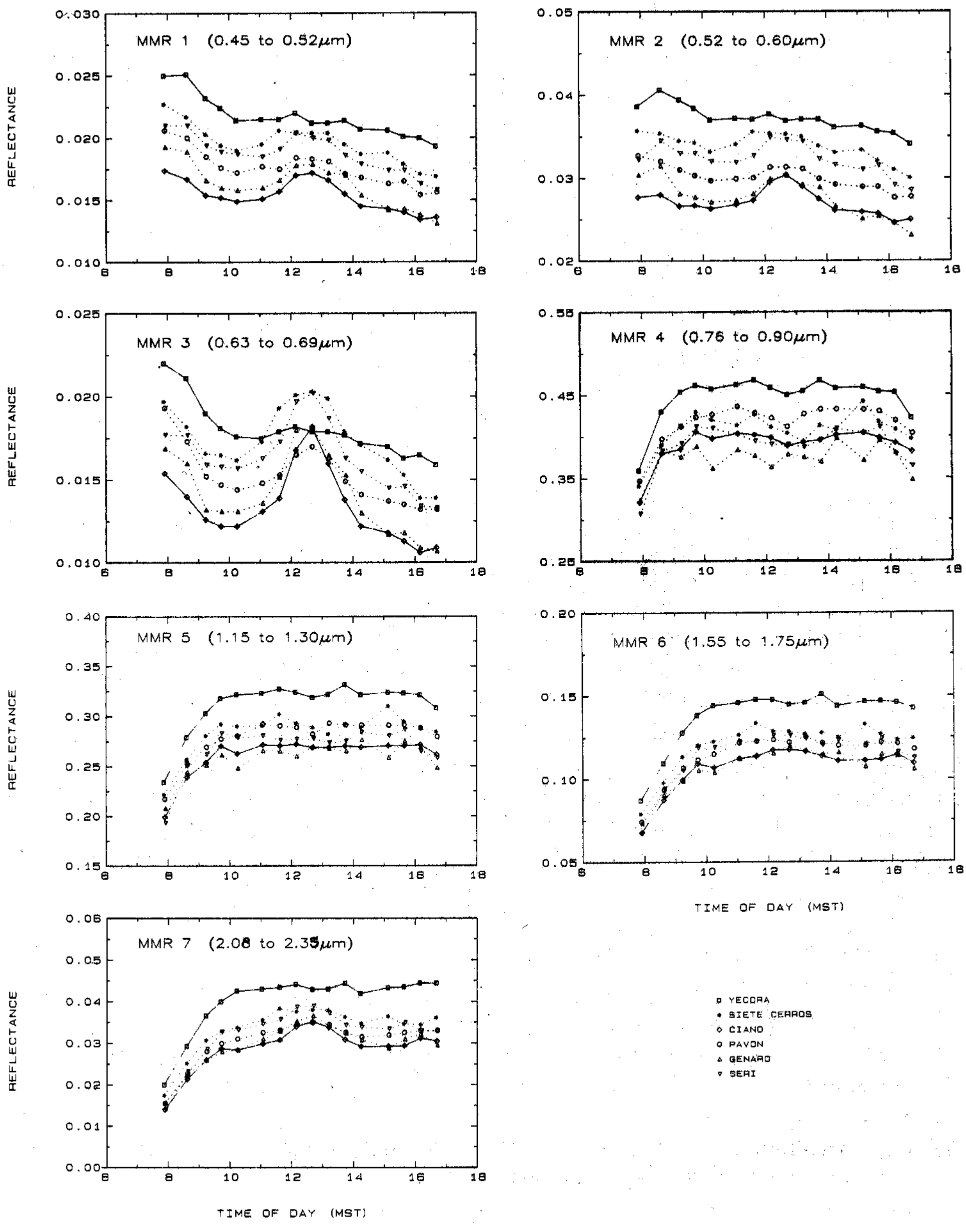

Figure 3. Diurnal patterns of reflectance in the Barnes MMR radiometer for each cultivar of wheat on 9 March 1983. Solid lines connect individual data points of the most planophile (Yecora) and most erectophile (Ciano) canopy. A similar convention is followed in figures 3 and 4.

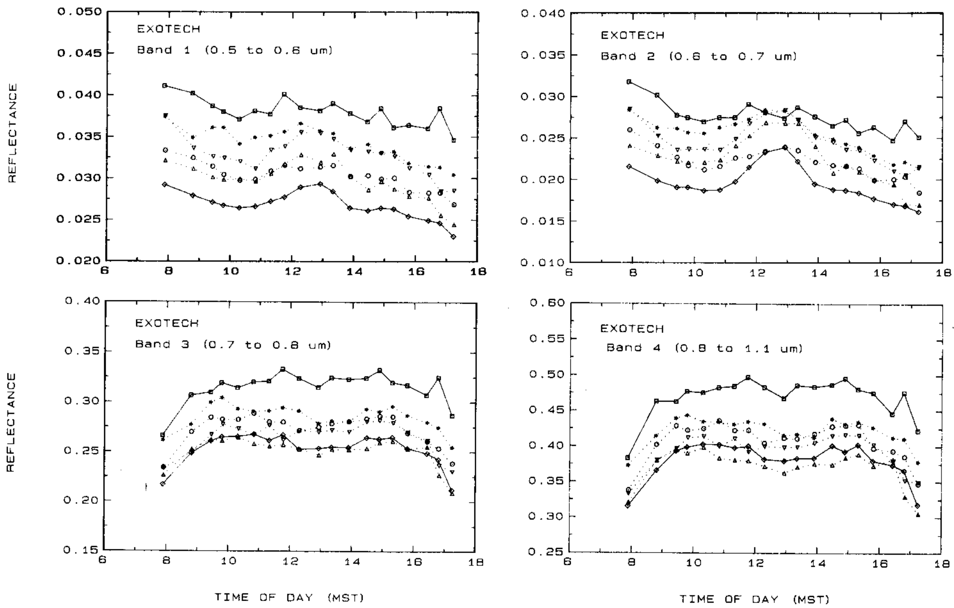

Figure 4. Diurnal patterns of reflectance in the Exotech wavebands for each cultivar of wheat on 9 March 1983. Symbols are identical to those shown in the legend of figure 3.

3.1.2. *Near-IR radiation*

Light reflectance in the near-IR portion of the spectrum revealed a different pattern from that observed in shorter wavelengths. We noted a tendency towards lower midday reflectance in Exotech bands 3 and 4 and MMR band 4 for each cultivar, with maximum values occurring 2–3 hours before and after solar noon. Minimum reflectances were documented before 09·00 hours and after 16·00 hours when lower solar elevations caused increased near-IR light absorption by multiple layers of leaves. Examination of near-IR reflectances showed that there were maximum differences among cultivars near solar noon. This contrasted markedly with the visible light portion of the spectrum where cultivar differences were minimal at that time. The pattern of reflected light for MMR 5 (1·15–1·30 μm) showed relatively uniform levels of reflectance during the day after an abrupt midmorning increase.

3.1.3. *Mid-IR radiation*

The mid-IR portion of the spectrum (MMR bands 6 and 7) revealed a third pattern of diurnal reflectances from wheat. The reflectances increased rapidly until 10·00 hours, then levelled off throughout the remainder of the day. Yecora reflected the highest amount of radiation in this interval, while Ciano, with its vertically oriented leaf arrangement, had consistently lower values. The more erectophile canopies showed some influence of the brighter background soil reflectance in MMR 7 from 12·00–13·30 hours as the direct solar beam became parallel with the row orientation and penetrated more deeply into the canopy.

3.1.4. *Bands ratios*

Band ratioing approaches tend to minimize the effects of changing illumination intensity on the relationships among spectral data and various agronomic characteristics (Tucker 1979), but they do not account for changes in the direction of illumination caused by changing solar zenith and azimuth angles (Duggin 1977). This can have an important influence on the interpretation of spectral data for inferring parameters like GLAI (Pinter *et al.* 1983). Band ratios from this experiment revealed that an additional complexity is related to canopy architecture. As an example, figure 5 shows diurnal patterns in a commonly used vegetation index, the ratio of near-IR to red reflectance (Exotech band 4/2 and MMR band 4/3). The behaviour of these ratios with time of day was very different among these six cultivars despite their close similarities in GLAI and biomass. Our results are also consistent with simulation

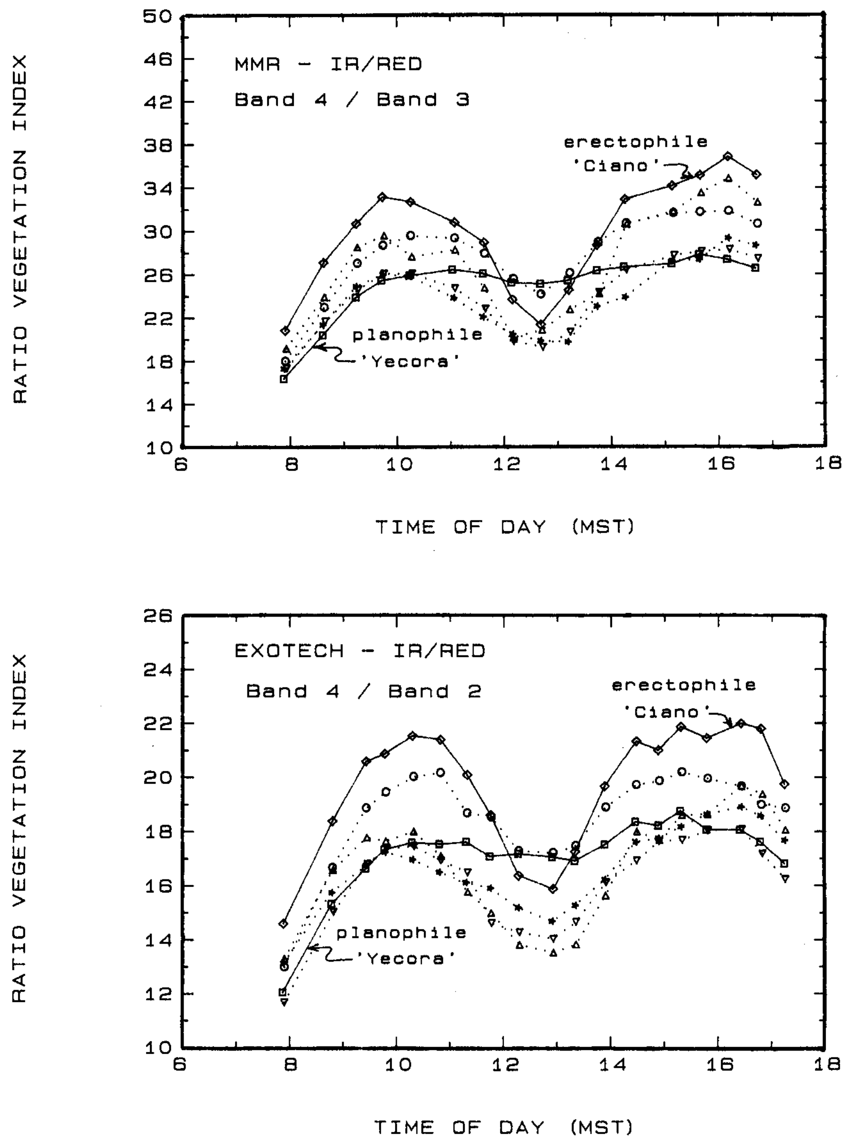

Figure 5. Diurnal patterns of two, band-ratio type indices measured over each wheat cultivar during 9 March 1983. Symbols are identical to those shown in the legend of figure 2.

studies by Bunnik (1978, his figure 94) which showed a 10–20 per cent reduction in the near-IR to red ratio if the average leaf angle distribution changes from predominantly erectophile to planophile.

An extreme diurnal asymmetry was observed in the ratios measured in all cultivars. This anomaly appeared to be independent of canopy structure and was a result of moderately heavy dew accumulation on the plants (Pinter and Jackson 1982). After 11·00 hours, however, the dew had completely dissipated and our data at solar noon revealed a sharp decline in the ratio of the more erectophile Ciano plant canopy. In contrast, Yecora exhibited a slight increase in the index during midday and then showed afternoon levels which were a little higher than midmorning values. Because of the architecturally related differences in the patterns of these vegetation indices, similar agronomic characteristics could be predicted correctly only if one coincidentally examined data from 12·00 or 13·00 hours observation times.

3.2. *Leaf reflectances*

Reflectances of excised single leaves from each cultivar were much higher than those observed for the canopy as a whole (table 3). Knipling (1970) has pointed out that increased attenuation of energy by multiple leaf layers, variation in leaf orientation, shadows and soil are responsible for this phenomenon. These results may partially denote differences in physiological status between *in vitro* and *in vivo* studies. The data of table 3 were subjected to an analysis of variance and showed no statistically significant differences ($p=0{\cdot}05$) among leaf reflectances of the cultivars. In fact, we found that the variability among leaves of the same cultivar often exceeded the differences observed between cultivars. Although these data were obtained about two weeks after the diurnal canopy measurements were made, we observed minimal visual changes in leaf colour during that interval. Sinclair (1971) maintained that the spectral reflectance and transmittance of normal green leaves does not vary significantly during the main part of the growing season.

Visible reflectance may be affected to some extent, however, by unusual stress

Table 3. Single-leaf reflectances for six wheat cultivars. Values were calculated from spectrophotometric data and response functions of seven MMR bands. Numbers in parentheses are standard errors of the measurement.

	MMR Bands						
	1	2	3	4	5	6	7
Seri	0·178	0·238	0·161	0·556	0·528	0·402	0·205
	(0·005)	(0·015)	(0·004)	(0·016)	(0·018)	(0·014)	(0·011)
Siete Cerros	0·176	0·229	0·158	0·554	0·519	0·389	0·189
	(0·007)	(0·016)	(0·007)	(0·016)	(0·020)	(0·015)	(0·009)
Ciano	0·173	0·235	0·156	0·555	0·517	0·391	0·194
	(0·005)	(0·011)	(0·004)	(0·013)	(0·014)	(0·012)	(0·012)
Yecora	0·179	0·236	0·161	0·570	0·538	0·411	0·208
	(0·006)	(0·014)	(0·005)	(0·016)	(0·018)	(0·017)	(0·013)
Genaro	0·175	0·232	0·158	0·547	0·518	0·396	0·199
	(0·005)	(0·015)	(0·005)	(0·012)	(0·014)	(0·013)	(0·011)
Pavon	0·169	0·220	0·153	0·542	0·531	0·377	0·186
	(0·008)	(0·021)	(0·008)	(0·022)	(0·021)	(0·019)	(0·016)

conditions such as severe salinity, nutrient toxicity and nutrient deficiency which greatly affect leaf total chlorophyll concentration (visible light reflectance increases and leaf chlorophyll concentration decreases (Gausman *et al.* 1978). None of these conditions developed in our experiment, however. Thus our laboratory findings further confirm that canopy architectural differences were the major cause of reflectance dissimilarities among the different cultivars.

4. Summary and conclusions

The spectral reflectance of wheat canopies in MSS and TM wavebands is not a unique function of agronomic parameters such as green leaf area index or green biomass. Instead, it is strongly dependent upon the direction of incident radiation and its interaction with the canopy architectural characteristics of individual cultivars. Significant differences were observed among reflectances of cultivars which had similar green biomass levels but which varied markedly in leaf inclination and size. We found that reflectances of all wavebands were usually higher for planophile than for erectophile canopies, a result also supported by modelling studies (Kimes 1984). In addition it was shown that reflectances from erectophile canopies varied more with changing sun zenith and azimuth. Planophile canopies, on the other hand, had a more uniform spectral response throughout the day. These observations further emphasize the complexities of crop canopy reflectance. They suggest that multiple reflectance observations at differing Sun zeniths could be coupled with model inversion approaches analogous to those proposed by Goel and Strebel (1983) to extract the agronomic information required for agricultural resource management.

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