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Improving irrigation scheduling using infra-red thermometry

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Final Confidential Report to Sponsors

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1. PRACTICAL SECTION FOR GROWERS

Application

With the increasing uncertainty of water supplies for horticultural crops and the increasing costs of storage required to secure supply during the summer, there is a need to develop new approaches that optimise the use of water for crops and that can help avoid wastage. The purpose of this project was to improve the precision in UK conditions of the infra-red thermometry (IRT) technique beyond what is provided by a commercially available instrument, the 'Scheduler'. The new approach developed should provide an alternative and cost-effective method for scheduling irrigation of a range of field vegetable crops, and one that can either complement or replace existing approaches based on soil moisture measurement or calculation. The improved sensitivity of the IRT approach was based on a new understanding of the crop energy balance and its relation to crop water status.

Main results and conclusions

1. Water stress effects on canopy temperature. Extensive data confirmed that water stress leads to significant elevation of canopy temperature, and that such temperature increases could be readily detected using infra-red thermometry. Canopy temperature differences between well irrigated and stressed crops could be as great as 10^{o}C, though differences were more usually in the 1.5-4^{o}C range. The changes in canopy temperature were very sensitive to irrigation, with differences being detected within 24 h of cessation of irrigation in runner bean. Although it is recognised that 1995 was an unusually hot and dry year, similar data were also obtained in 1994 and 1996 which confirmed that infra-red thermometry (IRT) holds great promise for detecting plant stress even in UK conditions, especially when the technology is modified to increase the sensitivity above that provided in current commercial equipment.

2. Theoretical analysis. Theoretical analysis of leaf energy balance equations led to the development of a new crop stress index which was shown to have greater theoretical sensitivity than the commercially available stress index calculated by the 'Scheduler'. This should lead to the possibility of new approaches to the more precise control of irrigation in horticultural crops. More recently the analysis has been taken further to derive a theoretical approach for directly estimating stomatal conductance (the underlying measure of stress detected by IRT). The full impact of this latter advance was not evaluated in the present project due to the unavailability of instrumentation for estimating canopy boundary layer resistance, but it appears to hold real promise for the future.

3. Evaluation of new stress index. Experimental evaluation of the performance of different stress indexes in the field showed that the new stress index, which is based on comparing crop temperature (as measured with the IRT) with the temperatures of wet and dry reference surfaces, was significantly more sensitive and more reliable than existing IRT approaches at detecting crop water stress in runner bean crops under the rather variable and unfavourable weather conditions in the UK. The reference surface temperatures can be obtained using either physical leaf models or real leaves which can be either wetted or covered with petroleum jelly.

4. *Development of new sensing equipment.* The equipment currently commercially available for IRT measurements is not designed for use with the new technique, so its successful implementation will require the development and construction of new, purpose-built equipment and further testing and development work to develop robust protocols for its use in irrigation scheduling. Work on the development of reference surfaces has identified a candidate material for their construction. Initial design criteria for the necessary equipment have been drawn up on the basis of the extensive experience of the use of IRT in runner bean crops. All these steps are necessary before the new approaches can recommended for wide use in commercial practice. An instrument manufacturer has expressed strong interest in taking out a licence for further development of the ideas arising from this project and negotiations are presently in progress.

5. *Applicability to different crops.* In addition to the extensive IRT data obtained for runner beans at Wellesbourne and on a grower's holding (Top Barn Farm, Holt Heath); other data were obtained on potato and French bean crops at Wellesbourne. The more limited results for potato and French beans showed that their general behaviour was similar to that of runner beans and indicated that infra-red thermometry is likely to be equally applicable to these crops, though a measure of crop-specific calibration will be necessary. It should also be noted that because of the more continuous nature of the canopies of potatoes and French beans it may be more appropriate to use an IRT sensor to measure the temperature of significant areas of canopy, rather than the single leaves that were used for the runner beans in this work. A consequence of this is that there may need to be some modification to the model leaves for these other crops to allow for the aerodynamic differences between single leaves and whole crop canopies.

6. *Alternative measures of crop stress with potential for irrigation scheduling.* In the course of the three year project a number of alternative measures of crop water stress were evaluated, partly as a basis against which the IRT stress indexes could be compared. These included two well established research techniques for studying plant water stress: plant water potential as measured with a pressure chamber, and stomatal conductance as measured using a porometer. Although at the outset it was felt that these two techniques were probably too research-orientated to be of use for commercial irrigation scheduling purposes, it became apparent in the course of the project that the porometer was no more difficult to use than the 'Scheduler'; indeed reliable results could be obtained after minimal instruction in its use. The close relationship of porometer results to soil moisture content supports the concept that direct or indirect measures of stomatal conductance (including IRT) can be good and sensitive indicators of irrigation need, and that all methods for estimating stomatal conductance merit further effort. We therefore feel that there is good potential for further development of the use of stomatal conductance in irrigation scheduling. Other alternative measures of crop water stress that were briefly investigated included the use of stem and pod thickness sensors which were also shown to respond sensitively to irrigation differences and which could be useful in certain cropping situations.

7. *Specific application of infra-red thermometry in irrigation scheduling.*

An important feature of infra-red thermometry-based stress sensing techniques is that they are primarily appropriate for detecting plant stress; they do not give a direct estimate of the *amount* of water that is required at any time. Their primary use, and one where the portability and flexibility of the system is a particular advantage, is as an indicator of local variation around a farm where there is inadequate coverage of neutron probe access tubes. In addition they are particularly suited for local calibration of calculation approaches to irrigation scheduling, such as IRRIGUIDE. They are also well adapted to precision irrigation systems, including trickle, where the amount or frequency can be adjusted rapidly in response to changes in the stress index.

Summary of achievements and milestones

Year 1: All the original objectives for 1994 were successfully accomplished. In addition to the necessary development, setting up and testing of the equipment required to assess the performance and potential of infra-red thermometry for irrigation scheduling in the UK, preliminary field experiments were conducted both at Wellesbourne (on runner bean, french bean and potato) and on a grower's holding (runner beans). In addition, detailed 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 using air temperature as the reference as in the current commercial system.

Year 2: Again all project milestones agreed with the LINK consortium (including MAFF) after the annual review meeting were achieved. Extensive data were made during 1995 on potato, French bean and runner bean crops given a range of irrigation treatments (with an emphasis on runner bean at both Wellesbourne and Top Barn Farm). Routine measurements of soil moisture status and environmental conditions were obtained and in addition on a number of occasions detailed tests or comparisons were made of IRT sensing approaches. Limited data were obtained for potato and French bean crops at Wellesbourne. The fact that 1995 was an unusually hot and dry year was probably a factor in the very promising data obtained this year, though good results were obtained on less extreme occasions during the year.

Year 3: On the basis of the previous work further irrigation trials were established at Wellesbourne (runner beans and also French beans under mobile drought shelters) and at Top Barn Farm. Measurements on these experiments confirmed the previous results indicating the potential of the new approach. Unfortunately difficulties in concluding a satisfactory licensing agreement with the company interested in developing a commercial instrument, meant that it was not possible to test a pre-prototype during the final year, and we therefore had to rely on existing equipment which does not permit effective simulation of a commercial protocol. Some of the ADAS work, therefore, was reoriented towards identifying an appropriate material for construction of reference surfaces.

2. SCIENCE SECTION

2.1. INTRODUCTION

With the increasing uncertainty of water supplies for horticultural crops and the increasing costs of storage required to secure supply during the summer, there has been an increasing need to develop practical approaches for optimising the use of water by crops. The use of plant-based stress-sensing holds particular promise in comparison with the main techniques currently used. Presently used techniques include:

(i) direct soil moisture measurement using instruments such as neutron probe, time-domain reflectometry (TDR), or other electronic devices such as EnviroSCAN. These can be expensive to install and monitor an adequate number of sites on each farm.

(ii) calculation of soil moisture deficits (e.g. by the IRRIGUIDE service provided by ADAS). This technique can become increasingly inaccurate during the season as a result of local soil and crop deviation from the standard assumptions (e.g. of soil depth or crop cover) and for accurate application crop-specific calibration (for example with a neutron probe) is required.

A method based on sensing crop temperatures with an infra-red thermometer (IRT) had previously been proposed in the USA (Idso *et al.*, 1981; Jackson *et al.*, 1981) and equipment is now marketed commercially (the 'Scheduler', whose UK Agents are Agrichandlers Ltd.). Unfortunately in its present form it has limited applicability in the UK where humidity tends to be rather high and radiation and windspeed are variable, thus restricting the number of occasions on which reliable measurements can be made.

2.2. OBJECTIVES

The project therefore aimed to advance our 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 objectives were:

a) to identify the limitations to operating performance of leaf and canopy temperature sensing techniques in practice in the UK

b) on the basis of an analysis of the leaf energy balance equation to develop an improved method for normalising leaf temperatures in calculation of a Crop Water Stress Index (CWSI; later abbreviated to SI)

c) to develop a simple a reference surface for use with hand-held IRTs that improves the precision of the calculated SI, and which can be routinely used by growers

d) to modify the procedures for using IRT instruments in order to improve their operating performance in UK conditions

e) to compare IRT with other methods for scheduling irrigation and to evaluate benefits in the first instance for related field vegetables.

2.3. MATERIALS AND METHODS

The approach involved both theoretical analysis of the energy-balance equation, and experimental testing in the laboratory and in the field.

2.3.1 Equipment:

(a) Infra-red thermometry

Regular measurements were made on field crops with a 'Scheduler Crop Stress Monitor' supplied by Agrichandlers Ltd.. Except in 1994 measurements were made between late June and mid-October. Some additional measurements were made using a Barnes infra-red thermometer (model PRT-10). During the final year, as a first step towards developing a commercial instrument, two alternative low cost IRTs were evaluated. The first was an Agema (Thermopoint 20-50), the second was supplied by Protimeter Ltd.. Some of the ADAS measurements were made using an AGA Thermopoint 80 infra-red thermometer.

(b) Stomatal conductance:

The fundamental basis of the IRT method is that it estimates stomatal closure; this is commonly expressed in terms of *stomatal conductance*. Therefore regular measurements of stomatal conductance were made throughout the three years using a porometer (type EGM-1, PP-Systems, Stotfold, Beds) as a basis against which the IRT measurements could be compared.

(c) Soil moisture

During 1994 and 1995, soil moisture was measured directly using neutron probe access tubes installed in all experimental plots. In addition selected comparisons were made using time-domain reflectometry (TDR). In 1996 the main measurements were made with theta-probes (Delta-T Devices, Burwell, Cambs), with limited comparisons with neutron probe to check the performance of the theta-probes. All soil moisture monitoring at Top Barn Farm was based on neutron probe measurement.

(d) Meteorological data

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

(i) Solar radiation (Pyranometer sensor)
(ii) Air temperature
(iii) Windspeed; wind direction
(iv) Air humidity
(v) Rainfall
(vi) Soil temperature (at 5 cm under short grass)

The data logger was also used to record temperatures of the various 'model-leaf' sensors developed in the project, and to monitor the Theta probes during 1996.

(e) Other measurements

Leaf and model temperatures were also recorded using fine-wire copper-constantan thermocouples. Details of construction and testing of alternative materials for reference surfaces are presented in Section 2.4.2.1.

2.3.2. Field Experiments:

(a) Wellesbourne

The site (in Sheep Pens) at HRI, Wellesbourne is dominantly a slightly stony light loam overlying a calcareous gravel above a Mercia Mudstone formation (Beard, 1995).

In each year the main experiment was a randomised field trial with two or three (1996) replicates of runner bean with three levels of irrigation (well irrigated, mild stress and severe stress). Plants were trained up wig-wams at commercial spacing as used at Top Barn Farm. The runner beans were irrigated by seep hose and rainfall was largely excluded by the use of under-canopy polyethylene sheet. Soil moisture was monitored using one neutron-probe access tube per plot, in addition, in 1996 soil moisture was also monitored using theta-probe soil sensors. During 1996 once the treatment differences had been allowed to develop, irrigation treatments were modified to allow investigation of the effects on stomatal behaviour and crop stress indexes of stress development at different times during the season.

In order to gain some preliminary indication of the suitability of IRT for other crops, replicate plots of French bean (1994, 1995 and 1996) and potato (1994 and 1995) were also established at each of three irrigation levels: well irrigated (or 'wet'), mild stress (or 'intermediate'), and severe stress or 'dry'). Crops were kept well irrigated by overhead sprinklers until well established and canopies had reached *c.*100% cover. Differential treatments were then imposed by varying the amount and frequency of irrigation applied using seep hose providing 1.25 litres of water per minute per metre. In 1995 and 1996 all treatments were protected from rainfall using automatic mobile rain shelters. Throughout the season, 'Wet' treatments were given one or two hours irrigation weekly, with the 'Intermediate' treatments being irrigated approximately fortnightly.

(b) Top Barn Farm

Experiments were also conducted each year on a commercial runner bean crop with the kind permission of Mr David Harper at Top Barn Farm, Holt Heath, Worcs WR6 6NH.

In 1994 and 1995 four replicate 10-metre plots were established where the standard trickle irrigation system was bypassed to prevent irrigation, and neutron probe access tubes installed. Unfortunately in 1994, 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. In 1995 water stress treatments were imposed from 24 May onwards. Irrigation decisions were made by the farmer initially on the basis of measurements of soil moisture at three sites in the crop using a commercial neutron probe service. From 27 June the amounts of rain were insignificant and air temperatures generally exceeded normal maxima so that for most of this period irrigation was applied at a rate limited by the supply system which meant that it was simply applied on alternate days. In 1996 there were four replicate plots of each of four irrigation treatments (Full irrigation - determined by the neutron probe monitoring service; 2/3rds irrigation; 1/3rd irrigation and Zero irrigation).

(c) 'Scheduler' measurements and sampling

A great deal of experience was obtained on infra-red measurement of leaf and canopy temperature during the course of the study. The majority of IRT data were obtained using the 'Scheduler', though measurements with other instruments (e.g. Barnes, Agema and Protimeter) were also useful in guiding the design of future stress sensing system. The measurements in 1994 were primarily aimed at getting experience with the system, and at identifying the causes of variability.

In addition to the large number of occasions when specific aspects of the sampling procedure, or the dynamics of the responses of real and model leaves, were tested, more or less standard measurements were routinely collected in each year with 'Scheduler' and porometer data being obtained at similar times. In 1994 such standard measurements were made on 10 occasions in August and September, with data on stomatal conductances being obtained on 28 occasions. In 1995 the standard measurements were obtained on 21 occasions between 28 June and 31 October at Wellesbourne and on 5 occasions at Top Barn Farm; porometer data were available for nearly all occasions. Full data sets were obtained on 24 occasions in 1996. Corresponding meteorological data were also recorded.

2.4 RESULTS

2.4.1 Theoretical developments:

The use of infra-red thermometry for irrigation scheduling depends on the observation that crop canopy temperature in crops subject to water deficit tends to be higher than the canopy temperature of a comparable well-watered crop. This difference in canopy temperature arises because of the reduced transpirational cooling that occurs as stomata close in response to water deficits. Idso and his colleagues (Idso *et al.* 1981; Reginato *et al.* 1981) proposed the use of an index called a Crop Water Stress Index (CWSI) for irrigation scheduling. This was defined as

$$\text{CWSI} \quad = \quad (T_{\text{crop}} - T_{\text{non-water-stressed}})/(T_{\text{max}} - T_{\text{non-water-stressed}}) \qquad (1)$$

where the crop canopy temperature (T_{crop}) at a given atmospheric humidity is related to the temperature of a non-transpiring surface (T_{max}) and to the canopy temperature of a well-watered crop ($T_{\text{non-water-stressed}}$). The value of CWSI should vary between 0 for well irrigated crops and 1 for severely stressed crops (the output of the 'Scheduler' actually adjusts this to a scale of 0 to 10, with negative values occurring if the crop temperature falls below the non-water-stressed baseline temperature). The 'Scheduler' comes with various so-called 'non-water-stressed baselines' ready programmed in for a range of different crops; in this work the non-water-stressed baseline for grape vine was used for the runner bean measurements. Unfortunately the calculated stress index does not take account of all the environmental factors (especially windspeed and incident radiation) that can affect leaf temperature; these factors are particularly important at the relatively high atmospheric humidities that are frequent in the UK and their absence from the calculations can lead to marked errors in estimates of CWSI.

The important theoretical developments from this project are outlined in the confidential annex (section 5). In summary, the early work investigated the use of *either* wet or dry model leaves (rather than air temperature which is used in the calculation of the CWSI) as a reference, and the potential errors analysed in a range of environmental conditions. The detailed results of these analyses were presented in the first annual report, where it was pointed out that the choice of either wet or dry leaves as a reference could significantly reduce the environmental sensitivity of the stress index calculated as compared with the original CWSI (=SI(1)). Further analysis of the energy balance equation, however, led to the discovery that even greater improvements could potentially be made by the use of a stress index (SI(2)) that was a function of the temperatures of the leaf, a wet reference surface, and a dry reference surface. Therefore subsequent work in the project concentrated on this second stress index.

The theoretical analyses also derived a further index (SI(3)) that could be used directly to estimate stomatal conductance of the crop, if accurate estimates of the crop boundary layer resistance are available. Unfortunately, this last index, though potentially even better than SI(2), was derived too late on in the project to allow us to test its value in practice as no boundary-layer resistance meter was available to the project. (In other previous unpublished work a possible design of such an instrument has been proposed but not yet fully tested, H G Jones, unpublished data).

2.4.2. Equipment development and testing

2.4.2.1 Development of reference surfaces:

(a) Estimation of time constants of the different model leaves in comparison with real leaves.

The basis of the method proposed involves the use of wet and dry 'model' leaves exposed to the same environment as the real leaves. The original concept had been to use model leaves which had a substantial time-constant for response to changing environmental conditions (i.e. react slowly to environmental change) on the basis that as the environment is constantly changing it would be best to have a fairly stable reference, which would *on average* be appropriate when making a large number of readings over a short time period (as is feasible with the IRT).

On this basis the initial model leaves developed and used in the first two years had an aluminium core to provide substantial thermal inertia. By analysis of the dynamics of temperature changes when incident radiation was changed it was possible to show that these models had time-constants in the field of between 1 and 2 minutes (which compares with the corresponding time-constants for real leaves of around 10 seconds). Typical dynamics of two such heavy model leaves are compared with temperature dynamics of real runner bean leaves in Figure 1a. During the course of the study, however, the true rate and magnitude of variation in leaf temperature in the field became apparent, and it became clear that the lag and the damping of extreme values shown by the slowly responding models could be a source of significant error leading to increased scatter in calculated stress indexes, especially where the environmental conditions were changing rapidly with time.

Therefore efforts were made to produce a more rapidly responding model. The second design omitted the aluminium core and was made significantly smaller to reduce the boundary layer resistance. The temperature dynamics of this leaf are compared with real runner bean leaves in Figure 1b. Though better, with more rapid responses with a greater amplitude, this new model still has a time constant approaching 1 minute; therefore a priority for further technical development remains the development of an improved rapidly-responding design. Further reductions in the time-constant can be achieved by further reducing the size of the model, and more importantly by using thinner and lighter materials, especially for the evaporating surface.

Because of the difficulty of getting a model leaf to mimic accurately the dynamics of real leaves, work in the final year concentrated on the use of actual leaves from the crop canopy treated either so that they did not transpire (by covering them in petroleum jelly) or so that they behaved as a wet surface (by spraying them with water containing a wetting agent). In all cases models and 'wet' or 'dry' real leaves were exposed similarly in

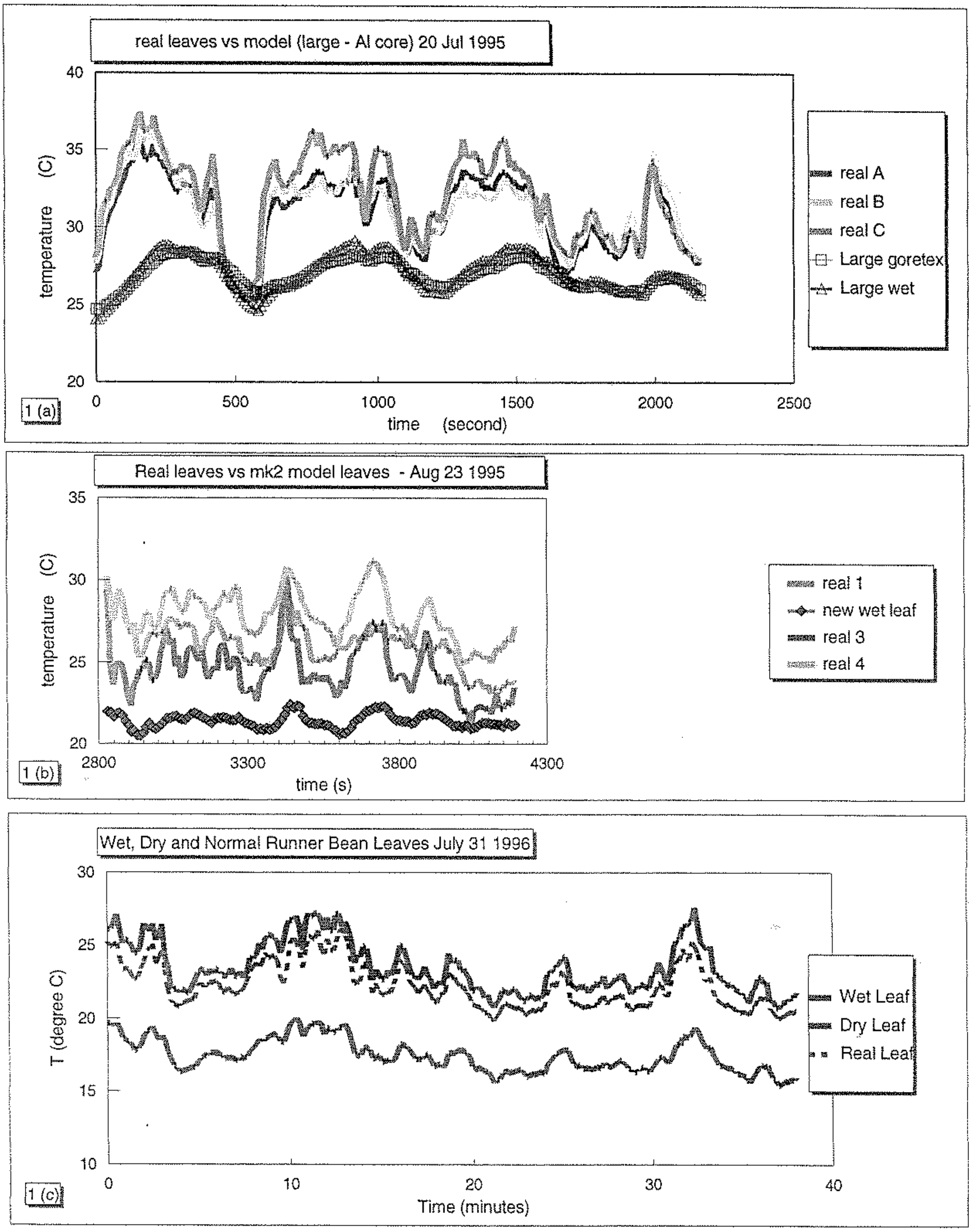


Figure 1: This compares the temperature dynamics of real leaves with (a) the original model leaves, (b) the modified models, and (c) 'wet' and 'dry' leaves

the plant canopy as the leaves whose temperatures were being monitored. The temperature dynamics of such leaves mimicked very closely indeed those of real leaves (Figure 1c).

Although a qualitative description of the dynamics can be inferred from the graphs showing temperature changes in relation to environmental fluctuations, only rough quantitative estimates are possible. To obtain more accurate estimates, it would be necessary to develop, fit and test a model that explicitly incorporates the kinetics of heat exchange and storage. An outline of a rigorous model for estimating the appropriate transfer resistances for model leaves has been developed by David Aikman. Whilst this is of theoretical interest, however, it was not felt necessary to spend time on its further development at this stage, as, on reflection, it became clear that approximate estimates of time constants are adequate to guide design of the systems and work therefore concentrated on other objectives.

(b) Selection and testing of materials for model leaves

In view of the problems with construction of the ideal model leaf (see above), ADAS work during 1996 aimed to determine the ideal material for construction of model leaves with time constants that approximate better the dynamics of real leaves. The range of materials considered as candidates, and their thermal properties, is summarised in Appendix 3.2, with stainless steel ASI 316 most closely approaching the ideal. The dynamics of models constructed from this material were compared with those of real leaves in the laboratory and in the field. Experimental details and some results are presented in Appendix 3.2.

The results of the tests by ADAS showed that although the temperature dynamics of the reference surfaces were not exactly equivalent to those of real leaves, they were a good approximation. A number of features could cause the observed differences. For example, runner bean leaves contain air spaces which reduce their mass density and possibly alter other thermal properties in comparison with broccoli. In addition the reference material was uniformly 100 μm or 200 μm thick whereas real leaves ranged between 100 and 300 μm (or more at the primary veins). It was also difficult to match the reflectivity of the real leaf and the wetting of the reference leaf (where the moisture became distributed in large droplets) was not as efficient as on the surface of the real leaf.

The behaviour of the stainless steel reference surfaces was close enough to that of the real leaves to consider their further development. This material has a further advantage in that it is a convenient and durable material for use in manufacturing a field instrument. A proprietary acid-etching process (e.g. Micrometallic Ltd.) can be used to reduce the reflectivity of the surface and to make it moisture absorbent. It may even be used to machine the steel so that it mimics the structural complexity of the real leaf surface or to create pores and water-conducting channels that would function like those of a real transpiring leaf. By this means the thermal properties of stainless steel could be tailored to those of real leaves of different crop species.

(c) The use of microporous membrane covering for model leaves

An alternative approach to the use of both wet and dry reference surfaces was considered during the project. Rather than using a complex formula based on the temperatures of both dry and wet reference 'leaves' it is theoretically attractive to use just one model whose surface conductance mimics that of a real leaf. The value of its conductance might be chosen equal to the threshold conductance at which irrigation would be triggered for that crop. A number of microporous materials were tested as coverings for model 'leaves' to simulate the critical conductance. Surface conductance of the various materials was tested by placing a sample of the material under test on dampened filter-paper from which excess moisture had been removed by blotting and measuring the conductance using the PP Systems porometer in controlled conditions in the laboratory. Information on some of the materials evaluated and on their measured surface conductances are presented in Appendix 3.3.

Some materials such as 'Goretex' are provided welded to a tough backing material, while others are rather fine and delicate and do not appear to be robust enough for field use. Nevertheless the consistency of results was often greater with some of the finer materials. In spite of extensive testing, no material yet investigated has had the properties required for construction of a commercial semi-porous reference surface, though development effort by a specialist company could lead to the production of an appropriate material. The potential simplification that the use of a single reference surface could provide means that a high priority for future work could be the selection and development of a suitable microporous material.

(d) Design criteria for the new scheduling system

During the course of the project a number of approaches for recording the 'model' leaf temperatures against which actual leaf temperature (as obtained with the IRT) could be compared were tested. Our current view on the 'ideal' design, whether using one or two reference leaves, is one that incorporates the following features:

- light, one-piece hand-held 'gun' type design that can be aimed at leaves or crop canopies as required
- inbuilt data logger that records all necessary environmental and crop stress readings for ready downloading to office computer or printer as required
- display which gives instantaneous user-friendly information on crop stress
- flexible software that allows entry of plot numbers or identifiers

The greatest difficulty is likely to be obtaining the required temperatures of the model 'reference' leaves to permit calculation of the stress index. Probably the ideal is for these reference temperatures to be recorded automatically and continuously so each temperature measurement with the IRT can be immediately converted in software to a calculated stress index. There are a number of practical considerations here which include whether the reference models can (or should be incorporated into the handpiece), or whether they can be placed in the canopy and temperatures recorded continuously and transferred (e.g. by telemetry) to the hand piece. An alternative approach, which was the one largely used during this project because of the limitations of the equipment available, is to use the IRT to record the temperatures of reference surfaces and the real leaves sequentially. This has the disadvantages that it takes longer to take the measurements and that the reference surfaces have to be carried around the crop being studied (if physical models are being used), or, as used in much of our work, created (by spraying some leaves with water and covering others with petroleum jelly) as one moves around the crop. Yet a third approach is to calculate, rather than measure, the 'model' leaf temperature using micrometeorological data (temperature, radiation, windspeed, and humidity; see Jones, 1992). Again limitations of equipment available to this project meant that it was not possible to evaluate this approach fully, but the limited testing of it undertaken in 1995 (see 1995 annual report) indicated that it could be a very useful approach.

It is clear that final evaluation of the practicalities of these alternative approaches requires an appropriate preprototype instrument. Although it had been hoped at one stage that the project might have been able to advance rather faster than had been envisaged in the original proposal by the involvement of a commercial company willing to help in the construction of preprototype equipment to test the relative merits of some of these possibilities, delays in negotiating licence terms meant that this was not achieved. Nevertheless, a company has expressed strong interest in becoming involved in such development in the future.

2.4.2.2 Infra-red thermometers

Development of a new infra-red thermometer system based on the principles derived in this project requires that the IRT used be low-cost, yet with a resolution of around 0.1 C. The absolute accuracy required is probably no better than ±0.5 C as the method is based on differences between temperatures. The Agema, though small and very convenient to operate, having a direct DC output for recording if required, unfortunately only had a resolution of 1^{o}F which was found to be inadequate for irrigation scheduling purposes. Tests of the small IRT supplied by Protimeter plc. showed that the instrument had reasonable linearity and appeared to be insensitive to ambient temperature. It therefore appears that this instrument would provide an appropriate basis for a new irrigation scheduling device.

2.4.3 Field testing - Comparisons of different measures of stress

The main objective of the project was to evaluate the infra-red thermometry (IRT) approach to early detection of water stress in horticultural crops as a basis for irrigation scheduling, emphasising runner beans as a crop that is known to be particularly sensitive to water deficits. A very clear and consistent picture emerged from the large number of measurements made during the project. All the studies confirmed that, as long as it was dry and reasonably sunny, IRT could readily detect *differences* between adjacent crops which had different irrigation histories, even if the differences in water status were quite small. This effect was illustrated for the benefit of the consortium, during the second-year project meeting at Top Barn Farm, when the opportunity was taken to compare adjacent rows of runner beans which had last been irrigated on different days. Measurements with an IRT showed that only 24 hours difference in the most recent irrigation led to leaf temperatures becoming elevated by 1.4°C (±2.7°C) compared with the more recently irrigated row. Similar results were obtained on a number of other occasions. In extreme cases the temperature difference between irrigated and stressed crops could reach 10.0 °C. The difficulty with this type of measurement, however, is that in normal commercial practice where one requires an irrigation scheduling system, one would not have well irrigated control plants available against which to compare the crop.

The project therefore concentrated on stress indexes which can be used in an 'absolute' mode to determine when irrigation is required. Although the standard Crop Water Stress Index used by the 'Scheduler' (SI(1)) was generally correlated with the water status of the crop, the correlation was often weak, with good data only being obtainable on hot dry days. The new stress index (SI(2)) proposed as a result of the theoretical and experimental studies in the first year was found to be consistently much more reliable than SI(1). As stomatal conductance is the basic plant characteristic which is sensed by IRT methods, the various indexes were compared with the measured stomatal conductance, and the results summarised below.

(a) Relationship of stress indexes to stomatal conductance.

Figures 2 and 3 show some typical examples of the relationship between the two main stress indexes and measured stomatal conductance for situations where there were clear treatment differences in soil water status. In almost every case, SI(2) was at least as good or significantly better than SI(1) as a predictor (estimator) of the stomatal conductance.

(b) Relationship of stress indexes to soil moisture status.

More important for irrigation scheduling purposes, however, is the precision with which the various indexes relate to the soil moisture status. Soil moisture was continuously recorded at depths of both 20 cm and 45 cm. Only the relationships with volumetric soil moisture (VSM) at 20 cm are shown here as these were consistently more closely related to the plant responses. Figure 4 shows how the mean values of stomatal conductance (gs), SI(2) and SI(1) relate to soil moisture across all the measurement dates in 1996. Relevant statistical analyses for the inverse prediction of VSM from these data are presented in Appendix 3.4. Using the data from these analyses it is possible to quantify the goodness of fit of regressions to each of the datasets in Figure 4. It is apparent from this figure that much the best relationship was obtained with stomatal conductance which explained 55.8% of the variance in Figure 4a. The relationship with SI(2) was also reasonable (Figure 4b), explaining 37.5% of the variance, while the relationship with SI(1) had the most scatter (Figure 4c), explaining only 16.8% of the variance. Bearing in mind the wide range of environmental conditions under which these measurements were made, the scatter in these graphs is not surprising. Much better precision can be obtained by restricting sampling to sunny periods.

(c) Use of other environmental measurements

Further statistical analyses (Appendix 3.4) were also used to investigate the feasibility of using other environmental or physiological data to derive alternative predictors of soil

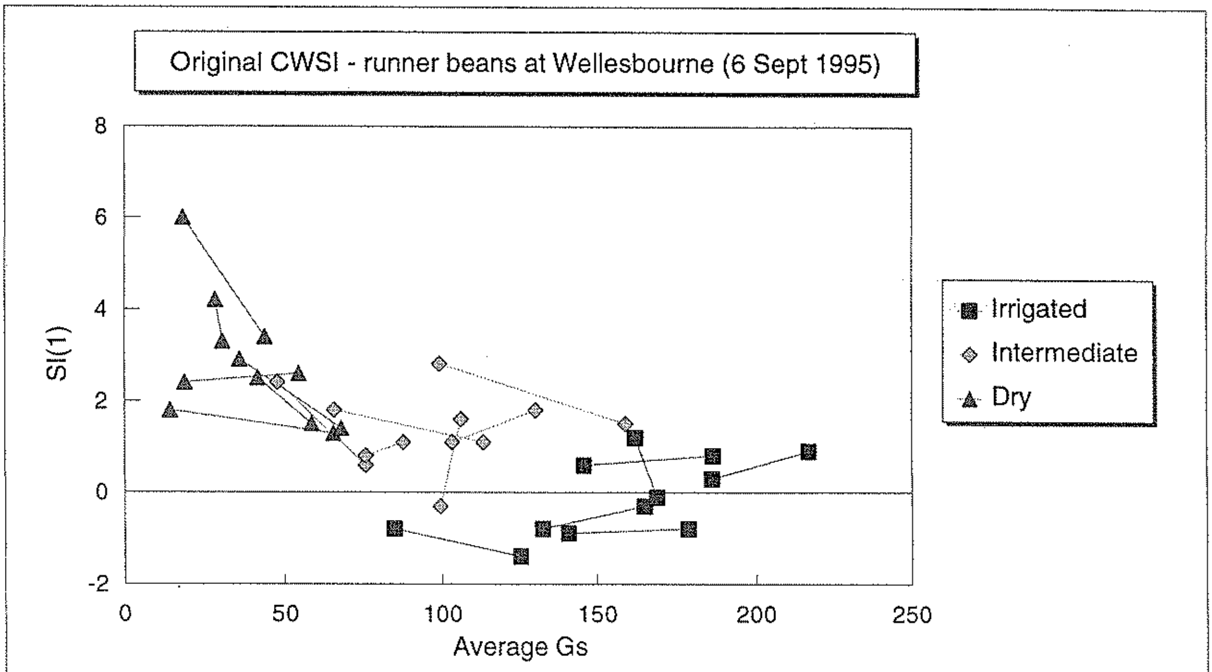


Fig 2a

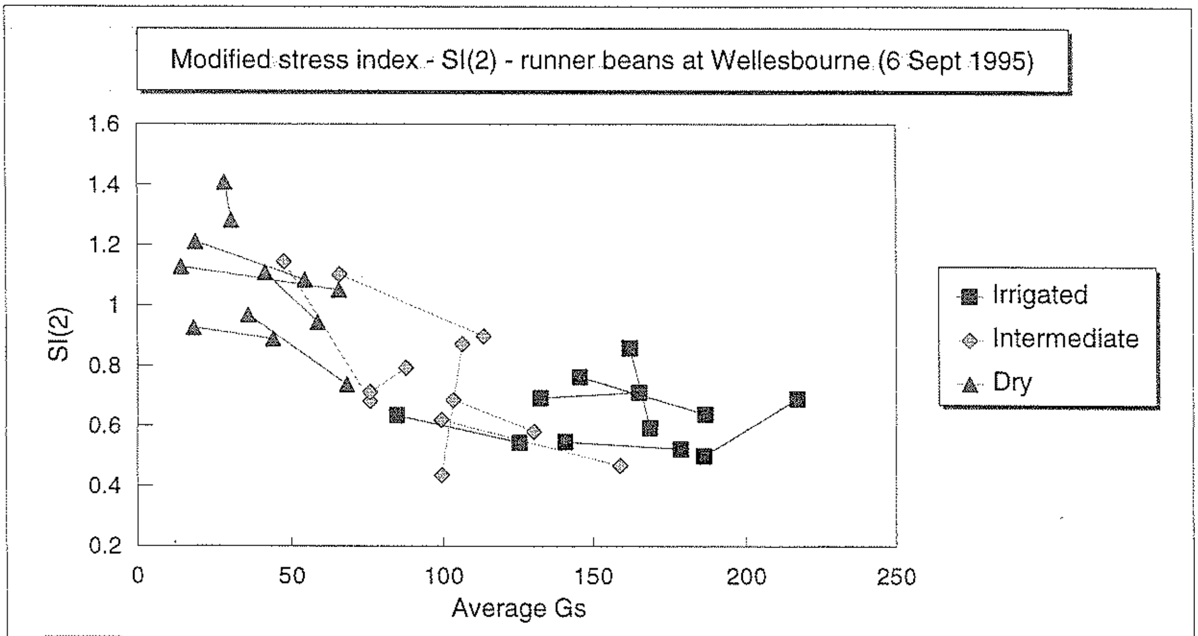
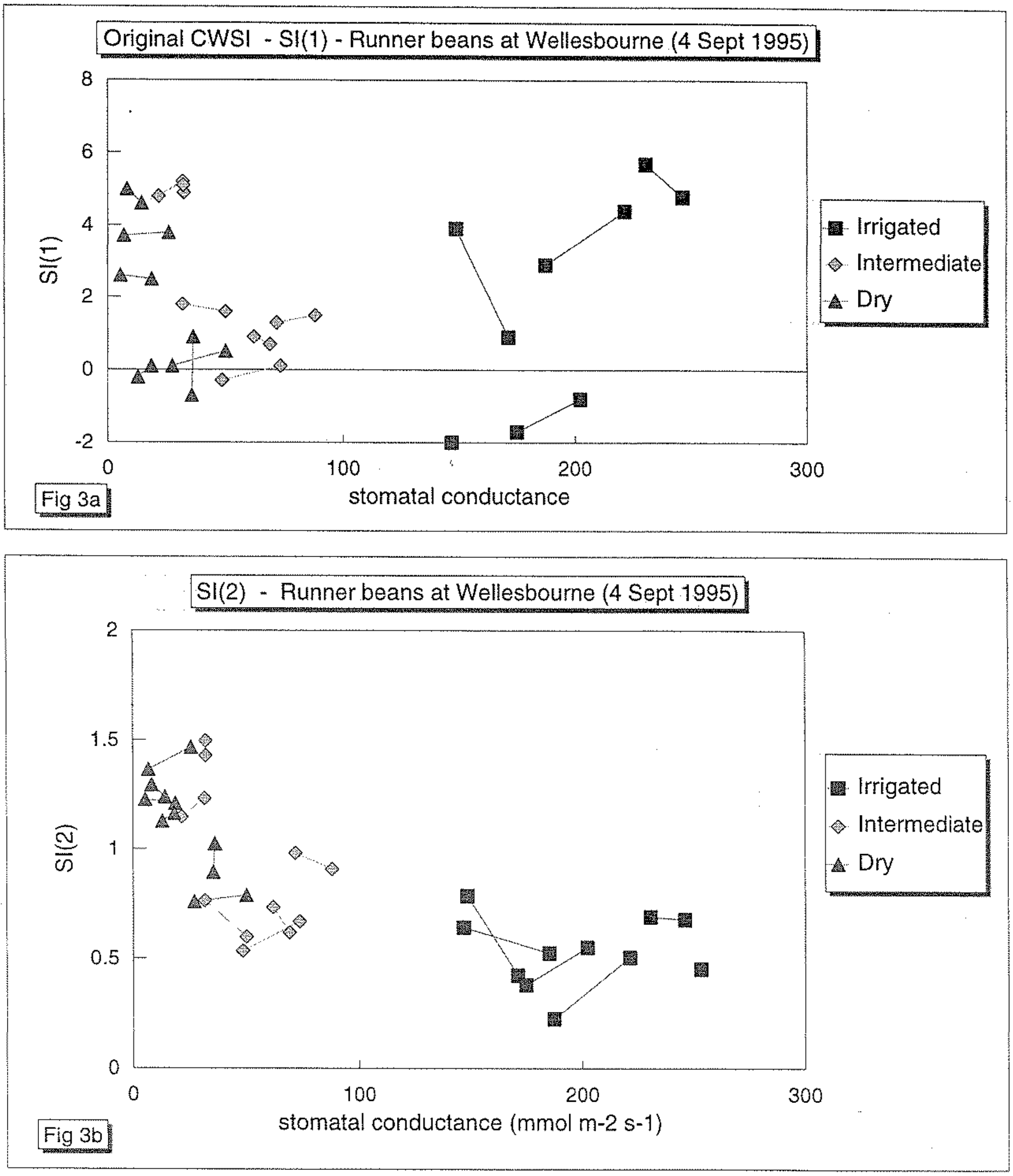


Fig 2b

Figure 2: A typical example for a hot day showing reasonably good relationships between both SI(1) and SI(2) and stomatal conductance. Well watered plants have a high stomatal conductance; values below c. 100 represent stress.



Original CWSI - SI(1) - Runner beans at Wellesbourne (4 Sept 1995)

Fig 3a

SI(2) - Runner beans at Wellesbourne (4 Sept 1995)

Fig 3b

Figure 3: An example for one day (4 Sept 1995) showinga case where the new stress index SI(2)is better than the 'Scheduler'SI(1) at distinguishing treamtents. The water status of the three treatments was clearly distinguished by stomatal conductance as shown on the abscissa.

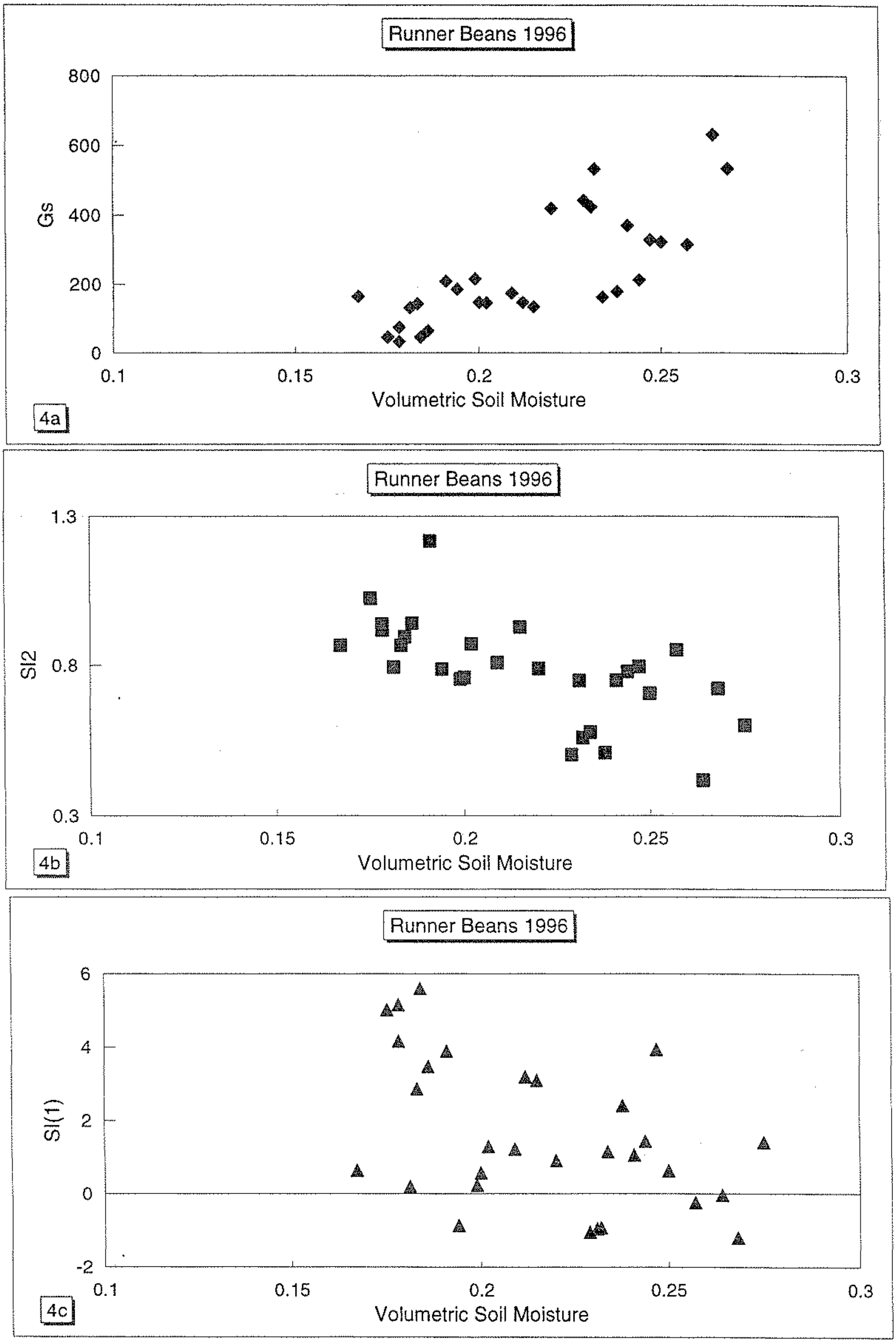


Figure 4: Illustrates the relationships between, stomatal conductance (gs), SI(2) and SI(1) and volumetric soil moisture in the top 20 cm.

moisture. The approach was based on stepwise multiple regression to identify useful combinations of measurements. Interestingly, it was found that a combination of seven variables including Sun intensity, crop temperature, air temperature and vapour pressure deficit explained a similar amount of the variation in volumetric soil moisture as did the use of stomatal conductance (see Regression 4 in Appendix 3.4). Adding two extra variables (Sun intensity and crop-air temperature difference) to stomatal conductance resulted in the regression explaining more than 70% of the variance in volumetric soil moisture (see Regression 5). Although these models are very good at explaining variation in soil moisture, it is commonly observed that this type of empirical model involving statistically-selected combinations of variables is not very robust and tends to be poor for extrapolating to untested sets of environmental conditions (see e.g. Jones & Higgs, 1989). We therefore conclude that at best the use of additional environmental variables is only likely to be of value for refining the precision of IRT stress indexes or stomatal conductance in rather limited, largely research-based, situations.

(d) Use of stomatal conductance for predicting soil moisture status

The IRT method for detecting plant stress depends on the fact that canopy temperature is an indirect measure of changes in stomatal aperture and hence stomatal conductance. It was originally considered that the direct measurement of stomatal conductance with an instrument such as a porometer was too technically demanding for it to be appropriate for commercial application to irrigation scheduling and hence effort was directed to the development of the IRT approach which had been shown to be reasonably feasible to operate by semi-skilled personnel and thus applicable to practical irrigation scheduling. Indeed the porometer was considered to be primarily a research tool, and was included in the project only because it provided a valuable reference against which the IRT measures could be evaluated. During the course of this project, however, it was found that the modern version of the porometer used in this project was extremely reliable and robust in operation and was capable of successful operation by a wide range of staff after only a couple of minutes instruction.

It is clear from the above analyses (see also Figure 14 in the second-year report) that direct measurement of stomatal conductance with a porometer appears to be particularly well suited as a stress measure with real potential for irrigation scheduling. Much of the development work that would be required to tailor IRT as an irrigation scheduling device for different crops and cropping systems would be equally applicable to the use of a porometer as a scheduling device.

(e) Other potential plant-based methods for irrigation scheduling:

Pod and stem thickness. Measurements of stem diameter or pod thickness at Top Barn Farm were made from the end of June to early August 1995. As described in the 1995 report, differences between treatments in the rate of increase in pod thickness were clear cut with diurnal shrinkage of stems apparent in the unirrigated plants. The characteristic increase in diurnal amplitude of bean pod thickness with increasing stress as irrigation was withdrawn from a previously well watered set of plants was apparent within three days of ceasing irrigation for a drought treatment started in August 1995. The diurnal fluctuations in pod diameter were greatly enhanced with a large shrinkage during the day in the unirrigated treatment. As this approach was not the main objective of the present project only limited data were obtained, but these were very encouraging and suggest that further work on tissue shrinkage could prove valuable.

Leaf water potential. Leaf water potential was measured with a pressure chamber on a number of occasions during 1995 and 1996 at both Wellesbourne and Top Barn Farm, on all three crop species. Although leaf water potential as measured with a pressure chamber is a powerful research tool for assessing crop water status, unfortunately measurements are very labour intensive, and ideally need to be performed around dawn to discriminate irrigation treatments (Jones, 1992). Nevertheless, when obtained, the leaf water potential measurements confirmed the results obtained by other measures such as soil moisture measurement or IRT or porometry. It is not envisaged at present that the pressure chamber could provide the basis of a grower-friendly irrigation scheduling system.

(f) Measurement of soil moisture status:

During the project we had an opportunity to investigate a number of techniques for soil moisture measurement. Currently the most widely used equipment for soil moisture measurement for irrigation scheduling is the neutron probe. This was used as the primary measure of soil moisture content in the first two years and was compared with a new capacitative device, the Theta-probe, in the last year.

The manufacturer's specification for the Theta-probe specifies an accuracy of ±5% moisture by volume using the supplied general calibration. In order to test the effect of soil bulk density on the calibration, tests were conducted where the bulk density was varied in test samples over the range 1.0 to 1.4 g m^{-3}. Over this range changes in bulk density were found to alter the calculated volumetric moisture content by only about 1%. In use the Theta-probes were found to have reasonable reliability with only two failures among the forty sensors used in 1996.

This instrument has been shown to have great promise as an alternative to neutron-probe for soil moisture measurement, though our experience is that care has to be taken in installation to avoid soil compaction. As long as care is taken, Theta probes have been found to be convenient to use, with the facility for continuous recording meaning that changes in soil moisture can be monitored continuously. Their convenience and ready remote recording means that they now provide a viable alternative to the neutron probe for routine soil moisture measurement. The principle used in the Theta-probe is similar to that used in another new system (the ENVIROScan system), but it appears much more suitable for research use because it is more flexible in its configuration. For commercial use, however, the ENVIROScan system is apparently provided with very useful software for monitoring changes in soil moisture though, as yet, we have no experience of its use in practice.

Extensive soil moisture measurements were also made with the time domain reflectometry (TDR) system during 1995, especially at Top Barn Farm. Again this instrument provided good results indicating that it can be a good alternative to the neutron probe.

2.5 DISCUSSION AND CONCLUSIONS

The extensive data obtained for contrasting soil moisture conditions, for different crops and for weather conditions (not just during the very hot year of 1995, but also during 1994 and 1996), provide very strong support for the view that the sensitivity of the IRT approach to crop stress sensing can be useful for UK conditions, as long as efforts are made to correct for radiation and windspeed by using the newly developed method for calculating a stress index.

Although the principles have been now well established, successful commercial application of the approach now requires the development of appropriate easily-used equipment that can be used to determine the precise protocols for use with any individual crop so as to optimise the use of water. For example it will be necessary to define the critical values for the new stress indexes, above which stress may be considered significant and irrigation advisable. Definition of the best method for using such critical stresses in actual irrigation scheduling systems for different crops will also require further development.

The main conclusions from the project, therefore, are:

1. Water stress effects on canopy temperature. Extensive data confirmed that water stress leads to significant elevation of canopy temperature, and that such temperature increases could be readily detected using infra-red thermometry. Canopy temperature differences between well irrigated and stressed crops could be as great as 10°C, though differences were more usually in the 1.5-4°C range. The changes in canopy temperature were very sensitive to irrigation, with differences being detected within 24 h of cessation of irrigation in runner bean. Although it is recognised that 1995 was an unusually hot and dry year, similar data were also obtained in 1994 and 1996 which confirmed that infra-red thermometry (IRT) holds great promise for detecting plant stress even in UK conditions, especially when the technology is modified to increase the sensitivity above that provided in current commercial equipment.

2. Theoretical analysis. Theoretical analysis of leaf energy balance equations led to the development of a new crop stress index which was shown to have greater theoretical sensitivity than the commercially available stress index calculated by the 'Scheduler'. This should lead to the possibility of new approaches to the more precise control of irrigation in horticultural crops. More recently the analysis has been taken further to derive a theoretical approach for directly estimating stomatal conductance (the underlying measure of stress detected by IRT). The full impact of this latter advance was not evaluated in the present project due to the unavailability of instrumentation for estimating canopy boundary layer resistance, but it appears to hold real promise for the future.

3. Evaluation of new stress index. Experimental evaluation of the performance of different stress indexes in the field showed that the new stress index, which is based on comparing crop temperature (as measured with the IRT) with the temperatures of wet and dry reference surfaces, was significantly more sensitive and more reliable than existing IRT approaches at detecting crop water stress in runner bean crops under the rather variable and unfavourable weather conditions in the UK. The reference surface temperatures can be obtained using either physical leaf models or real leaves which can be either wetted or covered with petroleum jelly.

4. Development of new sensing equipment. The equipment currently commercially available for IRT measurements is not designed for use with the new technique, so its successful implementation will require the development and construction of new, purpose-built equipment and further testing and development work to develop robust protocols for its use in irrigation scheduling. Work on the development of reference surfaces has identified a candidate material for their construction. Initial design criteria for the necessary equipment have been drawn up on the basis of the extensive experience of the use of IRT in runner bean crops. All these steps are necessary before the new approaches can recommended for wide use in commercial practice. An instrument manufacturer has expressed strong interest in taking out a licence for further development of the ideas arising from this project and negotiations are presently in progress.

5. Applicability to different crops. In addition to the extensive IRT data obtained for runner beans at Wellesbourne and on a grower's holding (Top Barn Farm, Holt Heath); other data were obtained on potato and French bean crops at Wellesbourne. The more limited results for potato and French beans showed that their general behaviour was similar to that of runner beans and indicated that infra-red thermometry is likely to be equally applicable to these crops, though a measure of crop-specific calibration will be necessary. It should also be noted that because of the more continuous nature of the canopies of potatoes and French beans it may be more appropriate to use an IRT sensor to measure the temperature of significant areas of canopy, rather than the single leaves that were used for the runner beans in this work. A consequence of this is that there may need to be some modification to the model leaves for these other crops to allow for the aerodynamic differences between single leaves and whole crop canopies.

6. Alternative measures of crop stress with potential for irrigation scheduling. In the course of the three year project a number of alternative measures of crop water stress were evaluated, partly as a basis against which the IRT stress indexes could be compared. These included two well established research techniques for studying plant water stress: plant water potential as measured with a pressure chamber, and stomatal conductance as measured using a porometer. Although at the outset it was felt that these two techniques were probably too research-orientated to be of use for commercial irrigation scheduling purposes, it became apparent in the course of the project that the porometer was no more difficult to use than the 'Scheduler'; indeed reliable results could be obtained after minimal instruction in its use. The close relationship of porometer results to soil moisture content supports the concept that direct or indirect measures of stomatal conductance (including IRT) can be good and sensitive indicators of irrigation need, and that all methods for estimating stomatal conductance merit further effort. We therefore feel that there is good potential for further development of the use of stomatal conductance in irrigation scheduling. Other alternative measures of crop water stress that were briefly investigated included the use of stem and pod thickness sensors which were also shown to respond sensitively to irrigation differences and which could be useful in certain cropping situations.

7. *Specific application of infra-red thermometry in irrigation scheduling.*

An important feature of infra-red thermometry-based stress sensing techniques is that they are primarily appropriate for detecting plant stress; they do not give a direct estimate of the *amount* of water that is required at any time. Their primary use, and one where the portability and flexibility of the system is a particular advantage, is as an indicator of local variation around a farm where there is inadequate coverage of neutron probe access tubes. In addition they are particularly suited for local calibration of calculation approaches to irrigation scheduling, such as IRRIGUIDE. They are also well adapted to precision irrigation systems, including trickle, where the amount or frequency can be adjusted rapidly in response to changes in the stress index.

2.6 REFERENCES

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Idso SB, Jackson RD, Pinter PJ, Reginato RJ, Hatfield JL. 1981. Normalizing the stress-degree-day parameter for environmental variability. *Agricultural Meteorology* **24**:45-55.

Jones, HG 1992. *Plants and microclimate, 2nd Edition,* Cambridge University Press

Jones, HG, & Higgs, KH. 1989. Empirical models of the conductance of leaves in apple orchards. Plant, Cell & Env. **12:** 301-308.

Jackson RD, Idso SB, Reginato RJ, Pinter PJ Jr. 1981. Canopy temperature as a drought stress indicator. *Water Resources Research* **17**:1133-1138.

2.7 OUTPUTS

2.7.1 Publications arising to date:

Jones, HG. (1994) Use of infra-red thermometry for irrigation scheduling. *Aspects of Applied Biology,* **38**, 247-253.

Jones, HG, Drew, RLK and McBurney, T. (1995) Improving irrigation by infra-red thermometry. *The Grower,* March 30, pp. 32-33.

Jones, HG, Aikman, D and McBurney, T. (1997). Improvements to infra-red thermometry for irrigation scheduling in humid climates. *Acta Horticulturae*, (in press)

[Jones, HG. (199). Use of infra-red thermometry for irrigation scheduling. (A manuscript has been drafted for *Agricultural and Forest Meteorology*, but submission will need to await clarification of some outstanding questions relating to intellectual property).]

Press articles have also appeared in *New Scientist*, *Coventry Evening Telegraph*, *Stratford Journal*, and *Cyanamid Agriculture*, while a colour brochure was produced for launch of the 'Technologies for sustainable farming systems LINK programme' at Boxworth .

2.7.2 Presentations :

i) The work was presented at the launch of the Sustainable Farming Systems LINK at Boxworth on 24 June, 1994. The poster for this event was also presented at the AAB meeting, Reading, 6-8 July, 1994.

ii) A spoken presentation was made at the Association of Applied Biologists Meeting, on *Efficiency of water use in crop systems,* Reading 6-8 July, 1994.

iii) The work has also been included in a presentation by HG Jones to the International Society for Horticultural Science, 2nd International Conference on *Irrigation of Horticultural Crops* (Chania, Crete September 1996).

iv) The work was also described to the Runner Bean Growers group by T McBurney on 17 October, 1995.

2.8 ACKNOWLEDGEMENTS

The help of a large number of people is gratefully acknowledged. In particular we are grateful to David Harper for allowing us to work at Top Barn Farm. The smooth operation of the field experiments at Wellesbourne was due in no small measure to the dedication and enthusiasm of Peter Morton and his field staff and to the engineering skills of staff in the Facilities Department at Wellesbourne who constructed the mobile rain shelters. Experimental work was largely done by Roy Drew and Nick Parsons with help from Emma Hewardine and John Stephen. David Aikman contributed to the modelling and James Lynn provided statistical advice and performed many of the statistical analyses.

2.9 GLOSSARY

ADAS - Agricultural Development and Advisory Service

Boundary layer conductance - a measure of how rapidly water and heat are transferred through the air adjacent to crop surfaces (sometimes quoted as its inverse, the boundary layer resistance, r_a).

CWSI - Crop water stress index; an index that can be used as a measure of crop water stress as a basis for determining irrigation need.

HRI - Horticulture Research International

IRT - infra-red thermometer or infra-red termometry depending on context; an instrument for remotely sensing crop temperatures.

Neutron probe - A soil moisture measurement device that relies on the detection of the scattering of neutrons emitted by a radioactive source. There are a number of commercial neutron probe services available in the UK.

Porometer - A portable instrument for measuring the stomatal conductance of plant leaves.

Stomatal conductance (g_s) - a measure of how open the stomatal pores on the leaf surface are and therefore how rapidly a leaf loses water. Sometimes quoted as its inverse, the stomatal resistance.

TDR - time-domain reflectometry: an electronic approach to the measurement of soil moisture (and salt) content using two (or three) metal probes inserted in the soil.

Theta-probes - these new soil moisture monitoring devices (produced by Delta-T Devices, Burwell, Cambs.) are based on measurement of the soil dialectric constant (which is largely determined by soil moisture content) in the volume of soil between the metal probes.

Time constant - this is a measure of how fast a quantity such as temperature changes in response to environmental conditions and is the time taken for 63% of the total change to occur. (An alternative expression is the half-time which refers to the time for 50% of the change to occur).

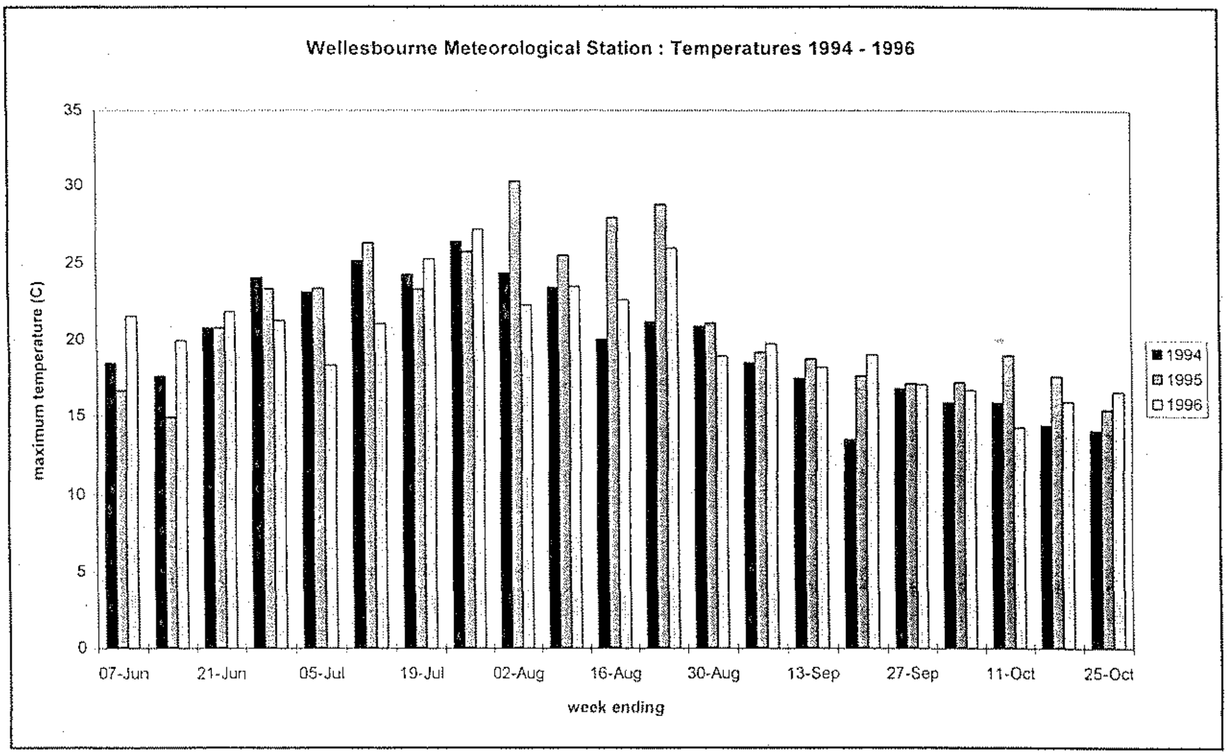
3. APPENDICES

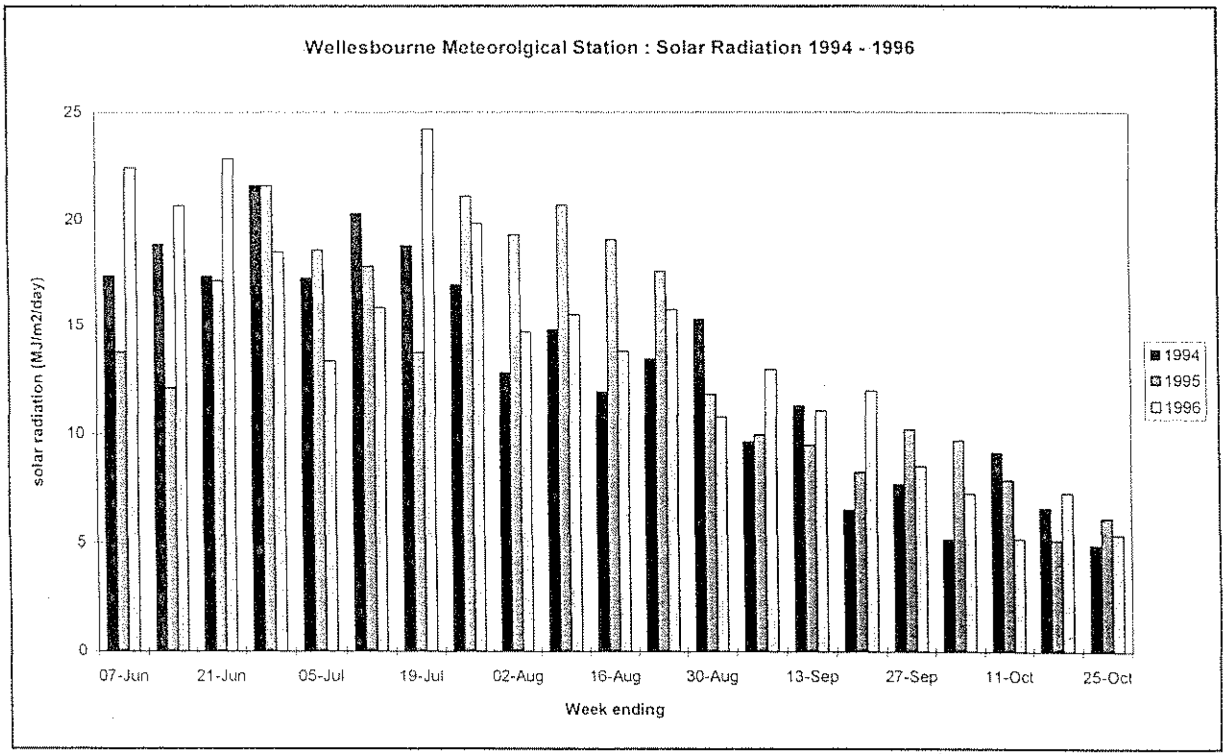
3.1. Weather and soil moisture data for the three years:

The following four pages summarise weather conditions and soil moisture deficits attained at Wellesbourne during the three years of the trial.

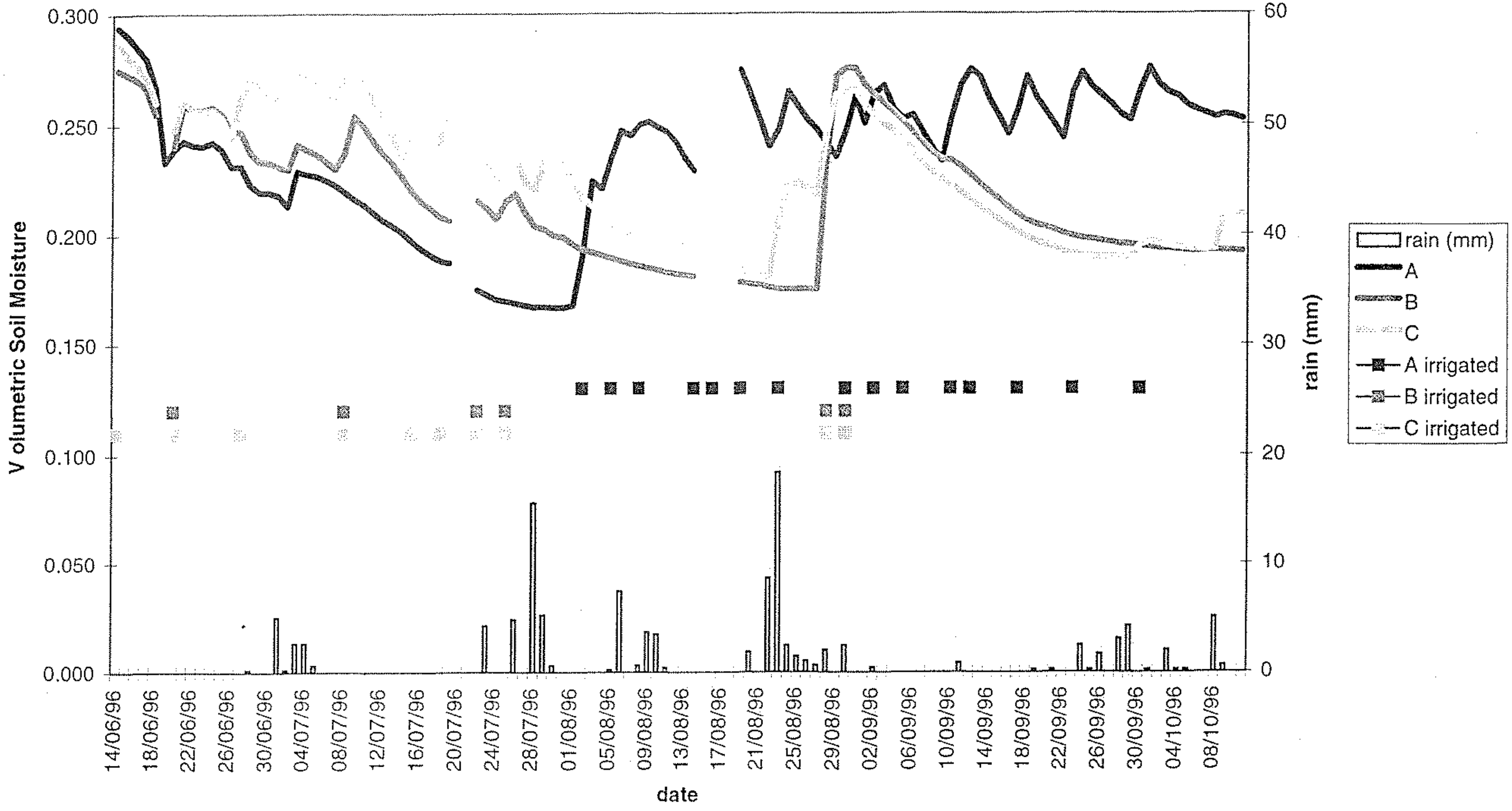
As can be seen from the attached data, June, July and August in 1995 were exceptionally dry with correspondingly high temperatures and high sunshine. In 1994 and 1995, the dry summer was followed by heavy rain in September, though September was dry in 1996.

As can be seen from the soil moisture data on the following three pages, in the first two years the experiments compared three treatments which were maintained throughout the summer period. In 1996, however, the stress treatments were periodically rewatered and subsequent stress development followed to allow us to obtain information on the rate of development of soil moisture deficits and its relationship to IRT measurements.

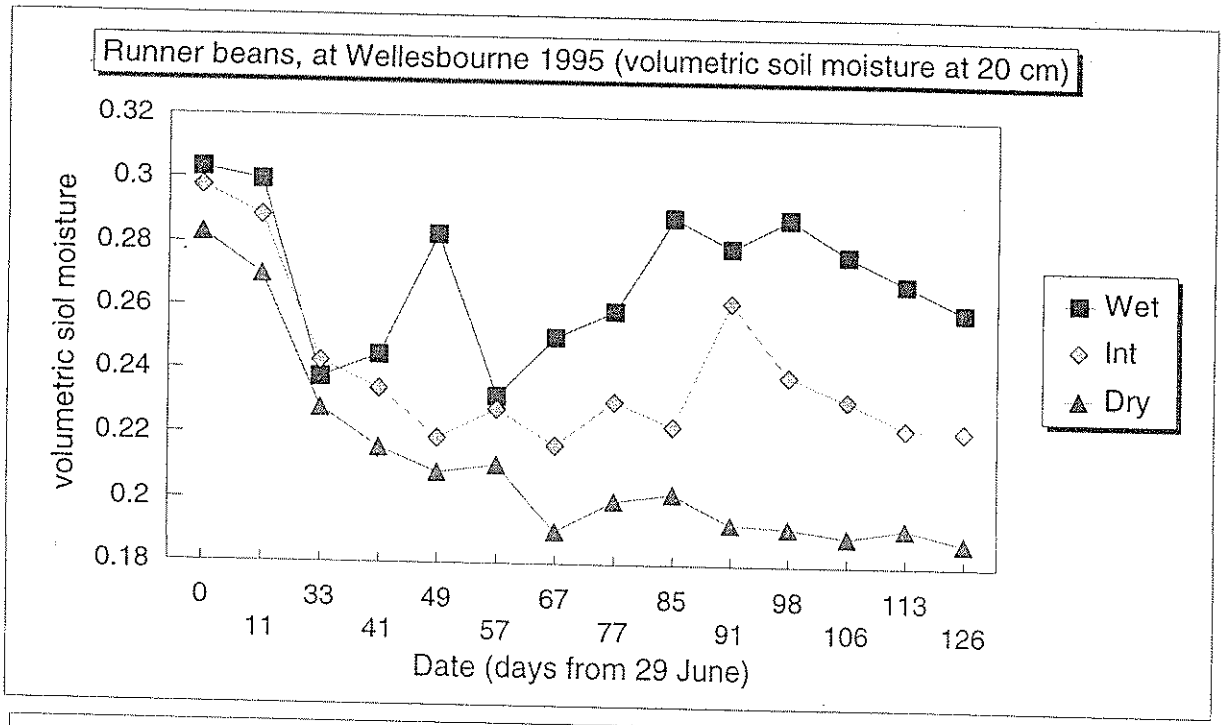


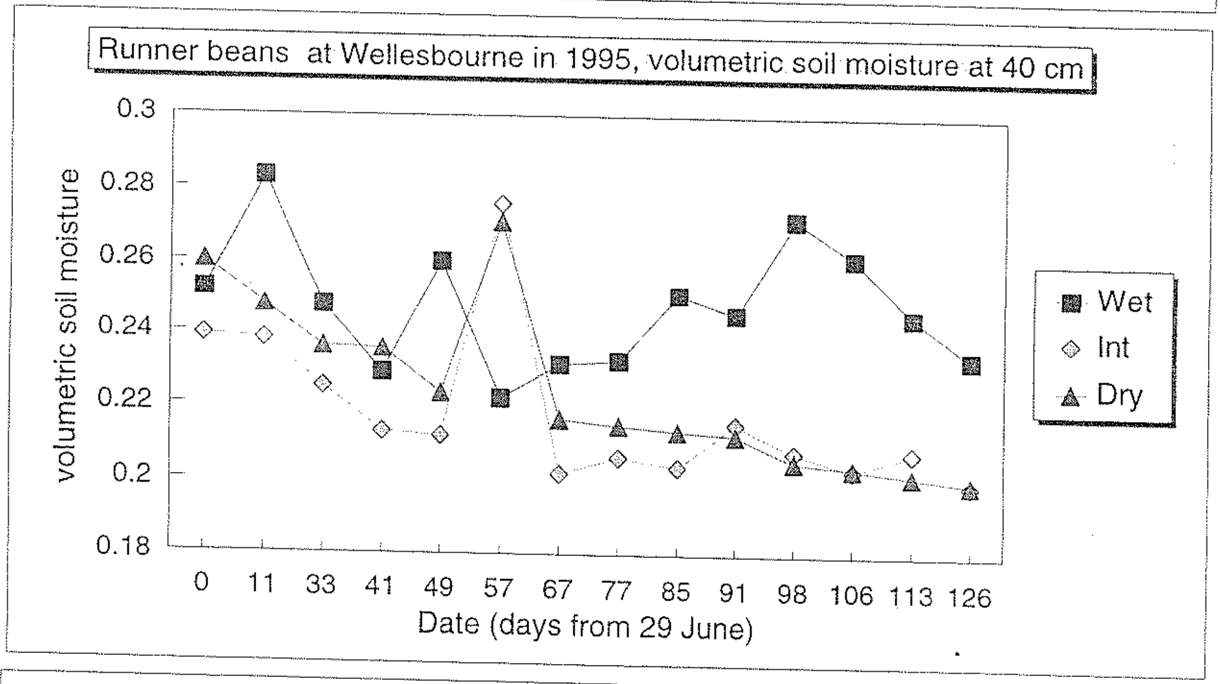


Monthly Rainfall (mm)	**1994**	**1995**	**1996**
June	11.6	7.3	16.6
July	40.5	9.8	42.1
August	44.3	3.1	51.6
September	110.2	102.0	11.2
October	56.2	27.0	46.5



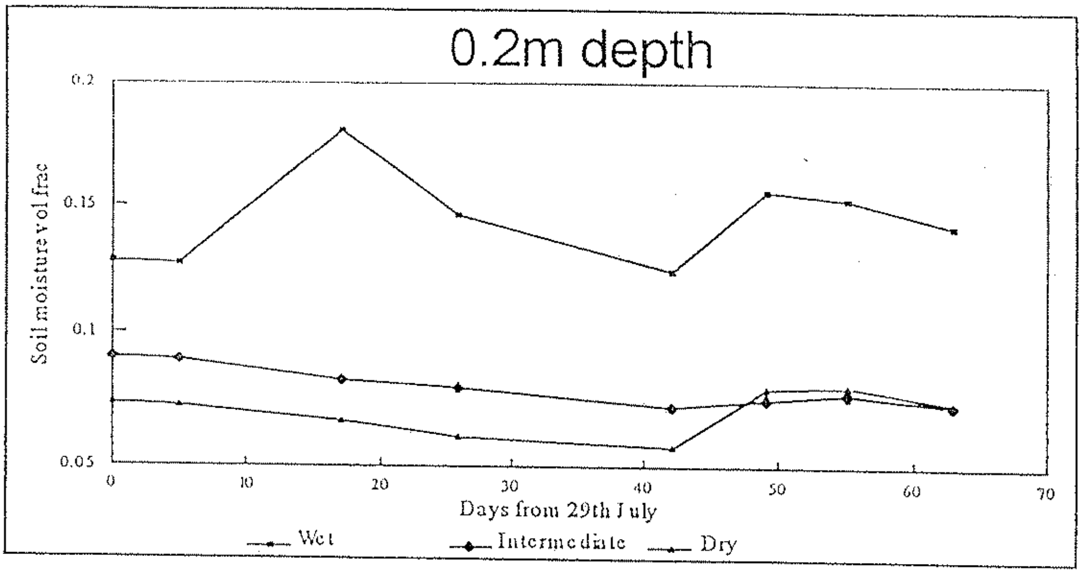
1996 Runner Beans : Volumetric Soil Moisture, Irrigation, Rain

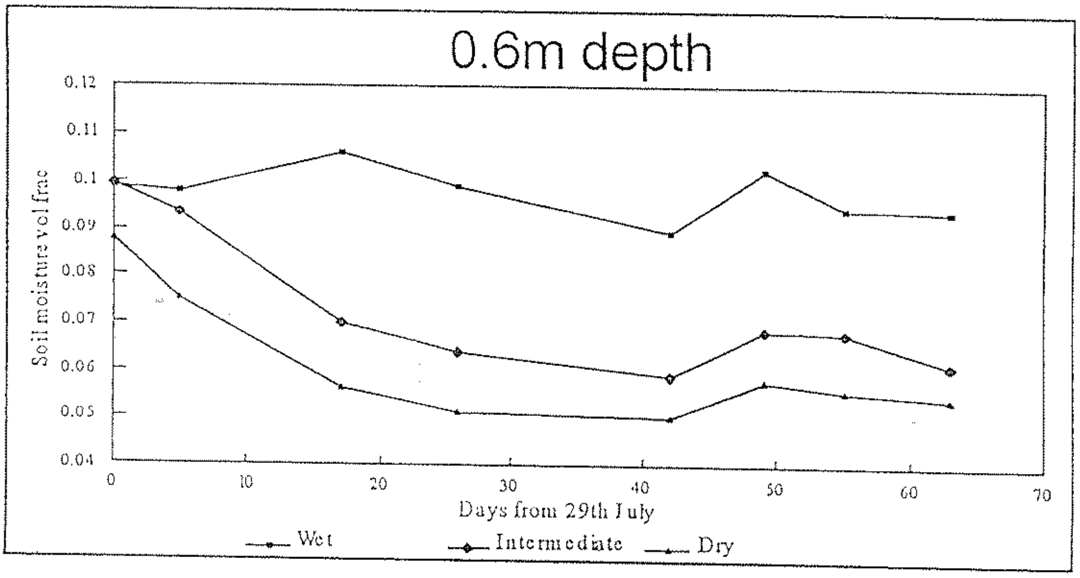


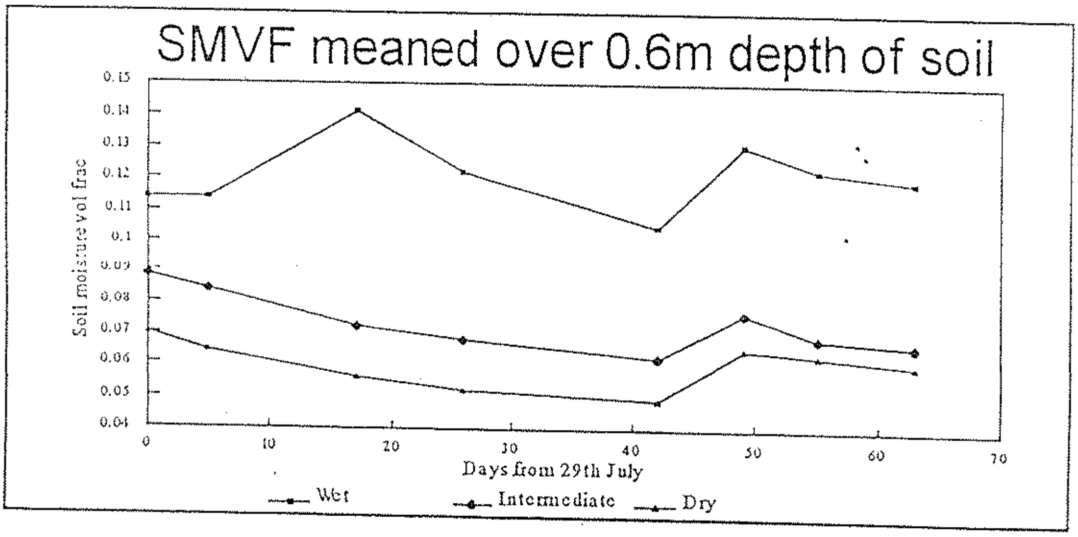


Soil moisture trends as measured with the neutron probe in 1995 under runner beans. Sub-optimal irrigation was applied to the wet treatment in July and late-August/early-Sept.

1994


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

3.2. Selection of material for reference leaves:

An ideal reference material must have the same thermal time constant τ_t as a real leaf. The thermal time constant is approximated by the 'lumped capacitance' equation:

$$\tau_t = (1/hA_s)\ (\rho\ V\ c_p)$$

where h is a heat transfer coefficient, A_s is surface area, ρ is mass density, V is volume, c_p is specific heat. Assuming that the reference surface will have the same dimensions and transfer coefficient as the real leaf, the product of ρ and c_p provides a crude comparison of different materials for use as a reference surface. The material that most closely approximated the $\rho.c_p$ of broccoli tissue (Table 3.2.1) was stainless steel ASI 316.

Table 3.2.1 Selected examples of material thermal properties from various published sources

MATERIAL	**ρ** **kg/m^3**	**c_p** **kJ/kg.K**	**k** **W/m.K**	**$\rho.c_p$**
Broccoli	1103	3.473	0.4257	3830
water	1000	4.217	0.569	4217
paper	930	1.340	0.180	1246
paraffin	900	2.890	0.240	2601
aluminium	2702	0.903	237	2434
beryllium oxide	3000	1.030	272	3090
vanadium	6100	0.489	30.7	2983
rhodium	12450	0.243	150	3025
brass	8530	0.38	110	2241
iron	7870	0.447	80.2	3518
steel (carbon)	8131	0.434	41	3528
steel (stainless ASI 316)	7978	0.480	14.2	3829
nickel	8900	0.444	90.7	3952
copper	8933	0.385	401	3439

The dynamic temperature response of a material subjected to a thermal load partly depends on the thermal conductivity which may give rise to thermal gradients within the material. However, investigation of this effect using a transient solution of the heat flow equation and proprietary finite-element-analysis (FEA) software did not alter the choice of material. The solutions involved constructing 3-dimensional models of the leaf and reference materials with thickness up to 300 µm and boundary conditions of convection heat loss and changes in radiation load similar to those encountered in field environments. Models based on stainless steel or wet paper gave approximately the same thermal time constants as plant tissues but dry paper differed markedly (as would also be concluded from Table 3.2.1) and also showed significant thermal gradients. Although the thermal conductivity of real leaves might effectively be higher than that in Table 3.2.1 due to radiation penetrating the translucent plant tissues (H G Jones pers. comm.), further increasing the plant tissue thermal conductivity to take account of this effect did not alter the result of the FEA analysis.

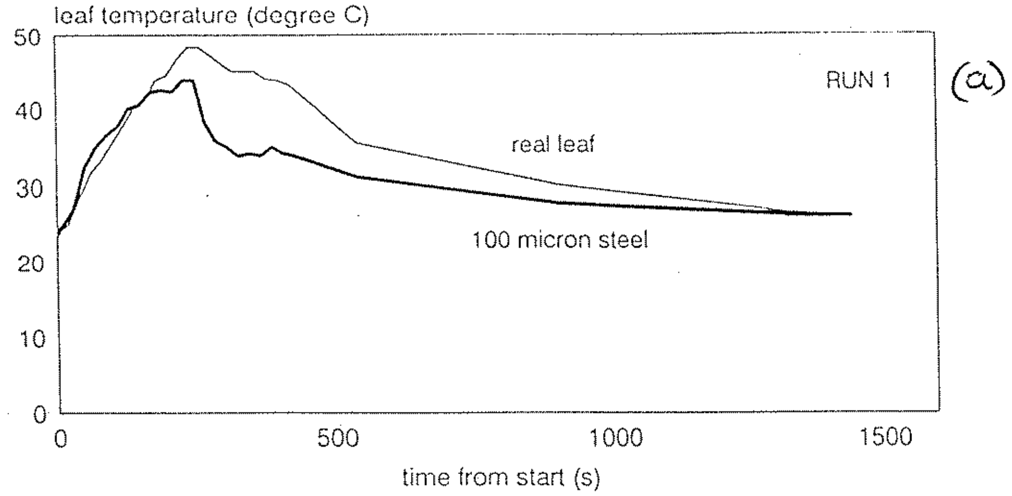
Materials and methods.

The temperature dynamics of reference strips constructed from 100 µm thick sheets of ASI 316 (Knight Strip Metals) bonded together using adhesive to obtain a range of thickness. One side was painted with a mat green enamel to enable manual recording of temperatures using the AGA thermopoint 80 IRT. A rapid response thermocouple (type-T, RS Components) was bonded to the surface with heat conducting adhesive and recorded automatically by a Delta-T datalogger. The read switch of the IRT was used to trigger logging to enable synchronisation.

For laboratory measurements a vaseline-coated mature runner bean leaf was detached and maounted horizontally on a 4 mm thick glass plate next to a 100 µm or a 200 µm thick sheet of reference material of similar dimensions and temperatures monitored continuously with the IRT, before, during and after a 200 s period of radiant heating by two 60 W tungsten bulbs situated 20 cm below the plate. Field measurements were taken during August around noon on mild days with transient cloud cover. Thrre mature leaves near the base of a fully irrigated runner bean plant were clamped perpendicular to the sun. One leaf was coated with Vaseline to limit water loss, one was periodically sprayed with water an one was untreated. Two 200 µm thick reference surfaces (one periodically moistened) were mounted in a similar orientation with the shiny surface towards the sun. Real leaf temperatures were measured with the IRT, those of the references using the in-situ thermocouples.

Results

Similar results were obtained in each of the three laboratory runs with each material, though with the 100 µm reference (Figure 3.2.1a) the rate of temperature rise during heating and decline during cooling were more rapid than with the real leaf. The rates with the 200 µm reference (Figure 3.2.1b) more closely approximated those of the real leaf. Field data (expressed as temperature differences from air temperature) are shown in Figure 3.2.2. In these air temperature increased to nearly 20^{o}C in full sun and dipped to 15^{o}C with passing cloud and it also declined with time. The temperatures of real leaves (and of Vaseline-coated leaves) was higher than that of air in the sun and lower in cloud. In general, though there were some differences in absolute temperature between reference and real surfaces the temperature dynamics were similar (allowing for the different frequency of observations on real and reference surfaces).



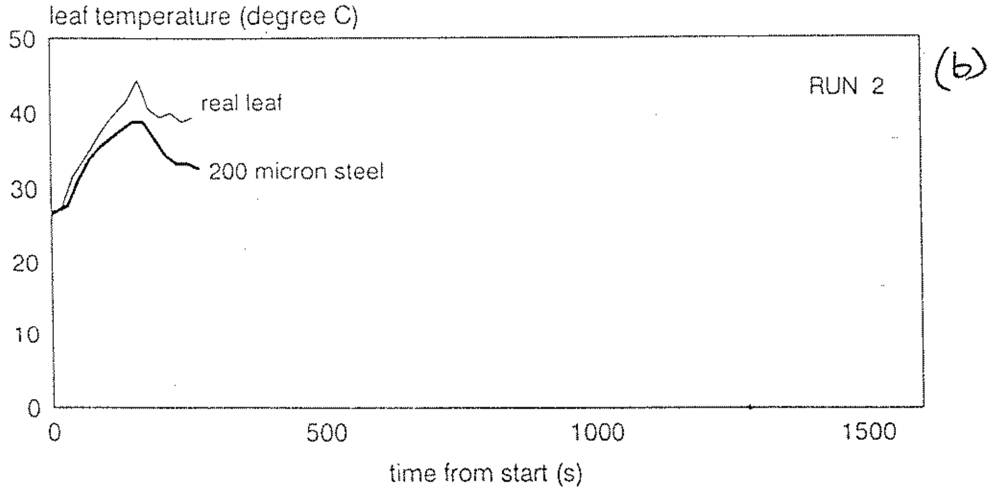


Figure 3.2.1. Dynamic thermal responses of a non-transpiring leaf and either (a) 100 μm thick, or (b) 200 μm thick stainless steel in the laboratory.

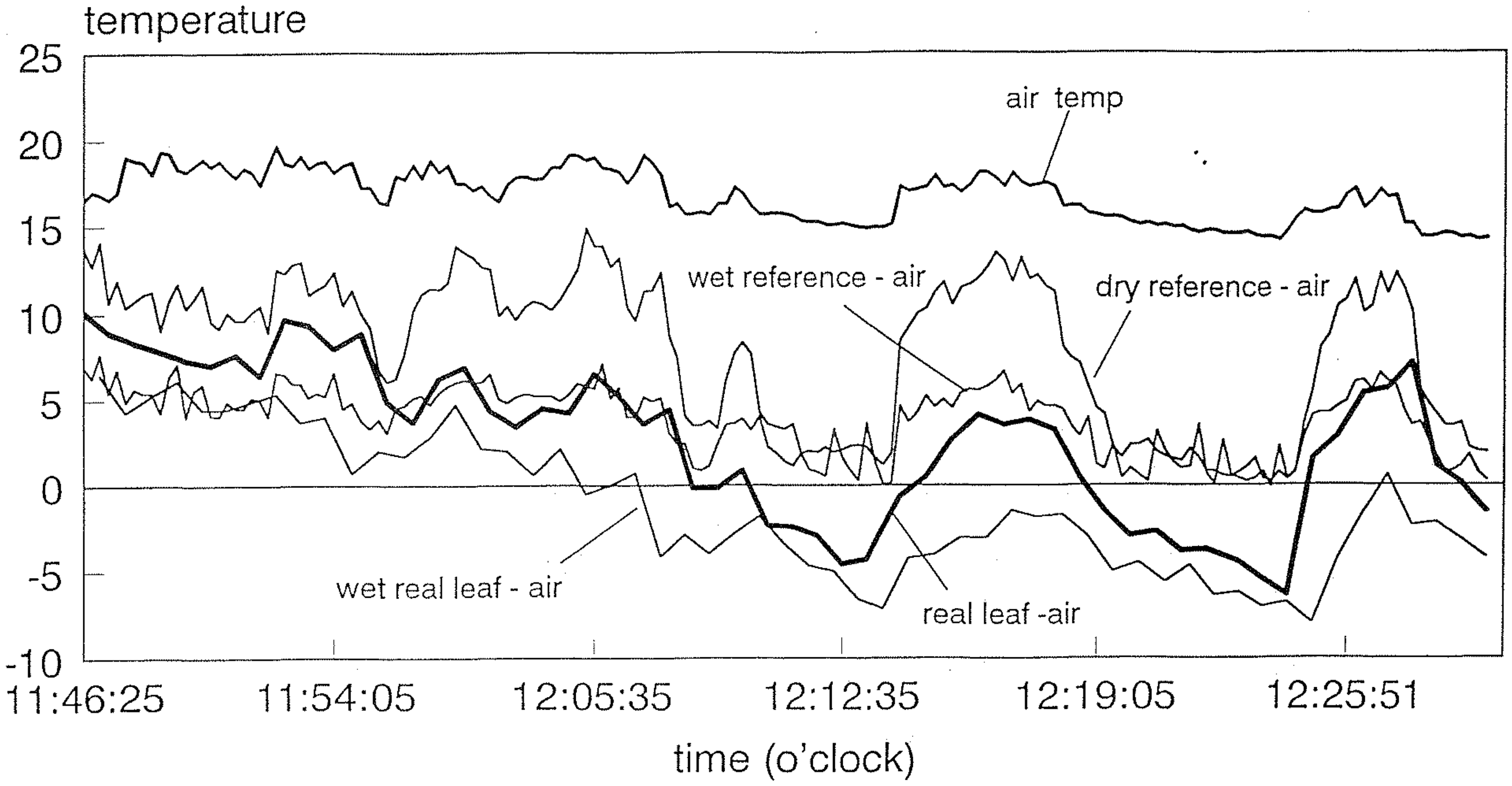


Figure 3.2.2. Dynamic thermal responses of leaves and reference materials (200 µm thick stainless steel) subjected to a transient sun and cloud cover in the field.

3.3 Tests of microporous materials:

A wide range of microporous materials were tested for their suitability as coverings for model 'leaves' to simulate the conductance of real leaves (Table 3.3.1). Measurements were made using the PP Systems porometer with the material being tested overlaying wet filter paper. The critical surface conductance of a real leaf that is indicative of substantial stomatal closure, and hence indicative of the need for irrigation, is likely to be in the range of 80 - 200 mmol m^{-2} s^{-1} depending on the plant species (see Jones, 1992).

As indicated in Tables 3.3.1 - 3.3.4, the actual measured conductances were either very far from the required values, or else there was substantial variation from measurement to measurement. The reason for this variation was not established, but it was noted, for example, that the second sample of PM2U had small holes visible on the surface while the original sample did not.

Table 3.3.1 List of microporous materials tested.

	Mean conductance (mmol m^{-2} s^{-1})	**Comments**
PM2U[1]	900 -1300	pore size 5-10 µm
PM3T[1]	680 -1000	pore size 2 µm
PM9P[1]	1470 - 1800	pore size 1 µm
PM28Y[1]	1200 - 1400	pore size 2.5 µm
Net909[2]	8 - 10	breathable sticking plaster
Hpu25[2]	50 - 100	very thin wound dressing (appeared to increase with use)
Opsite[2]	40 - 55	very thin wound dressing material
Goretex	300 - 800	microporous membrane bonded to rainwear material (very variable between positions)
StarPac	2 - 4	enclosed culture container system

[1] Microporous PTFE (Mupor Ltd., Alness, Ross-shire IV17 0XS)
[2] Surgical dressings (Smith & Nephew Ltd.)

Table 3.3.2. Data from porometer tests on first batch of PTFE materials from Mupor Ltd.. Mean conductances (mmol m^{-2} $second^{-1}$)

Material	24 April am	24 April pm	25 April am	25 April pm	Mean	Std. Error	Total Readings
PM2U	1529.9	1353.3	1153.2	1289.7	**1331.5**	**36.32**	**20**
PM3T	709.9	705.3	622.5	674.9	**678.0**	**9.52**	**21**
PM9P	1650.1	1457.9	1274.0	1504.0	**1471.5**	**49.67**	**20**
PM28Y	1296.0	1160.0	1059.0	1198.9	**1178.5**	**24.15**	**20**
OPSITE	51.0	50.2	45.7	52.2	**50.0**	**1.26**	**39**

Table 3.3.3. Data from porometer tests on first batch of PTFE materials from Mupor Ltd.. Mean conductances (mmol m^{-2} $second^{-1}$) with standard errors.

Material	9 May pm	10 May am	13 May am	13 May pm	14 May am	Mean	Std. Error	Total Readings
PM2U	984.8	979.1	884.7	892.9	778.3	**895.0**	**18.87**	
PM3T	943.4	1211.2	987.7	1048.7	937.4	**1005.1**	**46.06**	**18**
PM9P	2292.5	1660.5	1783.1	1802.4	1396	**1800.9**	**75.81**	**18**
PM28Y	1729.6	1354.6	1439.5	1462.6	1179.1	**1457.0**	**46.82**	
OPSITE	54.2	49.0	51.9	53.7	49.4	**51.8**	**1.25**	**48**

Table 3.3.4. Comparisons of first and second batches of Mupor materials with samples taken sequentially. Each value is mean of three readings (mmol m^{-2} $second^{-1}$).

Material	Old sample	New sample
PM2U	1539	976
PM3T	779	1077
PM9P	1704	2136
PM28Y	1368	1899
OPSITE	55.5	

3.4 Results of statistical analyses of relationships between different stress indexes and volumetric soil moisture.

The 1996 data for runner beans at Wellesbourne were analysed in some detail to determine the utility of various variables (different stress indexes or combinations of environmental variables) as predictors of volumetric soil moisture content (as measured with the Theta probes). Some of these data have been presented in Figure 4. It is worth noting that the scatter of the data is partly a result of including all measurements, even those taken on cloudy or wet days when the IRT measurements are subject to large errors. For the statistical analyses, stomatal conductance was transformed by taking square roots. In addition to the various stress indexes the value of the following variables, either alone or in combination, were tested as predictors of the soil moisture content by means of stepwise multiple regression. Those variables measured by the 'Scheduler' are indicated:

Crop	Crop temperature ('Scheduler')
Air	Air temperature ('Scheduler')
Diff	Tc - Ta
Sun	Sunshine 'intensity' ('Scheduler')
sd	(S - meanS) * (Td - meanTd)
sa	(S - meanS) * (Ta - meanTa)
sc	(S - meanS) * (Tc - meanTc)
gs	stomatal conductance
vpd	vapour pressure difference ('Scheduler')
a2	(Ta - meanTa)**2
c2	(Tc - meanTc)**2
s2	(S - meanS)**2

A simple correlation matrix between these variables is shown in Table 3.4.1. This shows that the original stress index (SI(1)) is extremely closely related to leaf-air temperature difference (r = -0.916) while the newer index (SI(2)), as expected, is less closely related to any individual environmental variable, though was most closely related to stomatal conductance (r = -0.669).

Crop	1.000												
Air	0.947	1.000											
Sun	0.675	0.656	1.000										
sd	0.136	0.176	0.054	1.000									
Diff	-0.620	-0.336	-0.378	0.030	1.000								
sa	0.395	0.546	0.099	-0.115	0.177	1.000							
sc	0.302	0.422	0.068	-0.467	0.146	0.932	1.000						
a2	0.684	0.801	0.332	0.030	-0.051	0.825	0.723	1.000					
c2	0.621	0.662	0.186	-0.303	-0.205	0.695	0.729	0.865	1.000				
s2	0.049	0.076	0.207	-0.331	0.042	0.529	0.592	0.103	0.067	1.000			
gs	-0.622	-0.458	-0.307	-0.092	0.706	-0.220	-0.163	-0.341	-0.392	-0.089	1.000		
SI[1]	0.823	0.614	0.621	-0.032	-0.916	0.040	0.044	0.312	0.408	0.049	-0.704	1.000	
SI[2]	0.397	0.302	0.123	0.099	-0.427	0.218	0.158	0.389	0.435	-0.170	-0.669	0.460	1.000
Vpd	0.864	0.949	0.721	0.117	-0.216	0.588	0.481	0.846	0.693	0.119	-0.422	0.545	0.343
	Crop	Air	Sun	sd	Diff	sa	sc	a2	c2	s2	Gs	SI(1)	SI(2)

Results of regressions with vsm (volumetric soil moisture at 20 cm) as response variate

1. Fitting: SI(1) alone (plus a constant)

*** Estimates of regression coefficients ***

	estimate	s.e.	t(28)
Constant	0.23	0.008	28.19
SI[1]	-0.0082	0.00313	-2.61

(Percentage variance accounted for = 16.8)

2. Fitting: SI(2) alone (plus a constant)

*** Estimates of regression coefficients ***

	estimate	s.e.	t(28)
Constant	0.33	0.026	12.59
SI[2]	-0.15	0.035	-4.29

(Percentage variance accounted for = 37.5)

3. Fitting: Gs alone (plus a constant)

*** Estimates of regression coefficients ***

	estimate	s.e.	t(28)
Constant	0.15	0.011	13.11
gs	0.0046	0.00076	6.14

(Percentage variance accounted for = 55.8)

4. Fitting: The best combination of independent variates as found by stepwise multiple regression

*** Estimates of regression coefficients ***

	estimate	s.e.	t(22)
Constant	0.014	0.0675	0.20
Sun	0.0018	0.00052	3.50
Crop	-0.027	0.0041	-6.56
sc	0.00040	0.000186	2.18
Air	0.035	0.0067	5.24
a2	0.0019	0.00065	2.92
sa	-0.00085	0.000264	-3.20
Vpd	-0.063	0.0223	-2.83

(Percentage variance accounted for = 62.5)

5. *Fitting: The best combination including Gs*

```
*** Estimates of regression coefficients ***

             estimate      s.e.        t(26)
Constant     0.12          0.0164      7.22
gs           0.0042        0.00088     4.82
Sun          0.0006        0.00018     3.55
Diff         0.006         0.0029      2.12

(Percentage variance accounted for = 68.6)
```

6. *Fitting: The best combination including SI(1)*

```
*** Estimates of regression coefficients ***

             estimate      s.e.        t(22)
Constant     0.023         0.0621      0.37
SI[1]        0.032         0.0126      2.55
Sun          0.0014        0.00046     2.94
Crop         -0.048        0.0109      -4.36
Air          0.055         0.0125      4.42
a2           0.0018        0.00060     2.96
sa           -0.00036      0.000096    -3.75
Vpd          -0.079        0.0240      -3.28

(Percentage variance accounted for = 64.9)
```

7. *Fitting: The best combination including SI(2)*

```
*** Estimates of regression coefficients ***

             estimate      s.e.        t(23)
Constant     0.30          0.049       6.19
SI[2]        -0.12         0.030       -4.07
Sun          0.00054       0.00026     2.06
Crop         -0.013        0.0026      -5.03
Air          0.012         0.0036      3.235
a2           0.00098       0.00039     2.49
sa           -0.00029      0.000084    -3.50

(Percentage variance accounted for = 70.2)
```

4. ORIGINAL CONTRACT

Contract between HRI (hereinafter called the "Contractor") and the Horticultural Development Council (hereinafter called the "Council") for a research/development project.

1. TITLE OF PROJECT

Amended Contract No: FV/140
for delayed start date)

IMPROVING IRRIGATION SCHEDULING USING INFRA-RED THERMOMETRY

2. BACKGROUND AND COMMERCIAL OBJECTIVE

Irrigation is essential to obtain high yields of premium quality produce for many horticultural crops. There is however an increasing premium on saving water to enhance the security of water supply, especially so that the need for expensive storage facilities for winter-abstracted water can be minimised. Without precise methods for irrigation scheduling there is a tendency to over-irrigate for insurance which can lead to wastage of as much as 50% of applied water, and potential improvements in irrigation efficiency that are offered by precise water application techniques (e.g. trickle) will not be achieved. In the UK irrigation scheduling is commonly based on water balance calculations using rainfall and crop evapotranspiration calculated from meteorological records (e.g. Penman 1948; and modifications such as MORECS and IRRIGUIDE), but for accurate calculations adjustments need to be made for the state and stage of the crop and for variation in micro-environment and in soil depth and type. Alternatively soil water can be measured directly using devices such as tensiometers or neutron probes, but tensiometers are notoriously unreliable and the expense and regulatory problems with neutron probes mean that at best they are only suitable for consultants. More importantly fully representative sampling of an area can be time consuming and expensive. Because yield and quality effects depend on the actual water deficit experienced by the plant an alternative, and potentially more generally applicable and accurate approach is to develop techniques that detect plant stress directly and which can be used routinely by growers.

Several direct stress detection techniques are being evaluated by research teams worldwide including stem diameter gauges, xylem cavitation sensing, leaf thickness transducers, and methods for measuring stomatal functioning (porometers and leaf temperature monitoring). Those methods based on stomatal function have been shown to be particularly sensitive (Jones, 1992), and the most promising is the use of infra-red thermometry (IRT) to measure leaf temperatures. Idso *et al.* (1981) proposed a method based on IRT to compare canopy temperatures to an empirical 'non-water stressed baseline' and hence calculate a 'crop water stress index' (CWSI) by normalising crop canopy temperatures for atmospheric humidity. Although this has been shown to work in arid regions such as Arizona, and commercial instruments and software developed, it is not reliable in more humid climates because of interactions with radiation and windspeed.

Aim of the project - 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.

3. POTENTIAL FINANCIAL BENEFIT TO THE INDUSTRY

A successful outcome from the project would allow the development of protocols for the use of cheap IRT sensors for rapid and reliable measurement of plant stress and irrigation scheduling in humid climates. This would benefit crop production and the environment in a number of ways:

1. improved accuracy in irrigation scheduling would contribute significantly to more efficient water use. Independent consultants estimate that up to 50% of water applied may be unnecessary. The resultant saving of water required will reduce the costs of on-farm water storage needed to maintain security of supply.

2. wide availability of cheap technology would replace or lower costs to growers of scheduling advice (eg. neutron probe monitoring costs up to £500 per crop site per season).

3. IRT methods could act as a local calibration for methods such as IRRIGUIDE.

4. precise monitoring of crop water status will greatly increase opportunities to improve crop quality through timely irrigation.

5. by reducing the potential for leaching of nitrogen by limiting application of water to that actually required.

Currently, IRT systems are only widely used in arid climates. The work should offer the potential to use cheaper sensors so increasing market penetration of the technology into 'humid' cropping areas worldwide and which are currently showing the greatest increase in the use of irrigation.

As a major cost of irrigation is in the construction of storage for winter abstracted water, small reductions in the necessary storage capacity from improved efficiency of use will rapidly pay back the costs of research. The use of IRT would lead to increased efficiency of water use. The total cost of the research c. £200,000 would be covered over a period of three years if the use of IRTs led to a reduction in water use of 6% (based on ADAS figures and

Pearce, 1992).

The major benefits of IRT, however, will undoubtedly be in significant reduction in N-leaching, the potential for greater security of water supply, and to ensure that the crops can be grown to the full potential yield, to meet harvest schedules and to enhance quality. All of these are extremely difficult to quantify, but if, for example, irrigation was mistimed and this led to a reduction in quality reflected in only a 1% reduction in loss of gross return to the grower this would lead nationally to a reduction in farm gate returns (based on the irrigated field vegetable and potato acreage) of £3.5m per annum. Any reduction in product quality could also jeopardise UK sources of supply.

The project will increase understanding of the environmental factors controlling stomatal aperture and lead to the development of novel ways to adapt existing IRT technology to humid climates. The anticipated modifications are to the 'hardware' of the machine to incorporate a reference surface and to the software or protocols for irrigation scheduling. The procedures developed will require wider testing and validation for at least two years beyond the project before they could be generally adopted. Further work will be needed to extend findings to additional crops. It is possible that the hardware developed could have IPR value. Within the UK the market for IRTs could be substantial as the technique would be applicable to sugar beet, potatoes, vegetables and soft fruit crops that are currently widely and intensively irrigated. World-wide, the scope for expansion is substantial.

4. SCIENTIFIC/TECHNICAL TARGET OF THE WORK

1. to identify the limitations to operating performance of leaf and canopy temperature sensing techniques in practice in the UK

2. on the basis of an analysis of the leaf energy balance equation develop an improved method for normalising leaf temperatures in calculation of a CWSI.

3. to develop a simple reference surface for use with hand-held IRTs so that they can be used routinely by growers

4. to modify the procedures for using IRT instruments in UK conditions

5. to compare IRT with other methods for scheduling irrigation (including IRRIGUIDE, neutron probe and TDR) and to evaluate benefits, in the first instance for selected field vegetables including runner beans as a 'model' crop.

5. CLOSELY RELATED WORK - COMPLETED OR IN PROGRESS

(i) There is currently continued interest worldwide in developments of the energy balance equation, both in terms of theoretical refinements to improve its precision, and in terms of its application to large areas of crop (see Jones 1992 for review), as well as in practical applications such as to the development of transpiration sensors (Harrison-Murray 1991). Within HRI there has been significant recent effort on the analysis of leaf energy balance leading to the development of transpiration sensors and methods for predicting evaporation in glasshouses, while recent work in HRI has also led to greatly improved understanding of the role of stomata both in controlling water status and as indicators of plant 'stress' (Jones, 1990). Other studies within HRI have concentrated the development of plant-based methods for sensing of plant stress and scheduling irrigation (Jones & Sutherland 1991; Higgs & Jones 1991).

(ii) Although much of the basic understanding of plant water relations and of the leaf/crop energy balance that is required for this project has been developed in recent years, there is still a major requirement for strategic research to optimise the application of this knowledge, including the need for significant theoretical development relating to the practical applications of the basic equations. In addition the project makes a number of novel proposals, especially the use of portable reference surfaces, that should, if successful, lead to practical solutions of benefit to UK growers and indeed to the majority of farmers worldwide in non-arid areas.

(iii) Basic studies in stress physiology within HRI are funded by the AFRC under PU 163. Although not directly related to the present proposal the expertise available within HRI will greatly support the development and evaluation of data.

(iv) As indicated above HRI obtains AFRC funding for basic stress physiology, while MAFF supports a range of more applied field studies in HRI and ADAS, some of which involve irrigation, but there is no directly related publicly funded project.

6. DESCRIPTION OF THE WORK

Three separate approaches will be developed in parallel using a common series of experiments.

1. Improve the technique by determining the dependence of the non-water stressed baseline and the calculated CWSI for contrasting vegetable crops in relation to

radiation and wind speed. Micrometeorological data and air and leaf temperature of well-watered and droughted samples of a range of contrasting field vegetables would be collected under a range of environmental conditions (wind speed and radiation) and the results related to stomatal conductance measured with a porometer. Examine the influence of plant spacing. These empirical studies would be used to devise corrections to the standard CWSI approach to stress measurement as a function of crop and environmental conditions. (HRI and ADAS)

2. Re-analyse the leaf-energy balance equation so as to optimise its application to the discrimination of stomatal aperture in humid regions. Develop theoretical corrections that would allow leaf temperature measurements to be normalised in relation to factors such as wind speed and crop aerodynamic properties. Develop parameters to allow for the effects of incident radiation and leaf distribution. All of these can significantly affect the accuracy of a calculated CWSI. These theoretical predictions would then be assessed against measurements of stomatal conductance and micrometeorological data in a range of contrasting crops and used for the development of an improved stress index. (HRI)

3. Develop an experimental approach to overcome the deficiencies of CWSI for UK conditions. Although it is possible to use an area of well-watered crops as a reference and determine the leaf-temperature difference between stressed and well-watered plants, this is unlikely to be convenient in commerce and we propose an alternative approach based on the use of a moist blotting paper reference surface, similarly exposed to the environment as the leaves of the crop being studied. The behaviour of this reference surface would be compared with prediction and with real crops. These results will be related to measurements of leaf conductance, soil water status measured using neutron probe and TDR equipment and crop growth rate in crops grown continually moist and those allowed to develop stresses at various stages of growth under a range of aerial environments. (HRI)

The time table of work is as follows:

First year:
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 soil water deficits

5. An initial test of methods for runner beans on a growers holding will be expected.

Second year:

1. Continued development of artificial reference surfaces should have led to definition of a favoured prototype.
2. Detailed tests of different crop stress sensing techniques (porometry, neutron probe, IRT) will have been conducted at Wellesbourne using irrigation and moveable shelters to control soil water status.
3. Initial trials of the various techniques will have been conducted on grower's holdings (concentrating initially on runner beans and other contrasting vegetable species).
4. Will have narrowed down possible IRT-based methods to no more than two.

Third year:

1. Will have conducted the first field comparisons of the chosen IRT-based methods with neutron probe and IRRIGUIDE at Wellesbourne and on grower's holdings. (Full validation and extension to other crops will require further work.)
2. Provide a draft protocol for use of IRT for irrigation scheduling.

7. COMMENCEMENT DATE AND DURATION

Start date 01.01.94; duration 3 years.

The consortium will hold an initial planning meeting and review progress at 6 monthly intervals, the second of such bi-yearly meetings will coincide with the planning of the following season's work. Annual reports will be produced by 01.01.95 (first year) and 01.01.96 (second year).

The final report will be produced by 01.01.97. Additional reports may be requested for publications in Project News and popular magazines, such as The Grower. It is also likely that the scientists will be invited to present results from the work at HDC sponsored grower meetings.

8. STAFF RESPONSIBILITIES

Project Leader:
Professor H G Jones, Horticulture Research International,
Wellesbourne, Warwick, CV35 9EF
Tel:0789 470382, Fax:0789 470552

Work at HRI:
The experimental work at HRI-W will be carried out using part time input from both an HSO and an ASO. The HRI work will be supervised by H G Jones with additional support

from biometrics staff.

Work on ADAS sites and growers' holdings:
Dr T McBurney
ADAS, Block C, Government Buildings, Whittington Road,
Worcester, WR5 2LQ Tel: 0905 763355, Fax:0905 763180

Industry Partner:
Agrichandlers (EmmaNash Ltd), Hartley Witney, Basingstoke,
Hants, RG27 8DH Tel: 025 126 3205

HDC Co-ordinator:
Mr P Effingham, Marshall Bros.

9. LOCATION

Wellesbourne, ADAS sites and growers' holdings.

Contract No: FV/140
Date: 11.8.94

TERMS AND CONDITIONS

The Council's standard terms and conditions of contract shall apply.

Signed for the Contractor(s)

Signature.......................................
Position....Commercial Director....
Date....19.8.94....

Signed for the Contractor(s)

Signature.......................................
Position.......................................
Date.......................................

Signed for the Council

Signature.......................................
Position....CHIEF EXECUTIVE....
Date....11.8.94....