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HORTICULTURE RESEARCH INTERNATIONAL

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RESEARCH AND DEVELOPMENT FOR THE HORTICULTURAL INDUSTRY

Improving irrigation scheduling using infra-red thermometry

Annual Report:	First annual project report period ending 31 Dec 1994
Project number:	FV140 (MAFF Sustainable agriculture LINK LK0410)
Project title:	Improving irrigation scheduling using infra-red thermometry
Project Location:	HRI-Wellesbourne
Project Leader:	Professor H. G. Jones
Collaborator:	Dr T. McBurney (ADAS Worcester)
Project Coordinator:	Philip Effingham
Date project started:	01 January 1994
Date completion due:	31 December 1996
Key words:	Runner beans (main crop) French beans Potatoes Irrigation scheduling Infra-red thermometry

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GROWER SUMMARY

The purpose of this project is to develop an alternative method for scheduling irrigation of a range of field vegetable crops. The existing methods are often rather imprecise for such crops, and may be improved by the inclusion of information specific to each field. Imprecise information on crop water requirement can lead to a tendency to irrigate at an 'insurance' level with the consequence that there may be significant wastage of water.

In the first year of this project all the original objectives were successfully accomplished. In addition to setting up and testing the equipment required to assess the performance and potential of infra-red thermometry for irrigation scheduling in the UK, field experiments were conducted both at Wellesbourne (on runner bean, french bean and potato) and on a grower's holding (runner beans). In addition, reanalysis of the energy balance equation demonstrated that, theoretically at least, there is scope to improve the performance of the existing infrared technology by using a model leaf (whether wet or dry) as a reference surface rather than air temperature.

The field experiments proposed for 1995 will be finalised at the next project meeting in February, but are likely to be similar in outline to the preliminary trials conducted during 1994. Following experience gained during this first year it will be possible to extend the range of measurements made on the crops to include better assessment of crop water status and to incorporate more systematically the use of reference surfaces in the IRT measurements. Among the priorities for study during 1995, the field experiments identified the following as requiring special effort:

(i) The need to develop appropriate sampling procedures that minimise short-term variation in leaf temperature

(ii) The need to ensure that appropriate reference measurements of plant water status are available against which to compare the performance of IRT or other measures of crop water status

We see no reason why the second year milestones should not be achievable on schedule.

I. AIM OF THE PROJECT AND FIRST YEAR MILESTONES

"The present project aims to develop the basic understanding of crop energy balance and its relation to crop water status to enable the IRT approach to be applied to irrigation scheduling in the UK." The specific first-year targets were:

1. Set up data collection system and software for manipulation of the large amounts of environmental data to be obtained

2. Construction and laboratory testing of possible reference surfaces

3. Preliminary reanalysis of the energy balance equations

4. Initial small scale field trials at Wellesbourne on three contrasting crops which are ideally suited for such studies (runner beans, French beans and potatoes) for preliminary evaluation of IRT techniques in the field under controlled water deficits

5. An initial test of methods for runner beans on a grower's holding will be expected. This objective was advanced from Year 2

II. SCIENTIFIC PROGRESS

II.1 General

Initial progress has already been summarised in the first six-monthly report submitted on 3 August 1994, but for completeness will be included in this report. In general good progress has been made with all aspects of the project with all milestones having been achieved in full. The main objectives of the first year were to get together the essential equipment for the project, to reassess alternative methods of applying the energy balance equation to irrigation scheduling, and to gain some experience of the experimental problems and opportunities for applying infra-red thermometry in the field in the UK. Further details in relation to each of the milestones are given below.

The first two milestones involved setting up the necessary equipment to measure and record meteorological data and sensor data, and the construction and laboratory testing of novel artificial leaves to be used as possible reference surfaces for the infra-red thermometer. These objectives were successfully achieved early in the year.

II.2 Development of reference surfaces

A range of possible reference surfaces were developed during the year. After some experimentation, a simple, yet hopefully robust design of model leaf was chosen which involved the use of an aluminium core to acheive temperature homgeneity and a reasonable degree of temporal stability. The structure of the model leaves is shown in Figure 1. In addition to the standard models, an alternative version was developed that

Figure 1

Expanded diagram of artificial leaf.

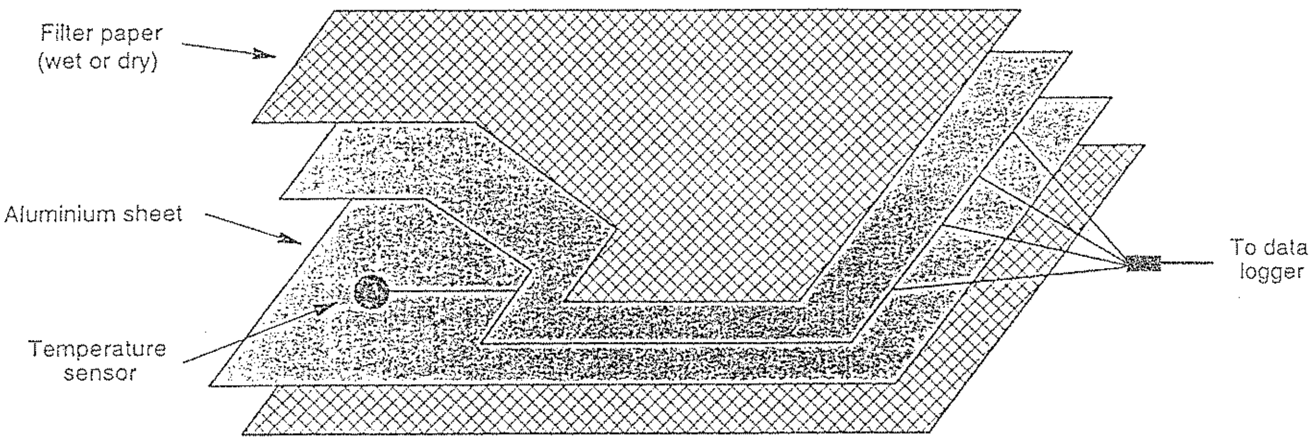
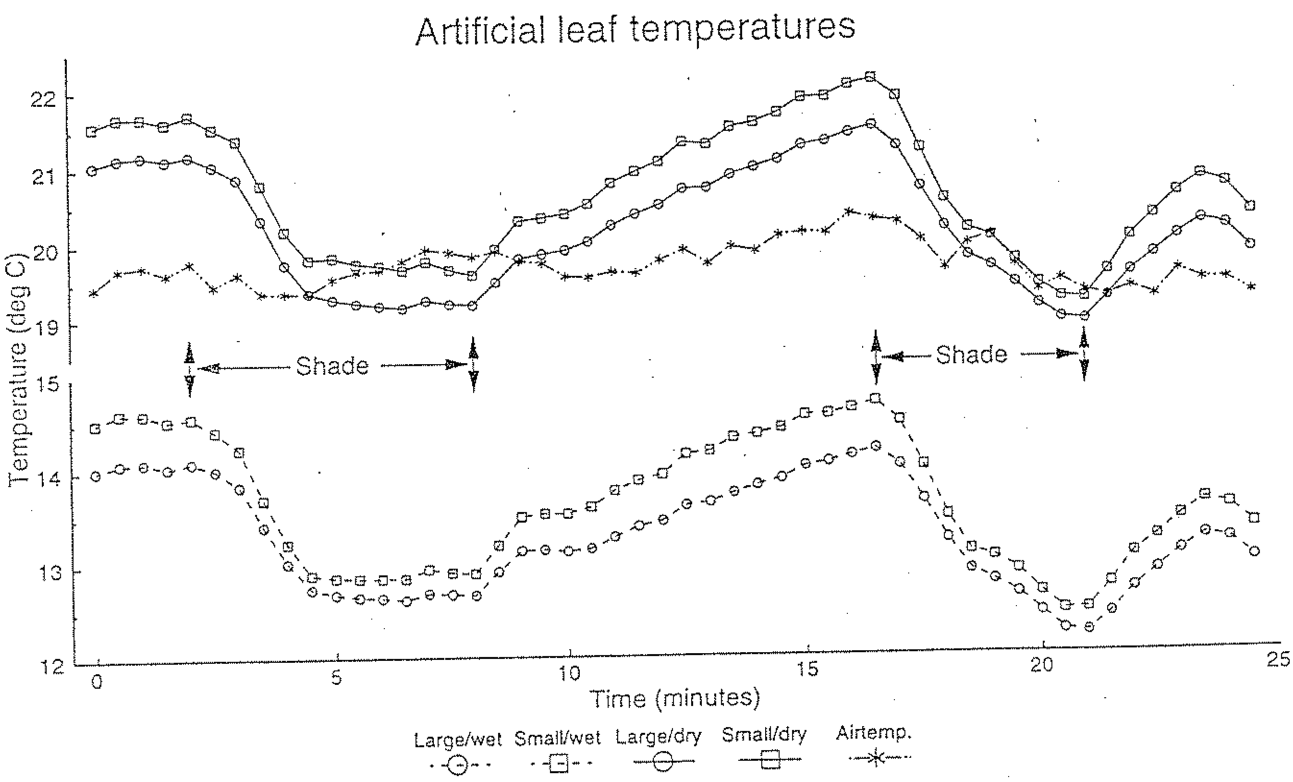


Figure 2



was covered by a microporous membrane ('Goretex') to simulate the surface conductance of a real leaf. Model leaves of different sizes were compared.

Figure 2 illustrates an example of the temperature dynamics for the artificial leaves when exposed outside to changing radiation. As expected the dry 'leaves' were consistently warmer than the wet leaves (by about seven degrees on this occasion), with a smaller, yet still consistent difference between the large and the small 'leaves'. The difference between the different sized leaves probably results from differences in their aerodynamic (or boundary layer) conductance to heat and mass transfer.

II.3 Reanalysis of the energy balance equation

The value of the leaf-to-air temperature difference (T_ℓ - T_a) was calculated as a function of leaf resistance to water vapour ($r_{\ell W}$), boundary layer resistance to water vapour (r_{aW}), net isothermal radiation (R_{ni}; the net radiation that would be received by an equivalent surface at air temperature), air water vapour pressure deficit (δe) and air temperature according to Jones (*Plants and Microclimate*, Cambridge University Press, 1992; equation 9.6):

$$T_\ell - T_a = \frac{r_{HR}(r_{aW} + r_{\ell W})\,\gamma\, R_{ni}}{\rho\, c_p\, [\gamma(r_{aW} + r_{\ell W}) + s\, r_{HR}]} - \frac{r_{aH}\,\delta e}{\gamma(r_{aW} + r_{\ell W}) + s\, r_{HR}}$$

where r_{HR} is the parallel resistance to heat and radiative transfer, γ is the psychometric constant, ρ is the density of air, c_p is the specific heat capacity of air and s is the slope of the curve relating saturation vapour pressure to temperature. The boundary layer resistance was calculated using equation 3.31 in *Plants and Microclimate.*

The behaviour of this equation was investigated using a spreadsheet (Lotus 1-2-3). Some aspects of this initial analysis have been published (H G Jones, The use of infra-red thermometry for irrigation scheduling, in *Efficiency of water use in crop systems*, eds M C Heath *et al.*, pp.247-253, AAB) and will be briefly summarised.

The theoretical sensitivity of T_ℓ to a 20% change in stomatal conductance (typical perhaps of a rather mild stress) was studied as a function of irradiance, windspeed, and air relative humidity. As expected, the magnitude of the change in leaf temperature (or the change in leaf-air temperature difference) increased with incident radiation and decreased with increasing air humidity. Typical results for a relative humidity of 50% (characteristic of a dry summer day) are shown in the Figure 3.

This figure shows that windspeed can have a very large effect on the change in leaf temperature expected for the stomatal closure that would be expected to be associated with mild stress. The typical temperature differences reaching 0.4 - 0.6°C for typical sunny conditions. This difference is well within the potential sensitivity of infra-red thermometry.

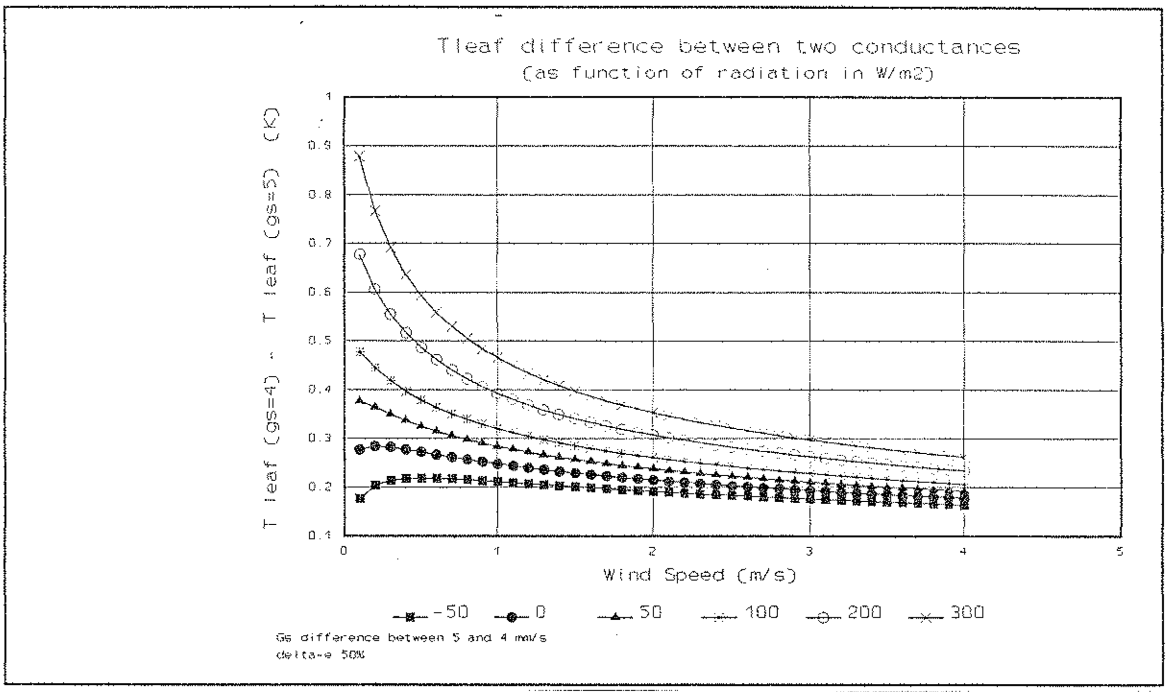


Figure 3. An example of how sensitivity of leaf temperature to stomatal conductance depends on windspeed and net radiation.

A theoretical analysis was also undertaken of the potential advantages of comparing leaf temperature, not with air temperature as is done in the calculation of the standard 'Stress Index' calculated by the 'Scheduler' software, but with either wet or dry leaf models. The results of some of these studies are summarised in Tables 1 and 2. (In these tables $T_\ell - T_a$ refers to the standard measurements with an air temperature reference, $T_\ell - T_d$ refers to the use of a dry surface as a reference, and $T_\ell - T_w$ refers to the use of a wet reference surface).

II.3.1 Conclusions from Theoretical Analysis

Although the results of the theoretical analyses are rather complex, the results do show that the use of a wet surface is the best reference for lack of sensitivity to windspeed when one is making measurements in sunny conditions. The calculations confirm that significant improvements in sensitivity of infra-red thermometry can theoretically be obtained by the use of one or other of these reference surfaces. It will now be necessary to show that this promise will be sustained in practice.

Table 1: Sensitivity of $T_\ell - T_a$, $T_\ell - T_d$, and $T_\ell - T_w$ to changes in windspeed and radiation. Figures in the body of the table refer to temperature difference between the two radiation values at the left. In this $T_\ell - T_d$ seems to be the best for low sensitivity to varying radiation (certainly very much better than $T_\ell - T_a$).

Rn change	u (m/s)	0.1	1.1	4.0
300-200	$T_\ell - T_a$	3.8	1.9	1.1
	$T_\ell - T_d$	1.8	0.4	0.2
	$T_\ell - T_w$	1.8	1.1	0.7
50- -50	$T_\ell - T_a$	4.0	1.8	1.1
	$T_\ell - T_d$	1.8	0.45	0.15
	$T_\ell - T_w$	0.7	1.1	0.7

Table 2: Sensitivity of $T_\ell - T_a$, $T_\ell - T_d$, and $T_\ell - T_w$ to changes in windspeed and radiation. Figures in the body of the table refer to temperature difference between the two windspeeds shown at the top of the column.

Radiation	du (m/s)	0.1-1	1.0-2.0	3.0-4.0
0 W/m2	$T_\ell - T_a$	1.0	0.2	0.15
	$T_\ell - T_d$	1.0	0.3	0.12
	$T_\ell - T_w$	1.5	0.35	0.15
100 W/m2	$T_\ell - T_a$	1.0	0.15	0.03
	$T_\ell - T_d$	2.3	0.48	0.15
	$T_\ell - T_w$	0.75	0.1	0.1
300 W/m2	$T_\ell - T_a$	5.1	1.0	0.3
	$T_\ell - T_d$	5.1	0.85	0.25
	$T_\ell - T_w$	0.5	0.4	0.15

II.4 Field experiment at Wellesbourne

II.4.1 Experimental details

As outlined in the six-month report a randomised field trial was established at Wellesbourne with three species (runner bean, french bean and potato) and three irrigation treatments (well irrigated, mild stress, and severe stress). A plan of the experiment is attached (Figure 4). Plants of potato and dwarf french bean were kept well irrigated by overhead sprinklers until well established and canopies had reached *c.*100% cover, and then 'dry' plots were kept unirrigated and covered during rain using mobile covers, while 'wet' plots received about 25 mm of irrigation per week, and 'intermediate' plots about 12-15 mm per week. The runner beans were irrigated by trickle tubing and rainfall was excluded by the use of under-canopy polyethylene sheet. Soil moisture was monitored using one neutron-probe access tube per plot. Treatments were imposed on 14 July.

Regular measurements were made of stomatal conductance using a porometer (type EGM-1, PP-Systems, Stotfold, Beds). Measurements were of two types: (a) records were taken three to four times per week close to midday between 9 August and 14 October on the control (irrigated) plots of runner beans, and (b) more detailed measurements were taken approximately weekly on all runner bean treatments. Additionally some measurements were obtained on the french beans and potatoes, but these began to senesce shortly after the arrival of the 'Scheduler' (see below) so were not reported in detail.

A meterological station (based on a data-logger from Delta-T Devices, Burwell, Cambs) was set-up on a 2-metre mast (Campbell) adjacent to the experimental site at Wellesbourne. This provided a continuous record of data on

(a) Solar radiation (Pyranometer sensor)
(b) Air temperature
(c) Windspeed; wind direction
(d) Air humidity
(e) Rainfall
(f) Soil temperature (at 5 cm under short grass)

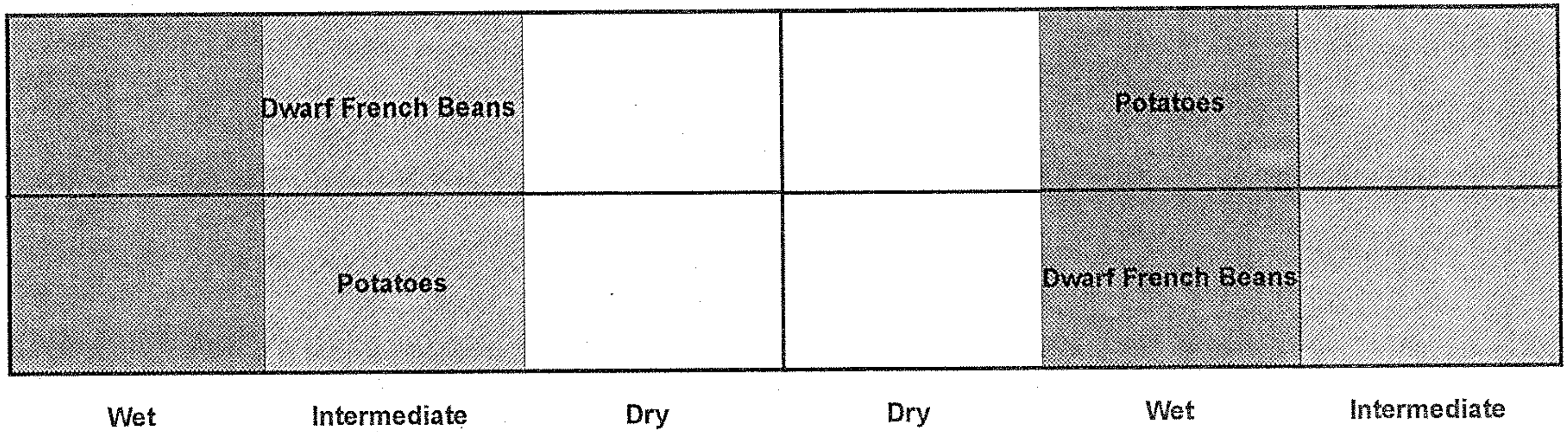
In addition, the data logger attached to the meterological mast was also used to record temperatures of the various 'model-leaf' sensors developed in the project, when they were subjected to initial field testing.

Regular weekly measurements were made between early August and mid October on the three crops using a 'Scheduler Crop Stress Monitor' supplied by Agrichandlers. The slightly late start with 'Scheduler' measurements arose because of the need to return the instrument to the manufacturers for calibration. Some additional measurements were made using a Barnes infra-red thermometer (model PRT-10).

Figure 4

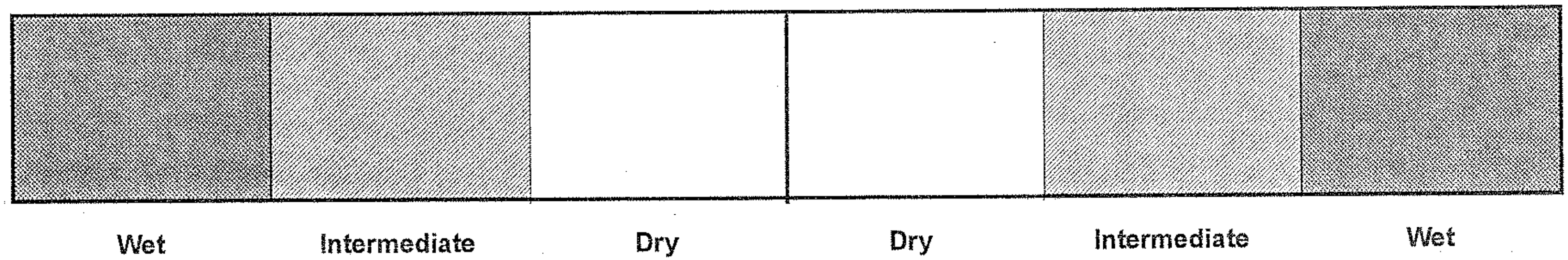
IRT project 1994; plot layout.

A. Dwarf French Beans and Potatoes



Cropped area: 3.4m x 2.5m per plot

B. Runner Beans



Cropped area: 4.0m x 3.3m per plot

II.4.2 Results of Wellesbourne Field Experiments

Figure 5 shows the changes in mean soil water content close to the surface (0.2 m), at 0.6 m and averaged over 0.6 m of the soil profile, as calculated from regular readings taken with the neutron-probe during the season. These results show that the irrigation regime imposed successfully maintained the soil water status of the 'wet' treatment close to ideal throughout the season, so that it provided a useful control for the experiment. Significant drying had occurred in both the drier treatments by 29 July, though only in the upper layers of the soil. Although the difference in soil water between the 'intermediate' and 'dry' treatments was not great and decreased in magnitude during the season, the greatest deficits were always in the 'dry' treatment.

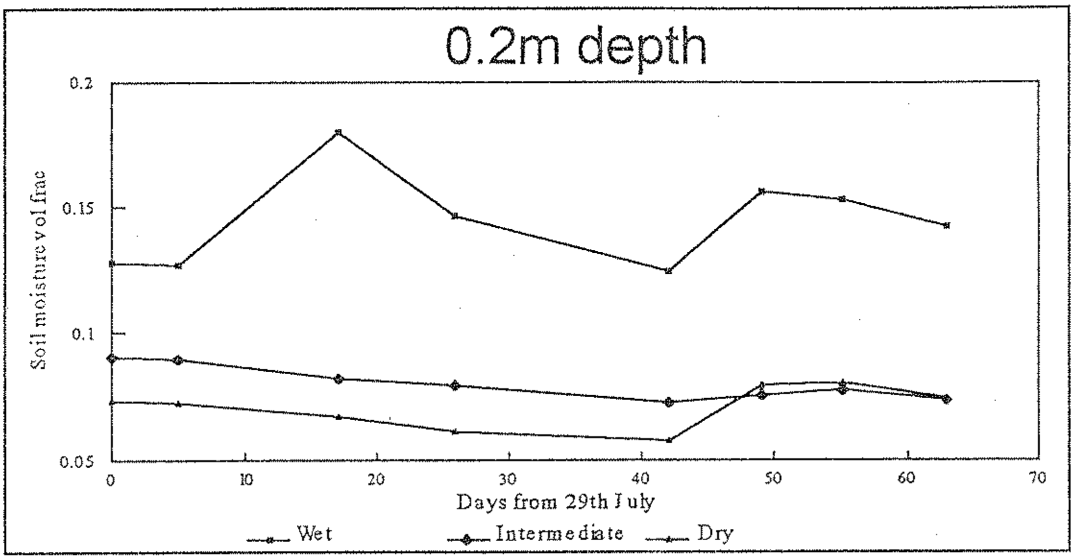
An important aspect of the first year's work was to determine the natural variation in stomatal conductance from day to day for well watered control plants as weather conditions vary. Results are shown for runner bean leaves from the 'wet' control plot both for leaves exposed to full sun (when sunny at the time of measurement) and for predominantly shaded leaves in Figure 6. It is clear that there can be large fluctuations in measured stomatal conductance from day to day as a function of weather conditions. Meteorological data (air temperature, relative humidity and solar radiation) corresponding to periods when stomatal conductance measurements were made are shown in Figure 7.

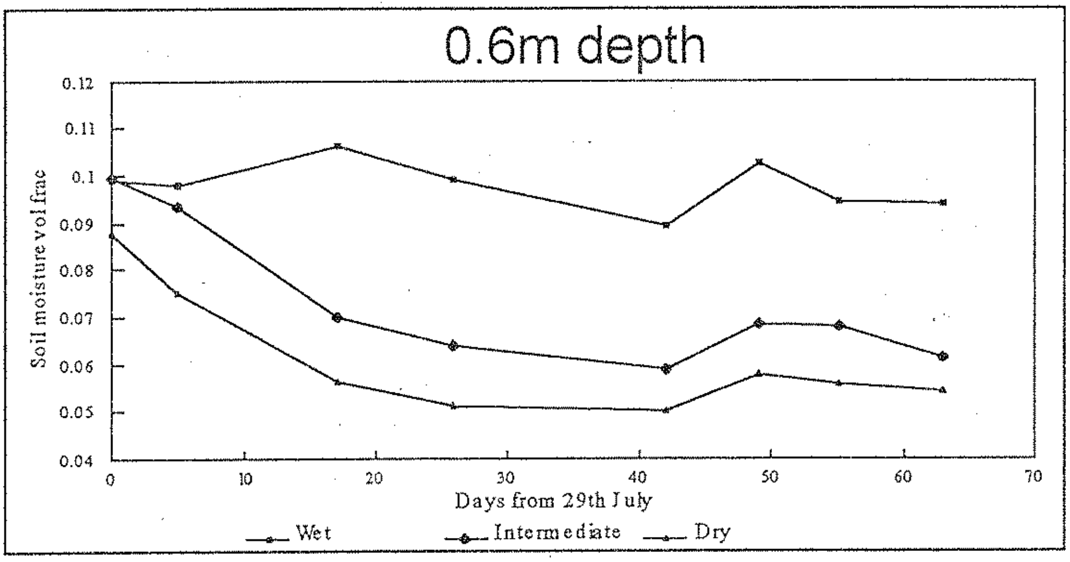
Detailed measurements were made on the runner beans using the 'Scheduler' on at least 10 occasions during the season when weather conditions were appropriate. Figure 8 shows the relationship between leaf-air temperature difference (where negative values represent high leaf temperature or 'stress') and sunshine (arbitrary units). A particularly encouraging result was that, even without applying any correction to the leaf temperature data, almost all (28 out of 32 occasions) when leaf temperatures were found to be above air temperature (negative values of Delta-T) occurred for one or other of the stress treatments, especially the 'dry' treatment. Figure 9 shows that the value of the 'Stress Index' calculated by the 'Scheduler' was, as expected, found to be very highly dependent on the actual leaf-air temperature difference (Delta-T). The data also confirmed that, as predicted from the basic energy balance, measurements made on shaded leaves, or on cloudy days were less sensitive to crop water stress than were measurements made on sunny occasions.

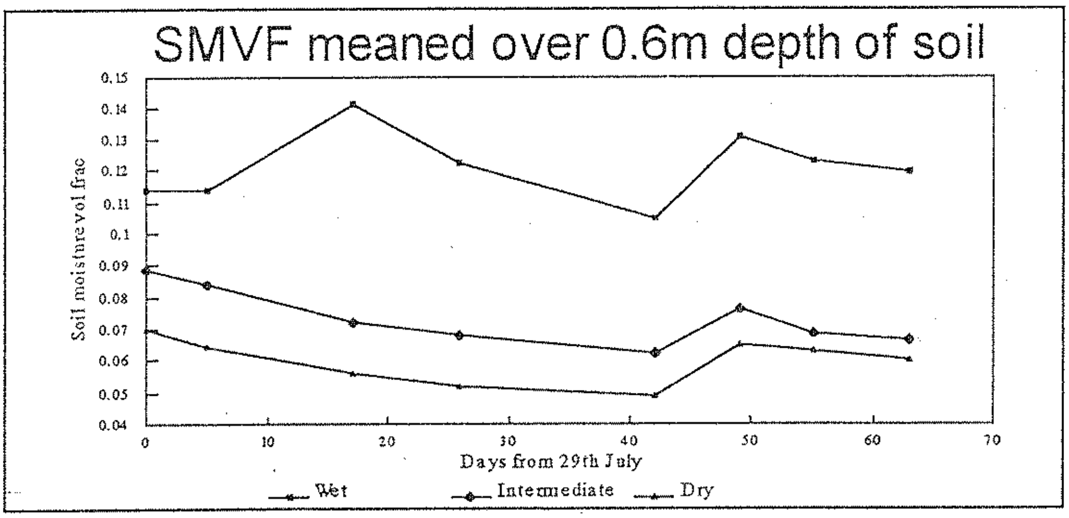
The observed values of stomatal conductance are plotted against the observed values of the calculated leaf-air temperature difference in Figure 10. Again these data are very encouraging in that even without careful selection of leaves, or correction for windspeed or radiation, there was evidence of a strong dependence on the water status of the crop.

II.4.3 Conclusions from Wellesbourne Experiments

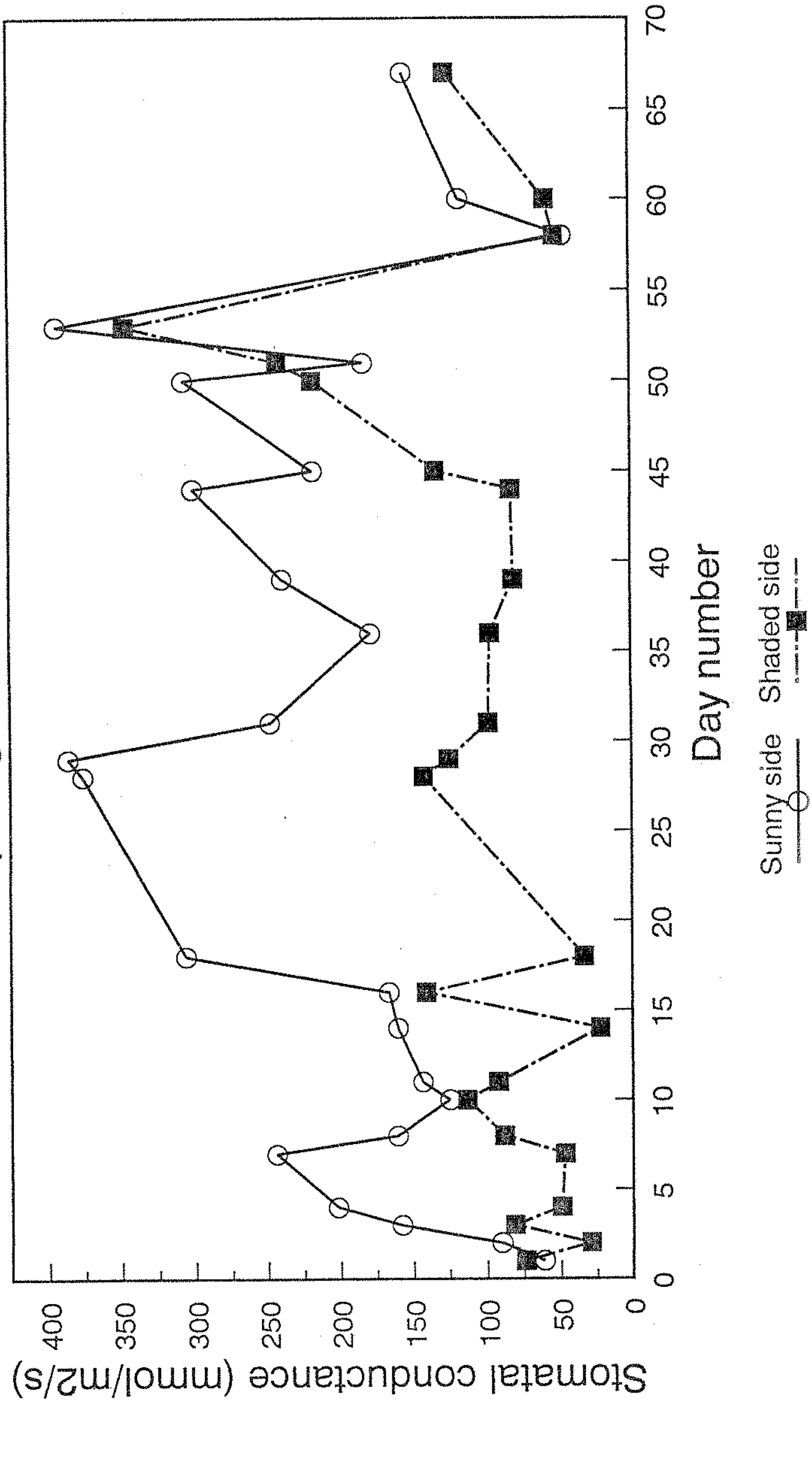
(i) Although the neutron probe gives a measure of the changes in soil water content during the season, it will be useful in future years to include also some measures of the resulting plant water status such as plant water potential, as can be obtained using a pressure chamber. This provides a basic estimate of the physiological effect of a soil water stress and provides the most widely used benchmark of crop water status. Water


0.2m depth
Soil moisture vol frac
0.2
0.15
0.1
0.05
0
10
20
30
40
50
60
70
Days from 29th July
Wet
Intermediate
Dry

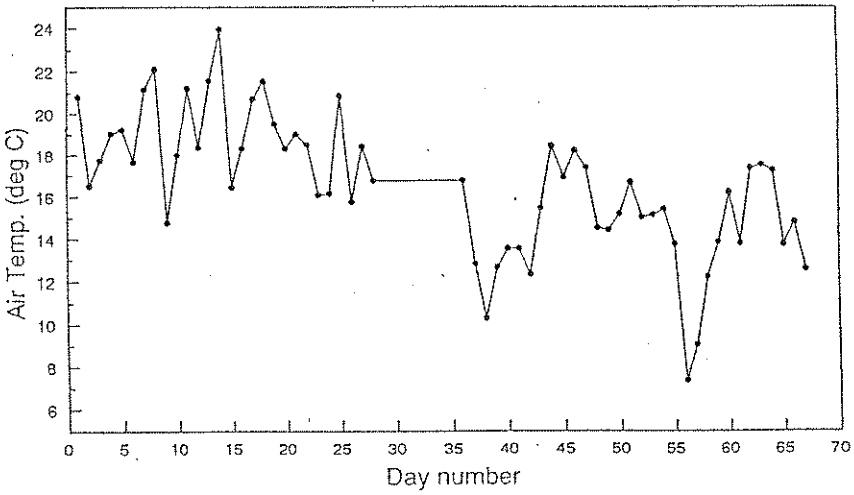

0.6m depth
Soil moisture vol frac
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0
10
20
30
40
50
60
70
Days from 29th July
Wet
Intermediate
Dry


SMVF meaned over 0.6m depth of soil
Soil moisture vol frac
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0
10
20
30
40
50
60
70
Days from 29th July
Wet
Intermediate
Dry

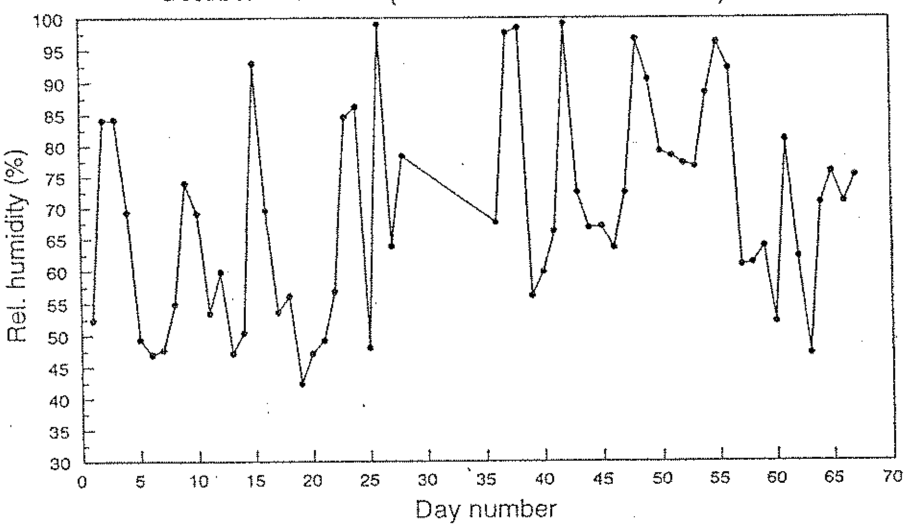
Variation in stomatal conductance for irrigated runner beans.(9 August to 14 October 1994)



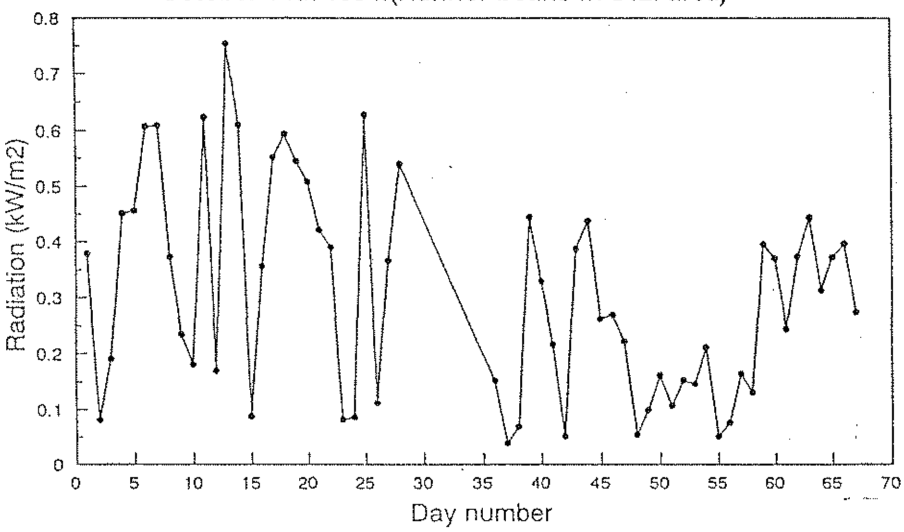
Air temperature (deg C) between August 9th and October 14th 1994.(Runner beans in D.L. area)



Relative humidity between August 9th and October 14th 1994.(Runner beans in D.L. area)



Radiation (kW/m2) between August 9th and October 14th 1994.(Runner beans in D.L. area)



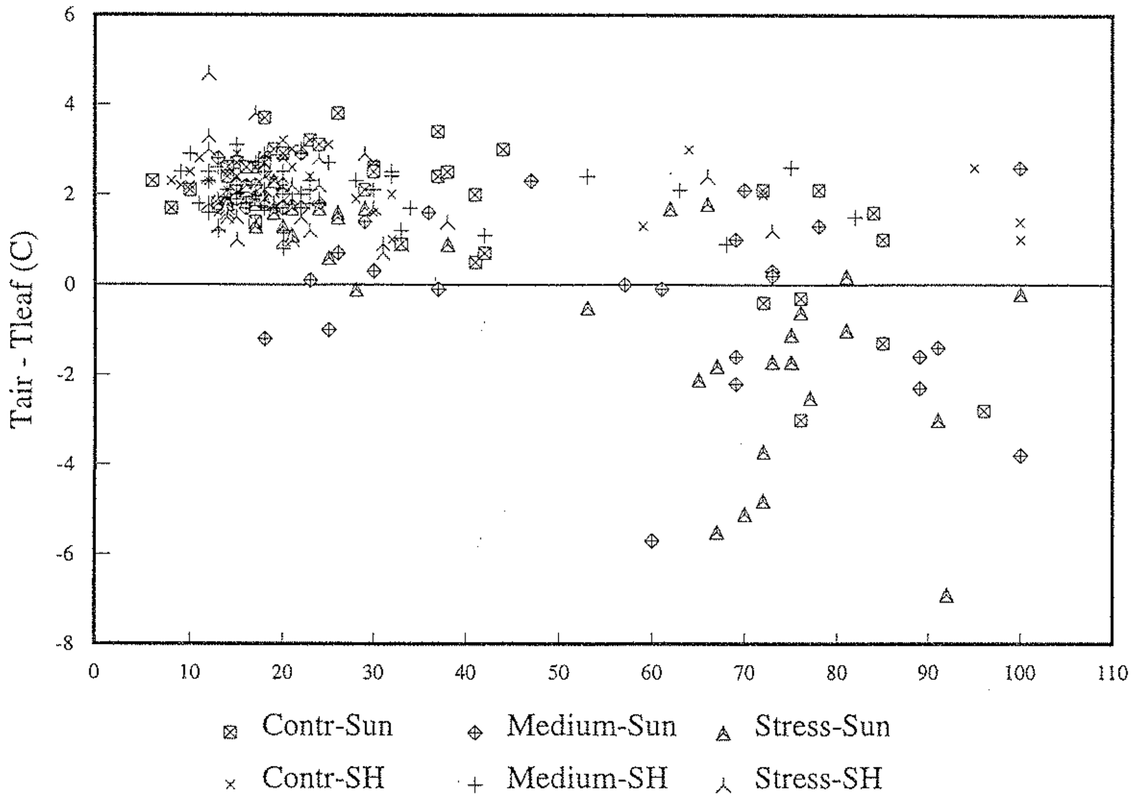


Figure 8. Dependence of leaf air temperature difference (Delta T negative values indicating leaf temperature higher) on sunshine for runner beans at Wellesbourne.

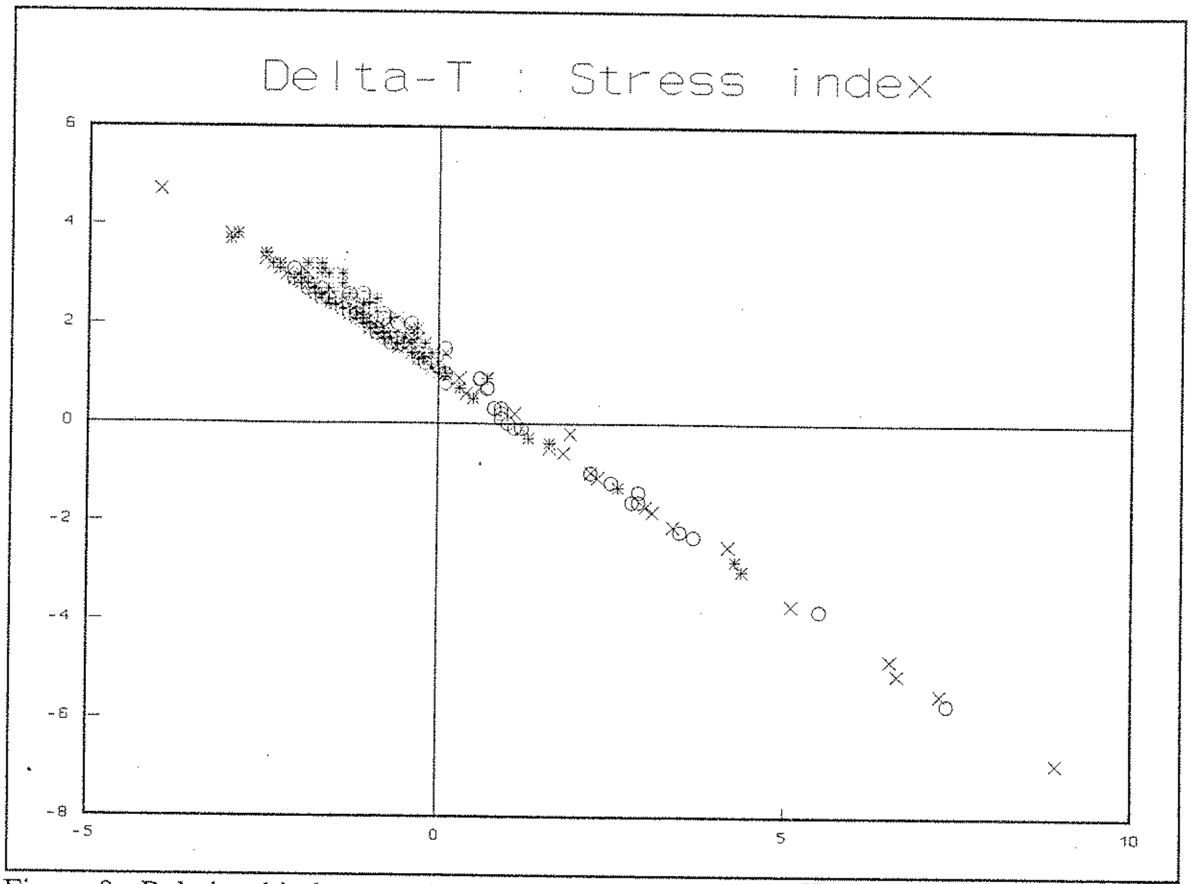


Figure 9. Relationship between leaf-air temperature difference and calculated stress index.

potentials as obtained with a pressure chamber or the psychrometer will be compared with the use of displacement transducers. The use of TDR (see below) will be evaluated as an alternative to the neutron probe for soil water measurement.

(ii) It is possible that the underlying day-to-day variation in stomatal conductance for well-watered plants may limit the sensitivity of any infra-red sensing technique unless the variation in stomatal conductance is to some extent predictable. Interestingly, even though large variation in stomatal conductance of well watered plants was observed during the course of the season, the occasions where significant stress indexes (or an excess of leaf-temperature over air-temperature) were very consistently related to the drier plots.

(iii) It is proposed during the winter to analyse (probably using multiple regression techniques) the dependence of observed stomatal conductance in the well-irrigated plants on weather conditions at the time of measurement so as to determine whether it will be possible to develop a correction technique that would eliminate this variability as a possible cause of lack of sensitivity of the IRT technique for irrigation scheduling.

(iv) The fact that a useful relationship between stomatal conductance and leaf-air temperature difference was observed is particularly encouraging for future application of IRT, as it confirms the validity of the underlying assumptions.

II.5 Field experiment at Top Barn Farm

II.5.1 Aims

The aim of this preliminary trial was to develop procedures for testing IRT in a commercial situation. An experiment was set up with three replicates of irrigated and unirrigated plots in an irrigated runner bean field at Top Barn Farm, Holt Heath, Worcs WR6 6NH with the kind permission of Mr David Harper. The specific objectives of this first trial included:

i) Monitoring moisture in the soil profile
ii) Testing independent measures of water status in the plant canopy
iii) Establishing irrigated and unirrigated plots
iv) Assessing simple yield/quality indicators

II.5.2 Experimental details

Four replicate areas in the plot were established where the standard trickle irrigation system was bypassed to prevent irrigation, and neutron probe access tubes installed. Unfortunately delays in getting regulatory approval for use of the neutron probe off the Wellesbourne site resulted in treatments being imposed rather late in the season, by which time the heavy rain in August and September limited soil drying.

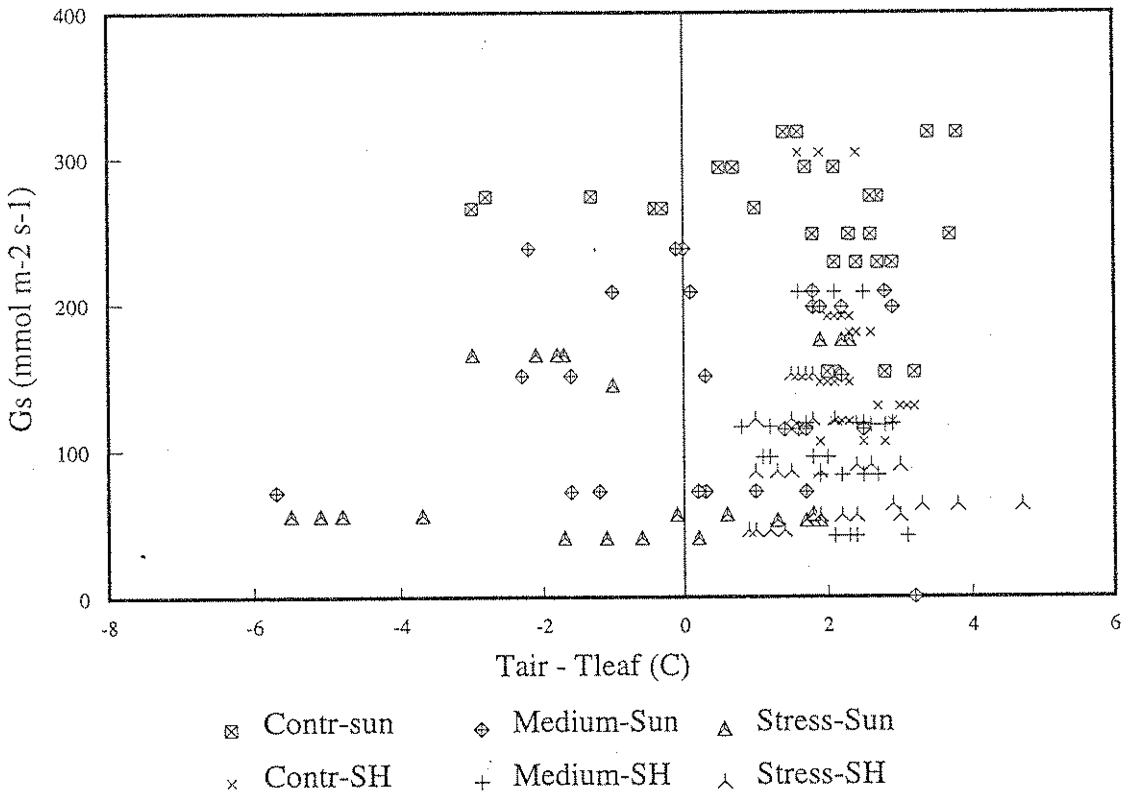
II.5.3 Top Barn Farm Results and Proposals for 1995

(i) Installation of access tubes and weekly monitoring of soil moisture to 1 m depth at sixteen points was found to be feasible but time consuming; in addition meeting the necessary safety precautions was also restrictive. An alternative method using 'time domain reflectometry' (TDR) has recently been acquired and will be tested in 1995. A range of probes up to 1 m length, and a tool for inserting them, have been constructed. Initial testing will compare TDR and eight neutron probe access tubes during early spring 1995 at ADAS Gleadthorpe in plots of overwintered oilseed rape growing under mobile shelters to impose a wide range of soil moisture treatments.

(ii) Effective evaluation of IRT requires independent techniques for measuring plant water status; IRT measurements will be compared with plant water potentials (as measured either with a pressure chamber or with a dewpoint psychrometer system which has been obtained for another project). In addition ten displacement transducers for monitoring stem or leaf thickness have been assembled to provide an alternative indirect measure of water status. Initial tests showed that the spring mechanism of these prototypes was too strong, tending to compress the plant tissue making interpretation difficult. This problem has been reduced by spreading the load of a larger area of tissue with a modified probe tip.

Preliminary IRT tests in the experimental field showed that variation in leaf temperature could in extreme cases fluctuate by as much as 10°C over a ten minute period when

Figure 10 Graph of Gs : Delta-T



incident radiation and atmospheric humidity were nearly constant (Figure 11); in other cases, however, where special care was taken in sampling comparable leaves, the magnitude of such short-term variation could be much reduced. The fluctuations in leaf temperature could be largely attributed to gusts of wind and the temperature variations were found to be smaller for the upper leaves in the canopy. During 1995 particular efforts will be devoted to developing sampling procedures for IRT measurements that minimise such environmental effects and to ensure that compensation using artificial leaves is as effective as possible (possibly by having the artificial leaves as close to the real leaf as possible).

(iii) As a result of the late imposition of irrigation treatments and the wet August and September, soil drying was limited in 1994, and adequate assessment of methods for detecting plant stress therefore not feasible. It is proposed that some form of plastic ground cover will need to be incorporated in the treatments in 1995. Even though this may interfere with normal crop husbandry, it will be a useful experimental tool to ensure that suitable treatment differences are obtained for evaluation of IRT, though it will be necessary to recognise that the plastic covers may modify the local microclimate.

(iv) Yield and quality indicators. Measurement of extension growth in individual bean pods is often a useful indicator of yield which can be monitored continuously in the field. In practice, however, it proved difficult to relocate tagged pods which presumably had been lost as a result of damage by pickers or possibly through natural pod drop. As it is not feasible within the constraints of this project to monitor yields of experimental plots directly, a different tagging system will be tried in 1995 with clearer labelling and instructions to commercial pickers to try to prevent inadvertent damage to the tagged pods.

Foliar disease due to *Uromyces fabae* (bean rust) is common in runner beans and is often extensive in late season eventually causing brown discolouration of virtually every leaf on the plant; this was the case for the 1994 crop. There is no chemical treatment available. The overcast conditions towards the end of the season precluded investigation of the possible effect of bean rust on IRT readings, but it will need to be considered in the future.

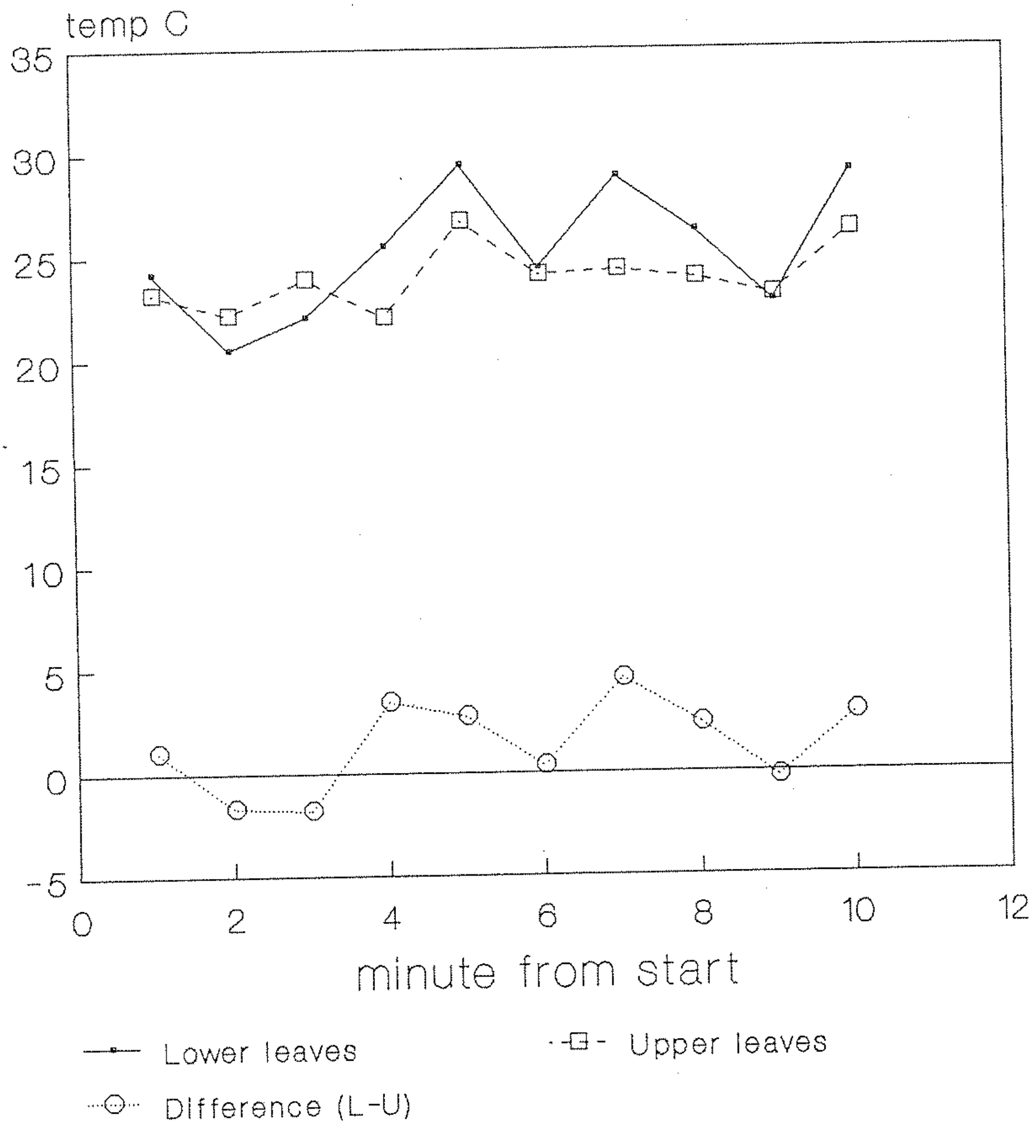
III. PUBLICATIONS

i) The work was presented at the launch of the Sustainable Farming Systems LINK at Boxworth on 24 June. The poster for this event was also presented at the AAB meeting, Reading, 6-8 July.

ii) Press articles have appeared in

New Scientist (2 July 1994)
Coventry Evening Telegraph (4 July 1994)
Stratford Journal (21 July 1994)

short-term variations in R.bean leaf temperature under a cloudless sky



iii) A spoken presentation was made at the AAB Meeting, Reading 6-8 July, 1994. The published paper relating to this talk was

H G Jones 1994. Use of infra-red thermometry for irrigation scheduling. In *Aspects of Applied Biology,* **38**, 1994 *Efficiency of water use in crop systems.*

iv) A *Grower* Article has been prepared and submitted to *The Grower*.

IV. ACKNOWLEDGEMENTS

In addition to the funding from HDC (FV140) and from MAFF through the LINK scheme on 'Technologies for sustainable farming systems', we are indebted to support from Graham Amos (Agrichandlers), and from Mr David Harper, Top Barn Farm, Holt Heath, Worcs WR6 6NH for providing a commercial crop of runner beans on his farm.