The Effect of Water Stress and Soil Compaction on Cotton Canopy Reflectance and Temperature

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Introduction

Satellites, airborne imaging systems and hand held instruments are frequently proposed as indicators of crop stress caused by water, soil compaction, lack of nutrients, diseases and mites. Laboratory experiments have shown this is possible, but many of these studies focus on stresses far greater than any good farmer would allow their crop to endure. In the absence of any field studies reporting cotton canopy reflectance in Australia, a study was conducted to investigate how crop reflectance and temperature changes with the onset of water stress in the green, red, near infrared and thermal infrared wavelengths of the electromagnetic spectrum. These wavelengths are the most commonly used by remote sensing tools.

The objective of this experiment was to determine if crop reflectance measurements could detect water stress before it was visible to the human eye. The emphasis of this project was not on the effects of prolonged water stress that are clearly visible to the eye, but rather subtle changes in the crop water status that farmers contend with as a crop irrigation approaches. Pre-visual detection of water stress using handheld radiometers, airborne or satellite imagery would permit more accurate timing of irrigations before crop yield is adversely affected.

Materials and Methods

The reflectance experiment was conducted at Togo Station, Narrabri, Field 88. Two varieties (Sicala 3-2 & Siokra 1-4) were planted in 96 metre wide strips. The thermal infrared experiment was conducted in Field 86 using the CS189 variety. Both sites were managed using normal commercial procedures.

Radiation measurements were made using a Licor* portable spectroradiometer (model LI-1800) with the remote cosine receptor attached. The radiometer was placed on a specially built tripod with the remote cosine receptor sensor head extended 1.2m away from the tripod on a metal support. Measurements were taken 0.8m above the crop canopy to ensure the whole canopy was in the radiometer field of view at exactly the same location in both plots. The tripod was difficult to move which prohibited data collection at more locations within the specified time frame.

Radiation data was collected from 0.4 to 1.1μm wavelengths at 0.05 μm intervals, within an hour of solar noon on each day of the experiment. At each site, incident and reflected radiation were measured above the canopy. Three scans were taken at each site and averaged. The data presented are means of the four north, south, east and west sites in each plot. Four thermal infrared 8- 14 μm sensors (Everest 4000) recorded canopy and soil surface temperatures every 15 minutes during the cotton season.

Soil moisture content was measured using a CPN* neutron probe. Three aluminum tubes were installed in each plot and soil moisture readings down to 120 cm. The data presented are means for three tubes. The DWU for the 0-70cm zone was divided by daily evaporation (EVAP) to stabilize data for climatic differences and is reported as the DWU/EVAP ratio.

Ground cover percentage (GC%) was estimated at the same time reflectance readings were taken using a one metre scale divided into 100 one cm squares. This technique was reviewed by Adams and Arkin (1977) who concluded it was as accurate, simpler and more economical than electronic techniques. To avoid damaging canopy architecture, eight measurements of GC% were taken and averaged on the first and last days of the experiment.

Results and Discussion

Reflectance of a Cotton Crop Canopy and Bare Soil

The spectral signatures of cotton crop canopies and bare soil are shown in Figure 1. Canopy reflectance of the mid season cotton canopies was low in the visible region (0.4 – 0.7 μm) with a small peak in the green band at 0.55 μm. Radiation absorption by chlorophyll and other plant pigments causes low reflectance values in the visible region (Knipling 1970). Internal leaf reflection of incident radiation that is dominated by leaf structure (Gausman *et al.* 1969) causes canopy reflectance to increase considerably in the near infrared region (0.7 – 1.1 μm). The small dip in reflectance at 0.97 μm was due to radiation absorption by water within the canopy leaves (Wanjura and Hatfield 1986).

Spectral reflectance of bare soil increased with increasing wavelength and was higher for dry compared to wet soil (Figure 1). An indication of how wet the soils were is given by the VSW % data at 20cm, which was 42.5% for the wet soil and 27.2% for the dry soil. The soil surface colour becomes brighter and cracks as it dries and should be considered when interpreting reflectance data and satellite images. The bare soil spectral signature exhibits higher reflectance in the blue and red bands, and considerably less reflectance in the near infrared region than mid season cotton canopies. In the green band, reflectance of bare soil is similar to a mid season cotton canopy, depending on the crop GC% and soil surface moisture content. It was not possible to obtain a cotton canopy spectral signature when the crop was at its peak GC% because the radiometer was unavailable at that time.

In the visible region, mature cotton canopies ready for harvest had the highest reflectance values (Figure 1). The absence of green foliage due to crop senescence, more soil background and the presence of white cotton bolls all contribute to the high reflectance values in the visible region. Crop senescence causes mature crops to reflect less near infrared radiation than mid season canopies because of reduced leaf cell structure combined with greater exposure of soil background. In the near infrared region, reflectance increased with increasing wavelength, which is a characteristic that could be used to distinguish mature crops. Reflectance was greater in all wavelengths for the higher yielding crop because there were more white cotton bolls on these plants.

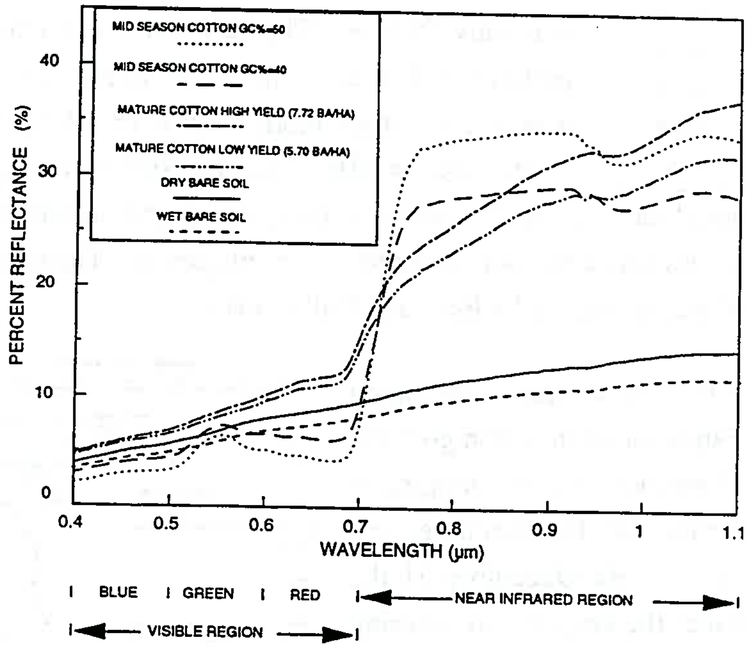

Figure 1:The reflectance of bare soil and cotton canopies

Water Stress on Cotton Canopy Spectral Signatures

The influence of water stress on canopy reflectance was investigated for two commonly grown cotton varieties with different leaf shapes. Both the Siokra and Sicala varieties were irrigated on December 16. The soil profile was still saturated two days later and the soil moisture deficit at the field experiment location remained at zero (mm). Visual crop wilting symptoms first became apparent for both varieties on January 2 which include darker coloured leaves with a more pendant orientation. The soil moisture level when a crop irrigation is due is known by cotton farmers as the refill point. Therefore, based on crop symptoms both varieties had reached their refill points by January 2.

Further evidence that both varieties had reached their refill points is shown by the drop in crop Daily Water Use/Evaporation ration (DWU/EVAP) figures after January 2 (Table 1). A decline in the DWU/EVAP ration indicates that after January 2, both varieties were suffering from water stress because soil water extraction was restricted.

Table 1: Soil moisture deficits and daily water use/evaporation (DWU/EVAP) figures for the Siokra and Sicala cotton varieties.

	Soil Water Deficit (mm)		DWU/EVAP Ratio	
Date	Siokra	Sicala	Siokra	Sicala
18/12	0	0	-	-
29/12	35	51	0.35	0.43
31/12	42	62	0.41	0.62
2/1	55	75	0.66	0.68
4/1	68	86	0.52	0.45
5/1	74	91	0.36	0.34

When both varieties had reached their refill points the Sicala variety soil moisture deficit was 75 mm while the Siokra variety deficit was only 55 mm. The soil water extraction patterns in Figure 2 show the Sicala variety was able to extract more water from all depths in the soil profile than the Siokra variety. These soil moisture extraction patterns identify that the soil was more compacted where the Siokra variety was growing because less soil water was available for plant growth. The effect of soil compaction on the refill point was discussed by Roth and Cull (1991).

Crops often remain water logged for a week after an irrigation due to the heavy clay soil characteristics found in cotton growing areas (Chan and Hodgson 1981). Evidence of water logging is shown by the low DWU/EVAP ratio up to December 29, following the crop irrigation (Table 1). By December 31 the rising DWU/EVAP ratio indicated that the crop was recovering from the water logging. The Siokra variety was more waterlogged on December 29 than the Sicala variety, which is shown by its lower DWU/EVAP ratio and wetter soil moisture or VSW% values in Figure 2. The Siokra variety remained waterlogged for longer than the Sicala variety because the soil was more compacted.

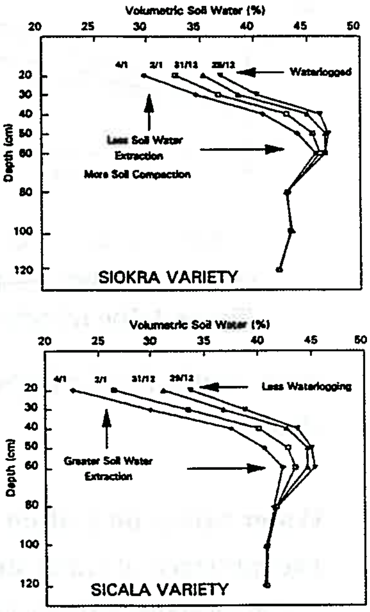

Figure 2: Soil moisture extraction patterns for the Sicala and Siokra varieties

During the five day period prior to both varieties reaching the refill point, canopy reflectance changes were greatest at the following wavelengths; 0.55 μm in the green band, 0.67 μm in the red band and 0.76 μm in the near infrared band. A one way analysis of variance was conducted at these selected wavebands for each variety separately with time (df=3,15). In Figures 3 and 4 dates assigned the same letter were not significantly difference ($P<0.05$), when Duncan's multiple range test was used to compare reflectance data means.

During the five day period prior to the soil moisture level reaching the refill point, green reflectance decreased by 0.7% (P<0.01), while near infrared reflectance decreased by 3.9% (P<0.001) for the Siokra variety (Figure 3). With further soil moisture depletion below the refill point between January 2 and January 4, no further significant decrease in reflectance was evident in the green band, however, reflectance decreased a further 2.3% (P<0.001) in the near infrared band. Red reflectance only decreased significantly (P<0.05) by 0.6% after the soil moisture status had declined below the refill point.

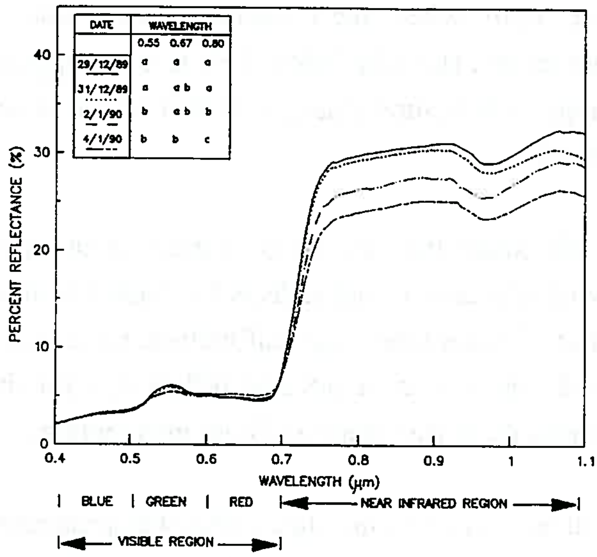

Figure 3: The effect of water stress on the cotton variety Siokra canopy spectral signature

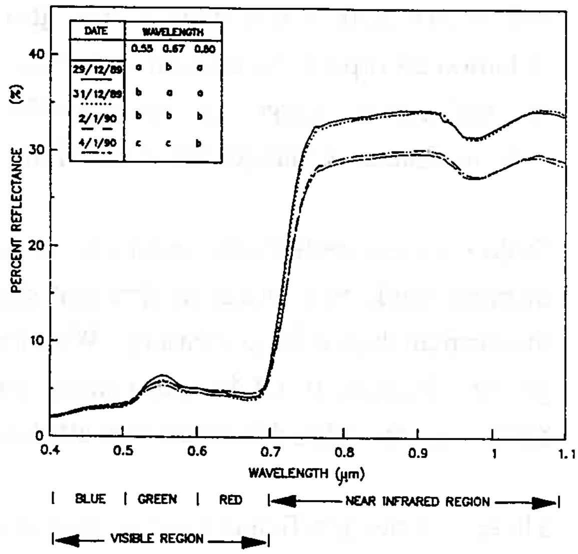

Figure 4: The effect of water stress on the cotton variety Sicala canopy spectral signature

Similar results were found for the Sicala variety (Figure 4). During the five day period prior to the soil moisture level reaching the refill point, green reflectance decreased by1.0% (P<0.001). Green reflectance did not decrease further as soil moisture declined below the refill point. In the near infrared band, reflectance decreased by 4.5% (P<0.001) during the five day period prior to the refill point with no further significant change in reflectance below the refill point. Red reflectance increased by 0.4% (P<0.001) only when soil moisture fell below the refill point.

Date	Siokra GC%	Sicala GC%
29/12	43.42	49.73
4/1	34.04	39.79

Table 2: Ground cover % (GC%) at the commencement and completion of the experiment for each cotton variety.

The GC% for the two varieties at the start and completion of the experiment is shown in Table 2. A paired *t* test (df = 2, 7; P<0.05) found a significant 9.38% decrease in GC% for the Siokra (t = 2.80) and 9.94% decrease (t = 2.83) for the Sicala varieties following the onset of crop water stress.

Reflectance decreased in the near infrared band because crop water stress reduced the canopy ground cover as the leaf orientation assumed a more pendant position. This conclusion is supported by Jackson and Ezra (1985), who found canopy geometry altered crop reflectance. Associated with leaf wilting is a greater contribution of soil background to the canopy spectral signature. Figure 1 showed that reflectance of bare soil was considerably less than crop canopies in the near infrared band. The results of this experiment showed a greater change in reflectance at 0.76 μm than at 0.97 μm wavelength, where the reflectance dip is due to radiation absorption by internal leaf water (Wanjura and Hatfield 1986). This further supports that reflectance changes are dominated by canopy architectural changes instead of leaf water content structural changes in the near infrared band.

Siokra variety reflectance values were generally lower than the Sicala variety in the near infrared band. Siokra has an okra leaf shape which intercepts and reflects less radiation than the normal shaped Sicala variety. With the onset of water stress and leaf wilting, there was a greater decrease in GC% and a more sudden decrease in near infrared reflectance for the Sicala variety. This difference was attributed primarily to leaf shape and light interception.

There was no significant increase in red reflectance until soil moisture stress was prolonged below the refill point. Although equipment was not available to measure leaf chlorophyll for this project, prolonged moisture stress reduces radiation absorption by reducing leaf chlorophyll content (Jackson and Ezra 1985; Richardson and Everitt 1987). Increases in red reflectance may also be explained by the exposure of more soil background due to leaf wilting as bare soil exhibits higher red reflectance than crop canopies (Figure 1). The emphasis of this project was not on the effects of prolonged water stress that are clearly visible to the eye, but rather subtle changes in the crop water status that farmers contend with as a crop irrigation approaches. Chlorophyll absorption may be responsible for results reported in the red band when water stress is severe (Jackson and Ezra 1985; Richardson and Everitt 1987), however, in this experiment the red band did not detect moisture stress until after the irrigation was due.

Green reflectance decreased with soil moisture depletion. A darkening of leaf colour from a bright to a dull green was observed, causing green reflectance to decrease. Leaf colour is a crop symptom used by farmers to identify water stress. In the green band soil exhibits similar reflectance values to an incomplete cotton canopy (Figure 1). It would be expected as the soil surface dried, reflectance would increase (Hoffer 1978; Tucker and Miller 1977), not decrease as in this experiment if soil background was dominating the green spectral response.

Crop canopy, soil surface temperatures and wheel track compaction

Crop canopy and soil surface temperatures change considerably during the day (Figure 5). During the night soil surface temperatures were warmer than the crop canopy. At about 7.40 am soil and canopy temperatures were similar. As the morning elapsed, the crop canopy was exposed to more sunlight and its temperature rose above the soil surface that remained shaded underneath the canopy. By 11.30 am the sun's elevation in the sky was high and soil temperatures rose above the crop as the soil surface was now in direct sunlight. The soil temperature peaked on this date at 44 °C while the crop canopy temperatures was 30 °C. Soil surface temperatures up to 50 °C were common in the middle of the day, while canopy temperatures of non stressed crops were usually around 28-30°C (Roth 1993).

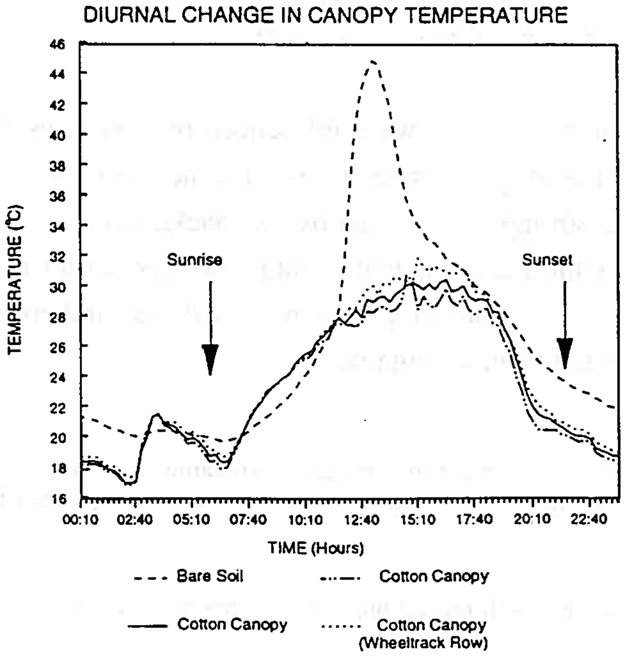

Figure 5: The daily change in crop and soil surface temperatures

Morning crop temperatures for all 3 cotton rows were similar, although by midday they began to differ due to the midday heat and variations in soil moisture availability (Figure 5). Figure 5 shows that the row with the highest afternoon temperature was a tractor wheel track row where the soil was more compacted, thus soil moisture was less available for crop transpiration, resulting in a canopy temperature rise

Conclusion

These results suggest that it is possible to monitor subtle changes in crop water status by measuring changes in crop reflectance with a ground radiometer. Most importantly for irrigation scheduling purposes, these changes were apparent pre-visually before the irrigation was due. During the five day period prior to the irrigation date or refill point, reflectance decreased in the near infrared and green bands. Red reflectance increased only after the soil moisture status fell below the refill point. The greatest change in reflectance was in the near infrared region, which was attributed to a decrease in GC% caused by canopy architectural changes including leaf wilting. Red and green band reflectance changes were very small and would not be practical for irrigation scheduling purposes under commercial operational conditions. Other, experiments showed that the crop reflectance was more strongly influenced by ground cover and plant height than the soil moisture status (Roth and Button 1994).

Potential crop yield, conventionally assessed as fruits counts, were not related to the reflectance data. The risk of using remote sensing technologies to predict yield is that the sensors respond to crop parameters such as leaf area, and not actual fruit numbers. Although advanced canopy development is indicative of high potential yield, poor insect control or unchecked proliferation of foliage negate this relationship (Roth and Button 1994). The effects of leaf senescence and appearance of white cotton bolls on crop reflectance indicate these remote sensing tools could be effective in monitoring crop defoliation.

Crop temperatures rose with soil moisture depletion and were influenced by soil moisture availability and soil compaction. Thermal infrared crop temperatures offer the most potential for irrigation scheduling, although the data is strongly influenced by soil background, for the first half of the cotton season. Finally, to monitor crop moisture status the thermal infrared temperatures offers the most potential, whilst to monitor crop canopy growth (ground cover, LAI, height) the near infrared wavelengths would be most suitable.

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