AN ASSESSMENT OF INFRA-RED THERMOMETRY FOR SCHEDULING IRRIGATION OF BEAN CROPS

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ABSTRACT

A study was made using an infra-red thermometer (IRT), to determine if crop canopy temperature (T_c) could be used to detect crop moisture stress in Canterbury and also to determine if an existing criterion based on canopy temperature could be used for scheduling irrigation of field crops. Canopy resistances to vapour transfer, calculated from T_c data, increased with increasing effective soil moisture deficit (ESMD) for *Vicia faba* and *Phaseolus vulgaris*. Criteria evaluated for irrigation scheduling were the stress degree day index (SDD), canopy temperature variability (CTV), crop water stress index (CWSI) and canopy temperature difference between stressed and unstressed crops (CTD). Dependence of the canopy temperature-air temperature difference on vapour pressure deficit (vpd) can be used under limited conditions when vpd >2.0 kPa. The difference between the canopy temperature of a stressed and unstressed crop seems to hold most promise as being suitable for scheduling irrigations of field crops in Canterbury. As a scheduling criteria however, it may have practical problems such as the maintenance of an unstressed control.

Additional Key Words: *canopy temperature, crop moisture stress, canopy resistance, canopy temperature difference, canopy temperature air temperature difference*

INTRODUCTION

Remote sensing of crop canopy temperature can, in some instances, be used to determine crop water stress (Isdo *et al.*, 1977; Clawson and Blad, 1982; O'Toole *et al.*, 1984; Steiner *et al.*, 1985). Several different criteria, based on canopy temperature, have been proposed as useful for scheduling irrigations (Aston and Van Bavel, 1972; Idso *et al.*, 1977, 1981; Jackson *et al.*, 1981; Beliner *et al.*, 1984).

However, most of this work has been conducted in regions with weather quite different from Canterbury. In this paper we report on an exploratory study the objectives of which were firstly to determine if, and under what conditions, crop canopy temperature can be used as a basis for detecting crop water stress. Secondly we sought to determine whether, with further research it would be possible to use existing criteria based on canopy temperature for scheduling irrigations of field crops.

THEORY

If physical and chemical storage of energy in the crop is negligible, the energy balance of a crop can be defined as:

$$R_n = ET + C + G \qquad [1]$$

where R_n is the net radiation (available solar energy), ET is evaporative heatflux, C is the convective sensible heat flux and G the soil heat flux which is usually and order of magnitude less than R_n during the day. Net radiation then, is predominantly partitioned between ET and C.

Convective heat and evaporative heat transport can be expressed as:

$$C = \frac{\rho C_p (T_o - T_a)}{r_a} \qquad [2]$$

and

$$ET = \frac{\rho C_p}{\gamma} \frac{(e_s(T_o) - e_a)}{(r_a + r_c)} \qquad [3]$$

it follows that

$$ET = R_n - G - \rho C_p \frac{(T_o - T_a)}{r_a} \qquad [4]$$

where ρ is the density of air, C_p is the specific heat of air, γ is the psychrometric constant, $e_s(T_o)$ is the saturated vapour pressure at T_o, e_a is the vapour pressure at height z, T_a is air temperature at height z, r_c is the resistance of the canopy to vapour transfer, and r_a is the aerodynamic resistance where $r_a = \int_0^z K(z)/dz$ and K is the diffusion coefficient. Here the assumption is made that the resistances to heat (r_{ah}) and vapour (r_{av}) transfer in the atmosphere are equal.

Convective and evaporative heat fluxes may both depend on surface temperature. One would expect a rise in surface temperature if a larger convective heat flux occurs when evaporation decreases because of water stress ([2]).

As stomata close and canopy resistance (r_c) increases so ET will decrease. With a decrease in ET equation [4] illustrates how T_o must increase to maintain the balance with $R_n - G$. Interpretation of crop surface temperature to study crop response to moisture stress is complicated by stomata responding not only to changes in soil water deficits (Szeicz and Long, 1969; Russell, 1980) but also to changes in irradiance, temperature, vapour pressure deficit (vpd) and CO_2 (Gates, 1980; Idso, 1983; Johnson and Ferrell, 1983).

Radiatively-measured canopy temperature (T_c) is unlikely to be identical to T_o, the canopy temperature of the "notional" canopy surface, which is the true source of convective heat within the canopy (Huband, 1983). When measured with an infra-red thermometer (IRT), T_c may vary depending on crop emissivity (ε) which may be related to viewing angle. As the temperature profile within a canopy is not always constant with depth, viewing angle and hence the depth to which the foliage elements are viewed may also influence T_c (Baldocchi *et al.*, 1983). IRT orientation to the sun also affects T_c (Hubbard, 1983; Nielsen *et al.*, 1984). Provided precautions are taken, T_c can be suitable for determining heat fluxes from the canopy and crop water stress.

Determining Crop Moisture Stress

Canopy resistance has been correlated with different soil moisture deficits (Sceicz and Long, 1969; Russell, 1980) and could possibly be used to indicate a moisture stressed crop. Combining equations [3] and [4], eliminating T_o, ignoring G for conditions of complete crop cover and short measurement intervals (Hatfield, 1985) and solving for r_c gives:

$$r_c = \frac{\rho C_p [e_s(T_c) - e_a]/[R_n - (\rho C_p (T_c - T_a)/r_{ac}]}{\gamma} - r_{ac} \quad [5]$$

Here r_{ac} is a stability-corrected aerodynamic resistance (Monteith, 1973; Hatfield *et al.*, 1983). This resistance was determined from the uncorrected value

$$r_a = [\ell n((z-d)/z_o)]^2/k^2u \quad [6]$$

and altered by

$$r_{ac} = r_a(1 - \frac{n(z-d)g\,(T_c - T_a)}{Tu^2}) \quad [7]$$

where z is the instrument height above the ground, d the zero plane displacement (assumed 0.13 x crop height), z_o the roughness length (assumed 0.64 x crop height), k is von Karman's constant (0.41), u is wind speed, n a constant set equal to 5, T is the average temperature of the surface and the air and g the acceleration due to gravity. Canopy resistance was calculated to determine if T_c can be used to detect crop moisture stress.

Irrigation Scheduling Criteria

Alternatively the following scheduling criteria have been proposed to help determine when irrigation should be applied:

1. *Stress-Degree-Days (SDD)*

The stress degree day index is defined as SDD = ($T_c - T_a$) with the temperature measurements taken close to noon. The rationale for the index is when $T_c - T_a > 0$ °C, the crop is moisture stressed. The higher $T_c - T_a$ and the more days over which $T_c - T_a > 0$°C the greater the stress (Idso *et al.*, 1977; Walker and Hatfield, 1979).

2. *Canopy Temperature Variability (CTV)*

Variability in soil properties, rainfall or irrigation distribution may lead to variation in soil water content. Because of such variability, differences in T_c measured at several locations within the same field may indicate crop water stress (Aston and van Bavel, 1972). CTV is defined as the maximum range in T_c measured at several locations in the same field. Clawson and Blad (1982) found with maize that a variability greater than 0.7°C indicated a need for irrigation.

3. *Canopy Temperature Difference (CTD)*

For the same species, the difference between T_c of an unstressed control crop and T_c of a possibly stressed crop is known as the Canopy Temperature Difference (CTD) (Clawson and Blad, 1982; Berliner *et al.*, 1984). There is probably a critical canopy temperature difference (CTD_c) corresponding to a yield reducing soil moisture deficit. Clawson and Blad (1982) found using a CTD of 1° C as the irrigation criterion for corn, a 40% saving in water and a 20% yield reduction.

4. *Crop Water Stress Index (CWSI)*

Idso *et al.* (1981) attempted to normalize the SDD criterion for environmental variability and quantify the degree of stress. The CWSI is defined as

$$CWSI = 1 - \frac{ET_a}{ET_p} \quad [8]$$

where ET_a is the actual evapotranspiration from the crop and ET_p the potential evapotranspiration from the crop. The CWSI cannot be calculated from equation [8] but can be derived from the linear relationship between $T_c - T_a$ and vapour pressure deficit (vpd) (Idso *et al.*, 1981; Reginato, 1983).

MATERIALS AND METHODS

Vicia faba (faba beans) is a tall crop and *Phaseolus vulgaris* (navy beans) a short crop. Fully irrigated and unirrigated treatments grown at Lincoln (43° 39' S, 172° 28' E) were used to test these models during the summer of 1983/84.

Vicia faba

The experimental site was 2.9 ha (143 x 200 m) of a Templeton silt loam with a plant available waterholding capacity of 168 mm/m. The southern half of the field (70 x 200 m) was irrigated twice with a sprinkler system. The irrigated and unirrigated areas were divided into 6 plots (or areas) 20 × 30 m, totalling 40 × 90 m. The irrigated treatment bordered on the southern boundary of the unirrigated treatments. Fetch to instrument height ratio (FH) from an instrument stand in the irrigated treatment upwind, was 33-38 to the north west, and 25-29 to the north east. Similarly FH for the unirrigated treatment was 31 to the north east and 42 to the north west. The minimum fetch upwind to the area where canopy temperatures were measured was 25 and 40 m to the north east on the fully irrigated and unirrigated treatments respectively.

Phaseolus vulgaris

This crop was grown on a Wakanui clay loam with a plant available water holding capacity of about 200 mm/m (Reid, pers. comm.). The experimental design was a randomised block with plots 3 × 14 m, with the longest dimension oriented east west. A 1.5 m wide guard plot separated fully-irrigated treatments. Areas 7.5 × 14 m containing irrigated and unirrigated plots, sheltered with vertical 1 m shade cloth, were located 6.7 m to the north or south of the plots used in this experiment. The total site area sown to navy beans was 97 × 60 m with the instrument stand located in the centre of the site. Minimum fetch, although interrupted by shelter, where canopy temperatures were measured was 19 m. Irrigation was applied when a predetermined potential soil moisture deficit (Penman, 1956, 1970) was reached. Initially this was 60 mm but was later (13 January 1984) decreased to 40 mm.

Effective soil moisture deficits (ESMD) allowing for changes in crop cover (Ritchie, 1972) up to the end of the previous day and potential evapotranspiration (ET_O) on the day of data collection, calculated from the formula given by French and Legg (1979) are presented in Table 1. The ESMD was the same as the potential soil moisture deficit except after rainfall or irrigation. After rain or irrigation the ESMD was set to zero and subsequently was assumed to be the sum of ET_O until the rain or irrigation had evaporated. The ESMD then reverted to the value of the potential soil moisture deficit immediately prior to the rain or irrigation and continued to increase with the sum of daily ET_O.

TABLE 1: Data collection dates, effective soil moisture deficit, ESMD, and potential transpiration ET_O (mm). ESMD's are those at the end of the previous day. ET_O refers to the day of data collection.

Data collection dates		ESMD	ET_O
Vicia faba			
3.1.84	Irr.	4	4.6
	Unirr.	167	4.6
4.1.84	Irr.	9	5.3
	Unirr.	172	5.3
9.1.84	Irr.	11	4.5
	Unirr.	11	4.5
10.1.84	Irr.	15	5.6
	Unirr.	15*	5.6
Phaseolus vulgaris			
30.1.84	Irr.	13	4.3
	Irr.	30	4.3
	Unirr.	89	4.3
1.2.84	Irr.	22	5.0
	Unirr.	98	5.0
13.2.84	Irr.	1	4.8
	Unirr.	1	4.8
24.2.84	Irr.	4	5.2
	Unirr.	113	5.2

* during the 10th, the unirrigated crop would have returned to an ESMD of 173 mm.

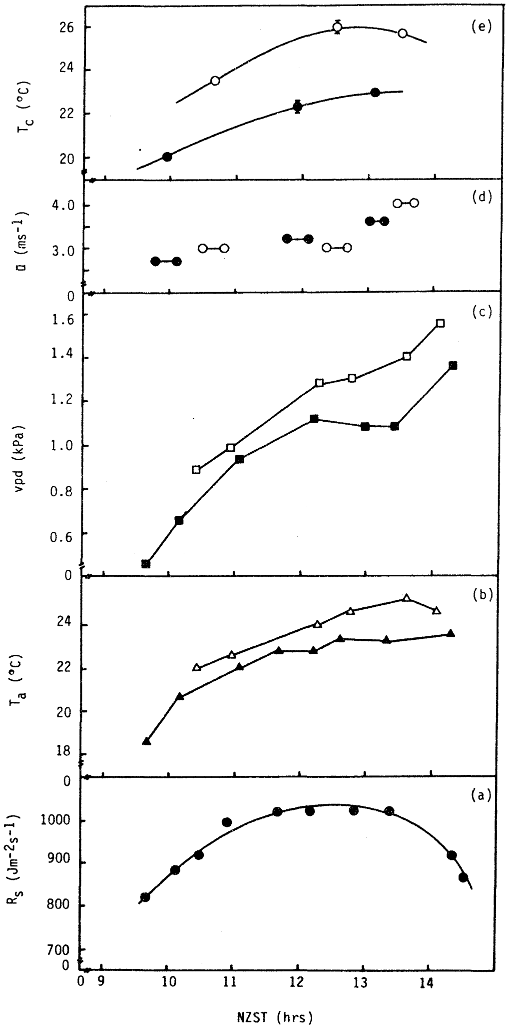

Figure 1: Solar radiation (●) (a), air temperature above irrigated (▲) and unirrigated (△) (b), Vapour pressure deficit above irrigated (■) and unirrigated (□) (c), mean wind speed at 0.5 m above the crop (d) and canopy temperature of irrigated (●) and unirrigated (o) *Vicia faba* on 4 January 1984. Distance between bars is two SE's.

Data Collection and Instrumentation

Crop canopy temperatures were calculated as the average of three easterly and three westerly oriented, hand-held readings made at an oblique angle to the crop about 25° from the horizontal. Emissivity assumed for both crops was 0.98. Wet (T_w) and dry (T_a) bulb temperatures, solar radiation (R_s) and windspeed (u) were recorded each minute, during IRT measurements from 10:20 to 14:24 NZST on 30 December 1983 and 08:10 to 15:20 NZST on 30 December 1983 and 08:10 to 15:20 NZST on 3 January 1984. On other days these variables were recorded at the beginning and end of each set of IRT measurements which took 18-20 minutes to collect. Windspeed, T_w, T_a and R_s were used for calculations of R_n, T_c-T_a, vpd and r_c.

The IRT was an Everest Interscience model 110 with a 3° field of view and a spectral pass band of 8-14 μm. The manufacturer claims an accuracy of 0.5 C, linearity of 0.3 °C and resolution of 0.1°C. Accuracy and linearity were checked using a partially immersed blackbody in a stirred water bath and an Everest 1000 blackbody calibration source. The calibration source's accuracy was confirmed against a bomb calorimeter substandard. Generally the IRT was within the manufacturers' specifications. Errors could occur when the IRT was at a temperature significantly different from air temperature. This was caused by the IRT either being left in the sun or used immediately after storage in a cold room. In the field, calibration checks were made before and after each circuit of the plots. Windspeed was determined with a Fuess small cup anemometer 0.5 m above the faba beans and 1.9 m above the navy beans using the manufacturer's calibration. An aspirated Assman psychrometer at 0.5 m above the faba beans and 1.0 m above the navy means was used to measure T_w and T_a. Incident solar radiation was measured using a Licor LI200S pyranometer sensor coupled to a LI185 meter. The Licor pyranometer was calibrated using an Eppley pyranometer substandard. Net radiation was estimated using data collected by Jamieson (1979),

$$R_n = 0.92\,R_s + 61 \text{ northwesterly and cloudy} \qquad [9]$$

$$R_n = 0.627\,Rs - 34 \text{ clear and sunny} \qquad [10]$$

Although R_n is affected by the difference between T_c and T_a (Monteith, 1981) adjustments for this were considered insignificant.

RESULTS

Figure 1 illustrates environmental conditions and T_c on 4 January 1984 for the faba bean crop. Air temperature was up to 1.5°C warmer and vpd about 0.1 kPa greater above the unirrigated crop. Canopy temperatures increased till after midday. On other days T_c was observed to decline after about 14.00 hrs NZST. Table 2 shows environmental conditions and maximum T_c on the type of days likely to be monitored with an IRT in Canterbury. Maximum canopy temperatures of the fully irrigated crops ranged from 19.9 to 27.1°C compared with 21.4 to 30.0°C for unirrigated. Maximum daily vpd's ranged from 1.0 — 2.4 kPa. The low and small range of maximum vpd is significant, compared

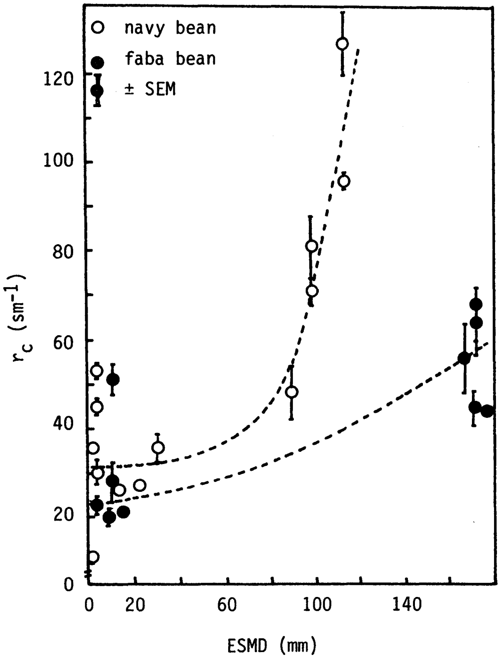

Figure 2: Change in canopy resistance (r_c) of *Vicia faba* (●) and *Phaseolus vulgaris* (o) with effective soil moisture deficit (ESMD). Distance between bars is two SE's.

TABLE 2: Days in 1984 when data were collected that represent the weather and canopy temperature (T_c) most likely to occur when crops would be monitored with an IRT. T_a, T_c, vpd, R_n and u are maximum values.

Date	Type of day	ET_o (mm)	T_a (C)	T_c [Irr] (C)	T_c max. (C)	vpd max (kPa)	R_n max (J/m²/s)	u max (m/s)
3-1	Sunny, NE wind	4.6	20.0	21.7	24.4	1.0	603	4.1
4-1	Sunny, warm NE	5.8	24.0	23.1	26.5	1.5	610	4.0
10-1	Cloudy, strong NW	5.6	21.7	20.9	21.4	1.4	460	7.1
30-1	Sunny, cool NE	4.3	18.8	19.9	21.9	1.0	587	6.2
1-2	Sunny, warm NE	5.8	25.6	25.0	28.5	1.7	580	7.0
13-2	Sunny, mild NE	4.8	24.2	25.6	25.8	1.2	555	4.1
24-2	Sunny, hot NW	5.2	27.7	27.1	30.0	2.4	525	5.6

to continental climates where other remote sensing work has been done.

Determining Crop Moisture Stress

On sunny days when $R_n > 450$ J/m²/s and vpd > 0.6 kPa, and very cloudy days when $R_n > 250$ J/m²/s and vpd > 1.3 kPa, moisture stress was detected with calculations of r_c using [5].

Figure 2 shows r_c calculated using [5] as a function of ESMD. Generally r_c increases with increasing soil moisture deficit. The apparently lower r_c of the faba beans is probably associated with its larger leaf area (Monteith, 1965). In addition the stomata of the navy beans may have started to close at a smaller soil moisture deficit because of the crops shallower root system and possibly different stomata characteristics such as density, pore area etc. (Kerr, 1973; Idso, 1983). The high r_c value of 51 s/m at 11 mm ESMD for faba bean is not unexpected. It represents the unirrigated crop which was developing a fungus disease and was close to maturity. The latter two situations tend to cause increases in r_c (Wiegand *et al.*, 1983).

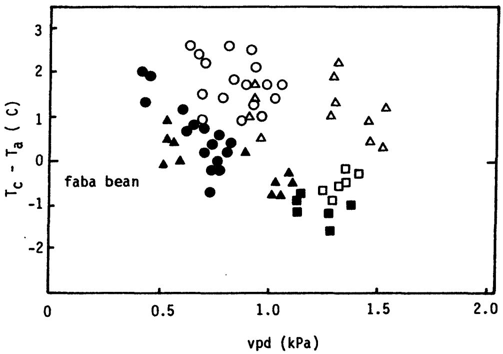

Figure 3: Change in *Vicia faba* Canopy temperature (T_c) air temperature (T_a) difference with vapour pressure deficit (vpd). Irrigated (●) unirrigated (o) 3 January 1984, Irrigated (▲) unirrigated (△) 4 January 1984, Irrigated (■) unirrigated (□) north westerly and cloud 10 January 1984.

Irrigation Scheduling Criteria

Stress Degree Day and Crop Water Stress Index

Both SDD and CWSI are $T_c - T_a$ dependent. Figures 3 and 4 illustrate the observed $T_c - T_a$ results as a function of vpd.

Canopy Temperature Variability

Although the variability in T_c across the field of the unirrigated crops was generally greater than for the irrigated ones, it was not consistent. The range in T_c between irrigated faba bean plots was up to 1 °C at times. Unirrigated T_c standard errors were two to three times higher than irrigated but occasionally they were also found to be the same or less. Variability in T_c of fully irrigated faba and navy beans at the same spot when viewed from opposite directions was often greater than 1 °C. When the

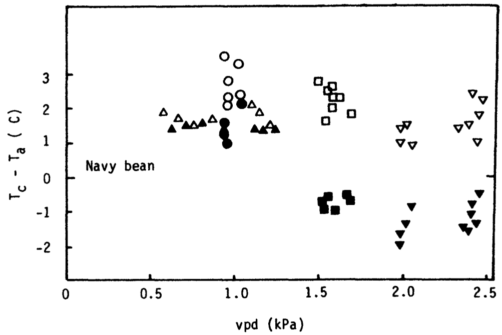

Figure 4: Change in *Phaseolus vulgaris* canopy temperature air temperature difference with vapour pressured deficit. Irrigated (●) unirrigated (o) 30 January 1984, Irrigated (■) unirrigated (□) 1 February 1984, irrigated (▲) unirrigated (△) 13 February 1984, irrigated (▼) unirrigated (▽) 24 February 1984.

same spot was viewed from the same direction variability was reduced by half.

Canopy Temperature Difference

Figure 5 shows the canopy temperature difference between unstressed and stress plots (CTD) as a function of the ESMD of the stressed plots. A general increase in the CTD with increasing ESMD occurred. The high CTD of 1.4 to 1.6 °C at 11 mm ESMD corresponds to the older, diseased faba bean crop with a high r_c. Cloudy northwesterly conditions caused a small (1 °C maximum) CTD in spite of the high 179 mm soil moisture deficit.

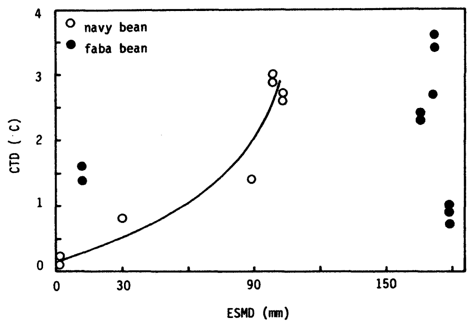

Figure 5: Change in canopy temperature difference (CTD) between fully irrigated and unirrigated *Phaseolus vulgaris* (o) and *Vicia faba* (●) with effective soil moisture deficit (ESMD) of the unirrigated crop.

DISCUSSION

Remote sensing of T_c in Canterbury can be used to detect crop water stress as illustrated by calculations of r_c (Figure 2). The data requirement, calculations required, and variability of r_c through the day render such a measure of stress impractical for field use. However simple criteria such as $T_c - T_a$ have their own problems.

Stress Degree Days

The SDD criterion does not account for environmental or crop characteristic variability. Figure 6 demonstrates the range in $T_c - T_a$ that is possible because of the inter-relationship between R_n, T_a, vpd, r_c and r_a. The graphs were drawn by combining and rearranging [1], [2] and [3]. G is assumed negligible and Δ is the slope of the saturation vapour pressure with temperature relation $(e_s(T_c) - e_a)/(T_c - T_a)$.

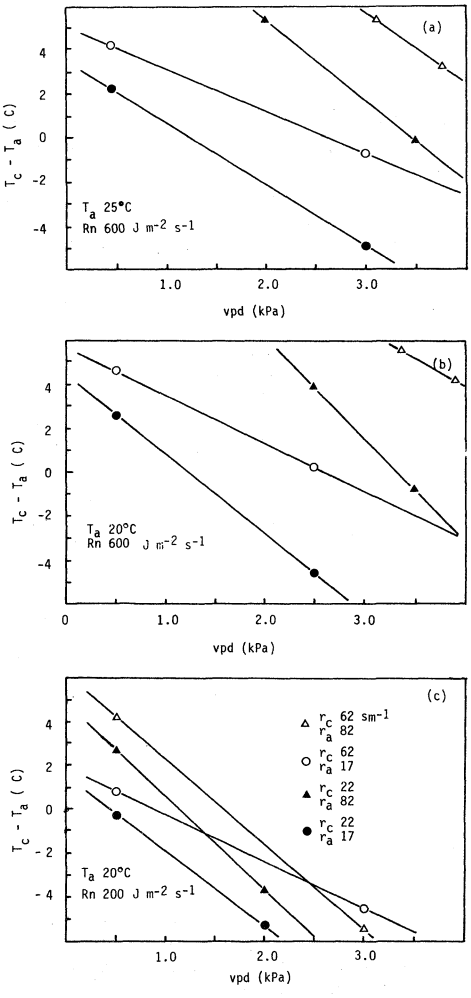

Figure 6: Change in calculated (theorectical, refer [11]) canopy temperature air temperature difference with vapour pressure deficit. r_c 22 s/m, r_a 17 s/m (●); r_c 22 s/m, r_a 82 s/m (▲); r_c 62 s/m, r_a 17 s/m (o); r_c 62 s/m, r_a 82 s/m (△).

So

$$T_c - T_a = \frac{r_a Rn \; \gamma(1+r_c/r_a)}{\rho Cp\Delta + \gamma(1+r_c/r_a)} - \frac{(e_s(T_c) - e_a)}{\Delta + \gamma(1+r_c/r_a)} \qquad [11]$$

Two different crops may be under the same degree of yield-reducing stress and same climatic conditions, but because of different characteristics like height and r_c, they may have different canopy temperatures. Similarly, crops may have the same $T_c - T_a$, or T_c but one may be stressed the other not. This criterion cannot therefore be used indiscriminately for determining irrigation need. But attempts to modify it so as to improve its general applicability have been made.

Crop Water Stress Index

This criterion has proved successful in some instances (O'Tool *et al.*, 1984). However the method has several disadvantages. The CWSI does not account for the effect of r_a which can be substantial (Figure 6). Empirical adjustments can be made however (O'Toole and Hatfield, 1983), but this introduces complexity to a simple method. The low vpds experienced mean the difference between $T_c - T_a$ maximally stressed and completely unstressed is close to the $T_c - T_a$ scatter experienced in the field (Figures 3, 4). Idso *et al.* (1981) found for lucerne in North Dakota that CSWI's changed through the day with a maximum at 13.30 to 14.30 hrs.

However a rule of thumb, based on the $T_c - T_a$ relationship with vpd can be used and perhaps refined.

On very warm (>25°C) sunny days when the vpd is between 2.0 – 3.0 kPa (a northwesterly day in Canterbury), and $T_c - T_a > 0$ °C, crops will most likely be moisture stressed.

As the vpd declines, the likelihood that $T_c - T_a > 0$°C for an unstressed crop increases. This obviates the $T_c - T_a$ relationship with vpd as a rule of thumb scheduling criterion.

Canopy Temperature Variability

In some instances CTV has been claimed to work well (Gardner *et al.*, 1981; Clawson and Blad, 1982), but Hatfield *et al.* (1984) found it unsuitable because a reduction in plant available water of 60% was necessary before significant CTV occurred. In this study CTV was greater when ESMD's were >90 mm than when ESMD 30 mm. Berliner *et al.* (1984) and the authors found under gusty conditions sufficient variations in T_c while measuring at the same spot to cast doubt on detecting stress by taking several spot measurements at different points in a paddock. Clawson and Blad (1982) observed yield reductions of 20% with a CTV of 1.0°C. CTV of 1.0°C was observed by the authors on fully irrigated plots when IRT view direction on the same spot was different and 0.7°C when view direction the same. Clawson ad Blad (1982) also found variability of 0.7°C when viewing a crop from one direction. Variability in T_c of fully irrigated crops and the high soil moisture deficits probably necessary for significant CTV, casts doubt on CTV as a satisfactory irrigation scheduling criterion.

Canopy Temperature Difference

The difficulty of detecting moisture stress with a simple criterion at low vpd's may be overcome using CTD. In addition CTD may overcome the complications of differing non-stressed $T_c - T_a$ vs vpd base lines for different crops and the effects of increasing r_c with vpd. The CTD method uses the same crop under similar environmental conditions other than soil moisture. Over time CTD appeared more stable than $T_c - T_a$, or r_c. However, because of the time differences between T_c measurements of irrigated and unirrigated areas, and insufficient measurements over the day for enough days, constancy of CTD over time requires more attention.

The maintenance of a small well-watered control plot on a farm was suggested by Berliner *et al.* (1984) but farmers are unlikely to have the time or inclination to maintain control plots of their crops. In addition the CTD between the small control plot and a moisture stressed crop may be different from the CTD using a fully irrigated paddock with a large fetch. This may be due to the lower T_a and vpd above a fully irrigated crop on a paddock scale than above small plots. With a lower transpiration rate of the crop in a large paddock, available energy would increase T_c. Therefore using a small plot, experiencing oasis conditions, as a control may give a misleading CTD. A simple alternative to eliminate the oasis control plot difficulty, would be to use the most recently irrigated paddock as the control (allowing a couple of days for the plants to adjust if they were previously stressed (Wiegand *et al.*, 1983)), as most farms have more than one paddock of a crop where irrigation is not required, to where irrigation is or almost is required. Further work is needed to determine the CTD_c and to check on its possible variability over an irrigation season and over the day.

CONCLUSION

Remote sensing of canopy temperature can be used to differentiate between a moisture stressed and unstressed crop when the vpd is as low as 0.6 kPa and $R_n > 450$ J/m²/s, and 1.3 kPa when $R_n > 250$ J/m²/s. The difference between the canopy temperature of stressed and unstressed crops (CTD) seems to hold most promise as being suitable for scheduling irrigations of field crops. Further research is needed so that account can be taken of important crop and weather variables which influence CTD in the field.

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