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Improving irrigation scheduling using infra-red thermometry

Second Annual Report

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Project title:	Improving irrigation scheduling using infra-red thermometry
Project Location:	HRI-Wellesbourne, and Top Barn Farm, Worcester
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Project Coordinator:	Philip Effingham
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GROWER SUMMARY

The purpose of this project is to develop an alternative method for scheduling irrigation of a range of field vegetable crops that can either complement or replace existing approaches based on soil moisture measurement or calculation. The current methods tend to be either expensive or rather imprecise. The project is based on the use of infra-red thermometry (IRT) to sense crop temperatures remotely as a basis for detecting crop stress, and aims to improve the precision of the technique beyond what is provided by a commercially available instrument, the 'Scheduler'.

Extensive data were obtained during 1995 on potato, French bean and runner bean (with an emphasis on runner bean at two contrasting sites). 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 sensing approaches. Extensive IRT data were obtained for runner beans at Wellesbourne and at Top Barn farm; other data were obtained on potato and French bean crops at Wellesbourne.

Although it is recognised that 1995 was an unusually hot and dry year, these data 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.

The key conclusions from the 1995 experiments were:

1. Canopy temperature differences between well irrigated and stressed crops could be as great as 7-10^{o}C, though differences were more usually in the 1.5-4^{o}C range. Such differences, even at the lower range, are readily detectable with IRT instruments, and provide strong support for the viability of the approach.

2. Theoretical analysis of leaf energy balance equations led to the development of a new stress index which was found to be significantly more reliable than the commercially available index calculated by the 'Scheduler'. This should lead to the possibility of more precise control of irrigation.

3. More recently the idea 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 has yet to be fully evaluated and will be assessed by reanalysis of existing data over the next three months.

4. A number of other measures of crop stress were measured in parallel with the IRT and soil moisture content measurements made. Both stomatal conductance as mesured with a 'porometer' and the diurnal shrinkage/expansion of fruit or stem diameter also showed promise as alternative approaches.

5. Extensive experience gained of the operation of IRT in UK conditions has led to the definition of design criteria for a pre-prototype instrument for further field testing of the robustness of the new stress index concept. Negotiations are under way with manufacturers to collaborate in instrument development.

6. It is proposed to set up further field trials both at Wellesbourne and on grower holdings in 1996 where contrasting irrigation regimes will be imposed to provide material with contrasting water status for testing the new IRT approaches.

1. AIM OF THE PROJECT AND SECOND YEAR MILESTONES

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

Following the February Review Meeting, revised second year targets were agreed **(see 18-month report)** and the following scientific report is related to those targets.

2. PROGRESS

Project meetings.

2.1 (a) The outcome of the project review meeting held at Wellesbourne on 17 February 1995 was outlined in the Interim report.

(b) A second review meeting was held at Top Barn Farm on 17 August, 1995. The meeting was attended by Dr C Wall (LINK), Dr B Pearce (MAFF), Dr E Moorhouse (HDC), Mr G Amos (Agrichandlers), Dr T McBurney (ADAS) and by Professor HG Jones, and Mr RLK Drew (HRI), Mr D Harper (Top Barn Farm).

At this meeting progress so far was reviewed and the opportunity taken to view the field experiments at Top Barn Farm. Operation of the Infra-red thermometers in the field was demonstrated, with the high potential sensitivity of the system being apparent from the observation that the effect of ceasing regular irrigation only 24 hours earlier was detectable in terms of raised leaf temperature.

Initial results for the 1995 season were outlined (see below for further details) and there was some discussion of the future programme for the project, and conclusions are outlined elsewhere in this report.

Scientific progress

2.2.1 The continued development of artificial reference surfaces to enable the definition of a favoured prototype.

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

2.2.1(a).1 METHODS

Initial analyses used the 1994 data, but there were not enough sets of measurements on real leaves to get reliable estimates of the comparable time constants for them. It was therefore decided to set up automated monitoring of leaf temperature in 1995 using a data logger to collect a wider range of more representative data for real and model leaves at the same time. The temperatures of both model leaves and real leaves were monitored in the field, using inserted fine-wire thermocouples. These measurements were made between July and September 1995.

2.2.1(a).2 RESULTS

As expected, the half-time of the response (the time for 50% of the total change to occur) for the real leaves was significantly shorter (at c.10 s) than the half-time for the prototype model leaves (1 - 2 min) which always took several minutes to reach a new 'steady-state' temperature (see Fig. 1). When lighting conditions were changed (for example by shading the leaves from direct sunlight using an opaque screen), the smaller sized model 'leaf' appeared to have a slightly faster response than that of the larger, but the difference between models was small. Similarly the half-time was also only slightly modified by variation in windspeed over the range of windspeeds observed.

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 could be made. To obtain a more accurate set of estimates, it would be necessary to develop, fit and test a model that explicitly incorporates the kinetics of heat exchange and storage. An outline model for estimating the appropriate transfer resistances for model leaves has been developed, and details are available if required. Whilst this is of theoretical interest, 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. This model will be developed further only if additional experiments planned for 1996 lead to the conclusion that the best approach for estimating the reference temperatures (wet or dry leaves) is that based on calculation (see Section 2.2.4.2(d)) rather than on the use of physical models.

The prototype design of the model leaves had included an aluminium core to slow the rate of temperature response of the models, with the idea that in a rapidly changing environment it would be better to have reference leaves that averaged environmental conditions over a significant period than to have very rapidly changing references. However, it became apparent during experimental field testing during the 1995 season, that the time lag between the response of real leaves and model leaves introduced by such a system could lead to increased scatter when relatively small numbers of individual estimates of the difference between leaf and reference surface temperatures are made. Therefore new models were constructed which omitted the aluminium core. Although the response of these leaves matched more closely that of real leaves, it still approached one minute, and the absolute magnitude of the temperature oscillations was still significantly damped. Further modifications will be tested in the coming months.

Fig. 1 shows some typical data obtained in the field for the leaf temperature dynamics of real bean leaves and for model leaves (both the original aluminium cored model and the mark 2 model with no aluminium core). It is apparent from this figure that the lag was greatly reduced with the mark 2 model leaves, but that damping of the magnitude of the fluctuations was still very marked.

2.2.1*(b) Theoretical developments.*

Previous theoretical analysis (see twelve-month report, and H G Jones, 1994. Use of infra-red thermometry for irrigation scheduling. In *Aspects of Applied Biology*, **38**, 1994 *Efficiency of water use in crop systems*) had shown that the difference between the temperature of a leaf and that of either a wet or a dry model (ΔT) is affected by all environmental factors to varying extents. This means that if one is to use infra-red thermometry to estimate stomatal conductance, and one uses only a wet *or* a dry leaf model as a reference, it is necessary to get simultaneous information on the full range of environmental conditions (wind-speed, temperature, radiation, and humidity) and to get the maximum precision one also needs information on how these vary with time.

An important theoretical advance was made during the year by adopting an analysis that had previously been developed for the estimation of evaporation rates from wet surfaces (H G Jones, D Aikman and K Loach, 1990, unpublished; H G Jones, 1992. *Plants and microclimate*, Cambridge University Press). This was to show that by using both wet *and* dry model 'leaves' as references it is possible to reduce greatly the environmental sensitivity of any stress index calculated. The first approach was to replace the theoretical 'non-water-stressed baseline' and the theoretical 'dry surface line' as used by Idso in the calculation of a 'Crop water stress index' (CWSI) by the temperature of the wet and dry models, respectively. On this basis an improved stress index, SI(2), could be defined as

$$SI(2) \quad = \quad (T_{leaf} - T_{wet})/(T_{dry} - T_{wet}) \qquad (1)$$

It had been expected that this would improve the resolution in comparison with Idso's original CWSI (as used by the 'Scheduler'), but the extent of the improvement had not been realised until the behaviour of this index was further analysed during the summer. More recently, this approach has been taken further by using the previously derived equations to show that the stomatal resistance (r_{lw}) is simply related to the temperature difference between the leaf and a corresponding wet surface divided by the temperature difference between that of a dry surface and the leaf, according to

$$r_{lw} \quad = \quad (T_{leaf} - T_{wet})/(T_{dry} - T_{leaf}) \times (r_{aw} + s.r_{HR}/\gamma) \qquad (2)$$

where the last term in brackets is a measure of the boundary layer conductance and is primarily dependent on windspeed. This represents a major advance, firstly because this calculation is *completely independent of both humidity and radiation*, and secondly because the measured temperatures are explicitly related to the leaf conductance. Over the next few months it is proposed to recalculate some of the data to enable a direct comparison between r_{lw} and the other measures of stress (CWSI and SI(2)).

The major consequence of this development is that it is no longer necessary to measure either humidity or radiation in order to get a good estimate of stomatal conductance, the critical measure of stress that is being detected by the IRT method.

2.2.1(c) Development of practical prototype for field testing of new protocols.

As indicated above, the use of lightweight reference leaves is being investigated for future use. In addition we are entering discussions with a number of potential manufacturers to help us provide both improved robust leaf models for a new field system, and importantly a prototype recording lightweight IRT and datalogger. Currently significant progress is being made in discussions with Protimeter, who have provided a very simple IRT with adequate resolution that is currently under test at Wellesbourne. In addition, Gottfried Pessl is also interested and some preliminary discussions were held when he visited the UK in January. However, he concluded that he was unable to help construct the necessary pre-prototype for the 1996 season experiments.

2.2.2 Detailed tests of different crop sensing techniques (e.g. porometry, neutron-probe, and IRT) at Wellesbourne using irrigation and moveable shelters as necessary to control soil water status.

2.2.2.1 METHODS

As outlined in the 18-month report, trials were established at Wellesbourne similar to those in 1994 for the three species of interest, but with the plant spacings adopted aiming to simulate better those used in commercial practice. In each case there were three treatments (well irrigated, moderate irrigation and stress), replicated twice. For the runner beans all treatments had a polyethylene soil mulch to ensure that any rainfall that might occur during the season would not eliminate the treatment defferences. Potatoes and French beans were sown on 19 May, and runner beans on 31 May. Irrigation was applied to assist seedling emergence of the French beans on 1 June, with experimental treatments commencing on 5 June (potatoes and French beans) and 12 July (runner beans). Irrigation was by seep hose providing 1.25 litres of water per minute per metre. Throughout the season, 'Wet' treatments were given one or two hours irrigation weekly, with the 'Intermediate' treatments being irrigated fortnightly. Because of the very dry season, it was also necessary to irrigate the 'Dry' treatment on a couple of occasions to maintain some growth.

2.2.2.2 GENERAL DATA FOR WELLESBOURNE EXPERIMENTS

(a) Soil moisture and weather conditions

The season was generally hot and dry (exceptionally so for much of its duration), with weather conditions summarised in Fig. 2.

The trends in neutron probe counts (which are proportional to soil moisture content) under the three irrigation regimes for the three crops are summarised in Fig. 3 where the day number refers to days from 29 June. For all three crops it is clear that throughout most of the season (except for a period with runner beans) there was at least one large treatment treatment difference in soil moisture for each crop and that these treatment differences continued to increase throughout the season until measurements were stopped (because of crop maturation in potatoes and French beans, or because of cold weather for runner beans).

(b) Crop growth.

Differences in soil moisture content were reflected in significant differences in crop growth and production (Table 1).

Table 1: Yields for French bean and Potato (1995 at Wellesbourne). For French beans the value is the mean weight of pods per replicate harvested from the two central rows, while for potato the value is mean across replicates of the total tuber weight from 12 experimental plants lifted on 17 Oct.

	Wet	Intermediate	Dry
French bean (g)	975	518	405
Potato (kg)	20.9	16.3	17.1

2.2.3 *Trials of the various techniques on grower's holdings.*

2.2.3.1 METHODS

The purpose of these field trials is to enable development and testing of the IRT scheduling technique in commercial crops. As in year 1, water stress treatments have been imposed from 24 May onwards by by-passing 10 m lengths of irrigation tape at four locations within a commercial runner bean crop. 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.

The development of soil and plant water stress was monitored independently of the irrigation decisions from 27 June. Soil moisture content was monitored using a time domain reflectometer (TDR) system with *in situ* probes at depths of 30, 60 and 100 cm in each irrigated and unirrigated plot. Changes in plant tissue dimensions were monitored on 16 occasions for periods between 1d and 7d using micro-displacement transducers attached to the stem base, leaf petiole or bean pods. Such changes have been linearly correlated with direct measurements of water potential made with a dewpoint psychrometer attached to the plant stem (McBurney and Costigan, 1986) after taking account of the effects of any plant extension growth. Leaf temperatures were measured with an IRT or with miniature thermocouples inserted into the leaf or bonded to the leaf surface with heat-conducting adhesive. Plant water potentials were also measured with the destructive pressure chamber technique.

2.2.3.2 RESULTS

Soil moisture measurements with the TDR system (Figure 4) showed that significant soil drying had occurred under the droughted plots by early July, and that these treatment differences were maintained until August. Results with several other indicators of water stress (leaf water potential, stem shrinkage, stomatal conductance and IRT measurements) are presented below (see Section 2.2.5) and confirm the development of stress by 4 July. In spite of the extensive evidence of plant stress in early July, visual symptoms of plant stress (poor vigour, leaf yellowing and re-orientation) did not appear until mid-July. Stress was so severe by early August in those plots that had been deprived of water that the original treatments were rewatered, and new stress plots set up. As was apparent at the time of the project visit on 17 August, detectable stresses could become apparent within 24 hours or so of cessation of watering (see also Section 2.2.5).

Interestingly, attempts to detect changes in leaf temperature (using inserted thermocouples) as water was withheld from cut leaves did not succeed in detecting clear changes in leaf temperature, even though increasing water stress was demonstrated by petiole shrinkage. The reason for this is not clear, but as comparable stomatal data were not available it is possible that the stomata did not close on this occasion. It could be appropriate to follow this up in further work.

2.2.4 Comparisons of the various IRT methods for measuring stress

2.2.4.1 METHODS

The major effort during the year involved testing different protocols for assessing a 'stress index' for the three crops being studied, using both the experiments at Wellesbourne and those at Top Barn Farm. On this occasion, the prime objective of the work was to assess the relationship of the various types of 'stress index' to stomatal conductance, rather than to attempt to relate the results directly to crop yield responses which will be an objective for the future.

A number of approaches were investigated and compared, and a large number of independent sets of measurements obtained of either absolute leaf temperatures (using one of three different IRTs: the 'Scheduler', an Agema Thermopoint 20-50 or a Barnes PRT10) for the different irrigation treatments or of a range of different 'stress indices' (either calculated by the 'Scheduler', or by one of several different algorithms). The 'Scheduler' was used to obtain leaf temperature data on eight occasions for the potato and French bean plots at Wellesbourne, on twelve occasions for runner beans at Wellesbourne and three for runner beans at Top Barn Farm during the 1995 season. This allowed calculation of the Crop Water Stress Index (CWSI) using the built-in software. On other occasions other IRT instruments were tested. These IRT data were compared with independent water stress estimates using either stomatal conductance, water potential, or neutron-probe measurements. Variation was achieved by sampling plants from the different stress treatments.

2.2.4.2 RESULTS

(a) Direct comparison of Irrigated versus Droughted plants

The most direct method for using the IRT is to compare adjacent irrigated and droughted plants. Such measurements were made on over twenty occasions during the year at Wellesbourne and on four at Top Barn Farm. Figure 5 summarises the mean temperature differences between the leaves of the Wet treatment and either the Intermediate (I) or Dry (D) treatments for both French bean and runner bean for measurements on different days at Wellesbourne. The maximum mean temperature difference reached 5.5^{o}C, but was generally less than that, normally being in the range 1.5-4.0^{o}C. Small differences can occur either because there was little difference in water status between treatments (for example as a result of incomplete watering of the controls) or because measurements were made during periods of particularly high humidity or low radiation.

At Top Barn Farm the mean temperature differences between irrigated and droughted leaves were 2.1 (± 2.0) ^{o}C on 3 July, 7.0 (±3.6) ^{o}C on 9 August and 4.2 (±1.5) ^{o}C on 17 August. Figure 6 shows some examples of individual paired measurements on irrigated and droughted plants at Top Barn Farm on different dates between 3 July and 17 August. The data for 9 August (Fig. 6c), which show the absolute temperatures, rather than the temperature difference, show that even though the absolute temperature may fluctuate, the temperature difference can be reasonably constant. This day was particularly hot, dry and sunny, so probably represents the most favourable conditions for use of the IRT in the UK.

Differences of this magnitude can be readily distinguished with even relatively unsophisticated IRTs. It is worth noting, however, that the magnitude of the treatment difference to be expected is very dependent on current environmental conditions, with the two periods of rather poor discrimination for the August 17 data coinciding with thick cloud cover.

It is important to remember, however, that this approach (involving a comparison of crops with well-irrigated controls) is unlikely to be appropriate for normal commercial practice as one would not normally have a well watered control crop readily available, therefore it is appropriate to concentrate on 'stress index' approaches that do not need well watered controls.

(b) Comparison with air temperature.

Using air temperature as a reference provides a useful method for correcting for some of the day to day variability in weather conditions when using leaf temperature as a measure of stress. However, as was pointed out in the previous annual report, this is not as useful as comparing leaf temperature to that of wet or dry 'model' leaves. Therefore this will not be considered further in this report.

(c) Comparison of the 'Scheduler' (CWSI) and 'new' IRT indices.

A large volume of data was collected throughout the 1995 season on the potato, French bean and runner bean crops that allowed a comparison between IRT stress indices (both the original CWSI and the improved indices such as SI(2)) and stomatal conductance. Figures 7 and 8 illustrate typical examples of the behaviour of the individual measurements of CWSI and the new stress index SI(2). It is clear from the data for the relatively cool day (September 4; Fig. 7) that on this occasion, the calculated CWSI did not distinguish the treatments at all well, even though there were large differences in 'stress', as indicated by stomatal conductance. Nevertheless the new stress index (SI(2)) did discriminate treatments well. On other occasions (e.g. September 6; Fig. 8) both stress indices were effective. Over all occasions so far analysed in detail, SI(2) was significantly more reliable than CWSI across a range of weather conditions; because the SI(2) index was particularly good at distinguishing irrigated crops, a grower using this index might apply water less often than when using CWSI.

Figure 9 summarises mean daily values for each treatment of the relationship between either (a) mean CWSI or (b) mean leaf temperature difference from well watered control treatments and mean conductance for the runner bean data at Wellesbourne. For both these measures there was a clear trend for higher values of CWSI or delta-T in the drier treatments; this trend was even more marked if one uses the observed stomatal conductances as the measure of stress. The exceptions, for example where CWSI or delta-T were small in spite of low leaf conductance, were associated with suboptimal weather conditions (cloud or lower temperatures and higher humidities).

In the next few months it is proposed to complete the reanalysis of the data to assess the magnitude of the improvement that can be obtained by using the newly developed equation (2) rather than either CWSI or the raw temperature difference between treatments, both of which are sensitive to windspeed and radiation.

(d) Determining the best way of using the model leaves in practice.

Three different approaches were tested for relating measured leaf temperature (as obtained with the IRT) to the temperature of model leaves, as is required for application of any of the new stress indices being developed in this project:

- In the first, measurements of model leaf temperatures with the IRT alternated with IRT measurements of real leaf temperature. It was found that the most convenient way to achieve this was to fix the model leaves at one site and return to them at intervals to reset the 'reference' (wet or dry leaf) temperatures. Unfortunately this means that there can be a time lag of a minute or more between model and real leaf temperature measurements. It is clear from data such as that in Fig. 1 or Fig. 6 that this can lead to significant errors.

- In the alternative approach, the temperatures of the model leaves were monitored electronically using the inserted thermocouples. Again, because of the need for the connection of the models to the data-logger used, it did not prove practical to move the existing models around the crop as measurements were made, but it was possible to relate IRT measurements to model leaf temperatures made within 10 s. There were, however, three disadvantages with the preliminary systems being tested:

  i) the thermal inertia of the models used was greater than that of the plant leaves which meant that they had not fully equilibrated (see Section 2.2.1 above).

  ii) because the models were not adjacent to all the real leaves studied, local variation in windspeed or sunshine could introduce some error into the reference values. (We believe that in general this is likely to be a relatively small error as long as the reference leaves are within perhaps 25 m of the crop being studied).

  iii) it is necessary to merge the data from the IRT and the data from the leaf temperature logger into one file for further analysis. This has to be done in the laboratory/office and is a very labour intensive process with the equipment and software currently available. As a consequence there is no immediate readout available in the field of the stress index.

- The third approach is to base the calculations entirely on a theoretical calculation of the behaviour of the model 'reference' leaves' temperatures. This requires continuous recording of the environmental variables (temperature, radiation, windspeed, and humidity) required by the Penman-Monteith equation (see H G Jones (1993), *Plants and microclimate*, CUP). Figure 10 shows how this calculation can successfully correct for variation in absolute temperatures as windspeed and radiation fluctuate.

The experience gained from these studies is being used in the design of a new pre-prototype instrument to test in this coming season (Section 2.2.1(c)). In particular we believe that an ideal system would incorporate the model leaves into the handpiece and record their temperatures directly by the same data system that records individual IRT readings. If the use of real model leaves proves difficult in practice, the theoretical approach used in Fig. 10 appears to provide a good alternative.

2.2.5 Other indicators of plant stress.

During the course of the year information was collected on the performance of a number of possible alternative measures of plant stress in addition to the use of IRT that could have value for irrigation scheduling.

(a) Porometer. The stomatal conductance is the basic plant charateristic which is sensed by IRT methods. Figure 11 shows the seasonal variation in stomatal conductance for runner beans and French beans for the different irrigation treatments at Wellesbourne. The low stomatal conductances of the controls between 30 and 50 days corresponds to the period where irrigation was not adequate to maintain control water status optimal as was confirmed by the low soil moisture data for the same period (Fig. 3).

(b) 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. By the 20 July differences between treatments in the rate of increase in pod thickness were apparent (Figure 12a), in addition diurnal shrinkage of stems was apparent in the unirrigated plants (Fig. 12b). The timecourse of appearance of the characteristic increase in diurnal amplitude of bean pod thickness with increasing stress is shown for an experiment starting on 16 August, when irrigation was withdrawn from a previously well watered set of plants (Figure 13). This figure shows that within three days of ceasing irrigation the diurnal fluctuations in pod diameter were greatly enhanced with a large shrinkage during the day in the unirrigated treatment. Measurements with an IRT only 24 hours after withholding irrigation showed that leaf temperatures became elevated by 1.4^{o}C (±2.7).

(c) Water potential. Leaf water potential was measured with a pressure chamber on a number of occasions during the year at both Wellesbourne and Top Barn Farm. These measurements provided further independent confirmation of the magnitude of the differences in water status between treatments. For example, even on 28 June there was a significant difference of approximately 0.2 MPa between well irrigated and droughted plots at Top Barn Farm, while for measurements on August 2 at Top Barn Farm, the leaf water potential was 0.37 MPa lower in the drought treatment than in the well irrigated plants. On 10 August at Wellesbourne the leaf water potentials for the different runner bean treatments were -0.89 MPa (Wet), -1.13 MPa (Intermediate) and -1.31 MPa (Dry). Again this represents a large treatment difference. Similar large treatment differences were obtained for both potatoes and French beans at Wellesbourne on 26 July and 10 August.

3. GENERAL DISCUSSION

The extensive data obtained for contrasting soil moisture conditions, for different crops and for different weather conditions during 1995 provide very strong support for the view that the sensitivity of the IRT approach to crop stress sensing can be adequate for use in UK conditions, as long as efforts are made to correct for radiation and windspeed as well as for humidity variation. The large differences in leaf temperature between irrigated and unirrigated plants measured by the IRT in 1995, which on occasions reached 10^{o}C, are likely to be unusual, since the season was one of the hottest ever recorded for the region. Nevertheless, the consistent success of the technique over a long period at detecting water deficits in the range of crops studied does provide exciting confirmation that the technique potentially has the required sensitivity, at least in a dry year. It will still be necessary to confirm this in a more typical year.

The data collected during the year did emphasise the sensitivity of absolute leaf temperature to both changing windspeed and air currents and to changing irradiance, and hence the need to take account of this variation in developing a commercial system. Any correction for these short term changes will need to handle the short-term variations in leaf temperature of up to 10 C^{o} within the same treatment (Figs. 1 and 5c). Nevertheless the rapid onset of water stress as indicated both by IRT measurements following withdrawal of irrigation and the pod thickness measurements (Fig. 13) demonstrated the speed with which stress can develop in a hot year and the need for a method that can be used for short-term irrigation scheduling. These results justified the grower's use of continuous irrigation in these conditions.

The extensive data on the temperature difference between leaves of the well irrigated and droughted treatments (Fig. 5) is particularly useful in that it gives an indication of the magnitude of the leaf temperature differences that will need to be discriminated in any commercial IRT system in the UK.

The recent formulation of a new approach to the analysis of the IRT data is particularly exciting, since it potentially avoids the requirement to measure radiation or humidity to achieve the greatest precision. The theoretical developments also open the way to basing the correction solely on locally collected environmental data if the use of models proves problematic.

Unfortunately there is, as yet, no absolute measure as to which is the best measure for predicting effects on yield in the crops being studied, but at least these data confirm that stomatal conductance (which is the quantity reflected by IRT measurements) is an appropriate character to emphasise. Figure 14 shows that the stomatal conductance as measured with the porometer was well related to the actual soil moisture deificit under the crop. Interestingly, in view of the very good reliability of the porometer for measuring stomatal conductance, it might even be worth reconsidering whether direct measurement of stomatal conductance might be a viable approach to irrigation scheduling, and information on point this will be obtained during the 1996 season. (Initially it had been felt that porometry was probably rather too temperamental a 'research' tool for it to be adopted by growers, but current instruments are increasingly reliable and cheap).

An important objective for the remaining part of the project will be the definition of the *critical values* for each of the stress indices, 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 require further development in a subsequent year.

4. CONCLUSIONS AND FUTURE WORK

1. Extensive data on IRT use for detection of stress in three crops have been obtained in a hot, dry year. These have demonstrated clearly the potential of the approach in such a year, but further comparable data are required in a less extreme year.

2. The data also provide good support for the use of stomatal conductance as the fundamental measure of crop drought stress. This is, indeed the basis of the IRT approach. Leaf conductance was closely related to both soil water status and to leaf water potential.

3. An exciting theoretical advance has identified what promises to be a robust approach for detecting stress using infra-red thermometry by directly estimating leaf conductance from IRT measurements. In the next few months available data will be reanalysed on this basis, and compared with the existing data (CWSI, delta-T and the 'new' stress index (SI(2)).

4. Design criteria have been drawn up for a pre-prototype for field testing and comparison of the approaches in 1996. Primary objectives of this coming year will be to develop and test a pre-prototype to apply the new approach to infra-red thermometry to UK conditions. This will involve

   (a) testing the accuracy and environmental sensitivity of the possible new IRT sensor from Protimeter (tests under way)

   (b) design and construction of a hand-held data logger linked to model 'leaves', appropriate environmental sensors and an IRT.

   (c) definition of the critical values of each of the stress indices which can be used to indicate when a 'significant' stress occurs.

   (d) major effort is required to determine the range of conditions under which the new stress indices work and the definition of their sensitivity in terms of stomatal conductance. This will be assessed by comparing IRT measurements with stomatal measurements, over a wide range of weather conditions using crops with contrasting water status as obtained in drought experiments at Wellesbourne, Top Barn Farm, and, if possible (if additional resources can be obtained), also other sites.

   (e) In addition we propose to do a theoretical analysis of historical meteorological data, to identify the proportion of time in a week that one would expect to be able to detect a given degree of stress.

5. In order to provide material with a controlled range of soil moisture stress for testing the pre-prototype during the coming year, we propose again to run similar trials at Wellesbourne. In addition we propose to use a range of other

field trials where treatment differences can be imposed, including additional grower sites. It is worth noting that FAST have expressed an interest in testing on strawberry any system developed.

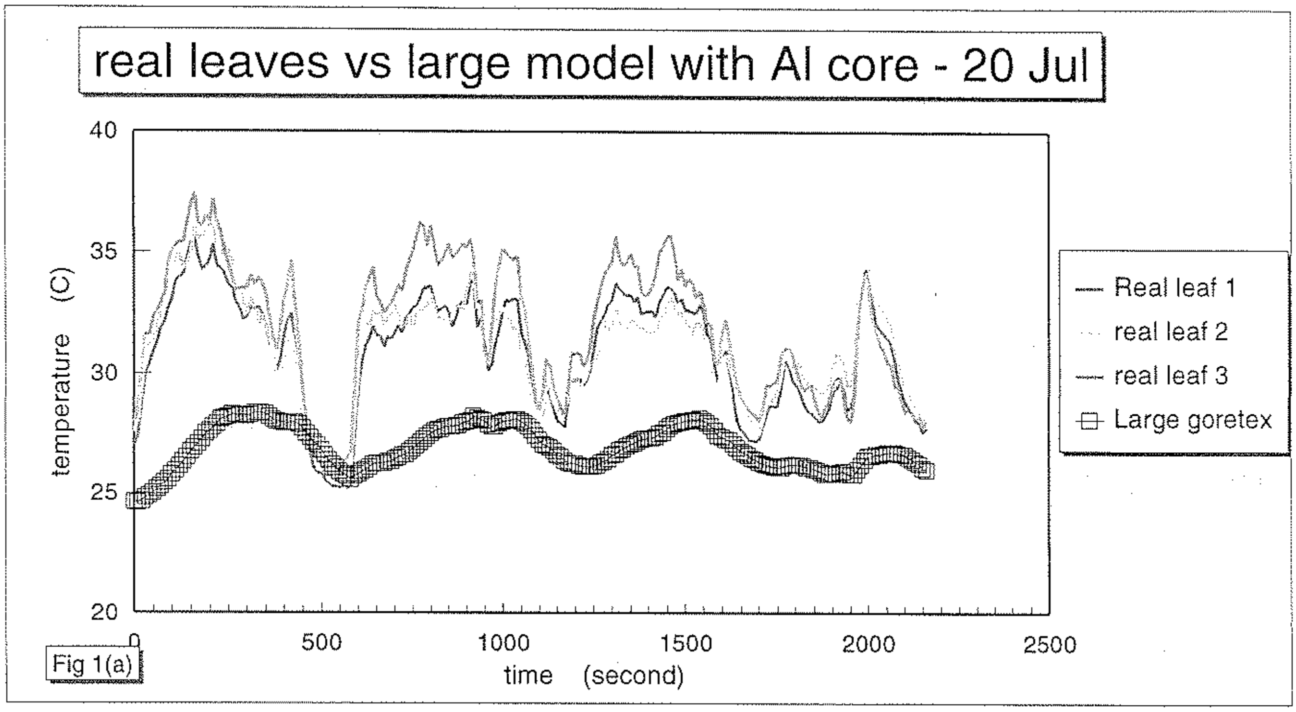
6. It is necessary to investigate with some urgency opportunities for funding the further development of the principle to practical application.

7. Detailed plans for the final year's trials will be drawn up for discussion at the next project meeting. The final choice of methods to be tested in field trials during 1996 will depend on the outcome of ongoing discussions with possible manufacturers of a pre-prototype as to what is the most feasible design.

5. PUBLICATIONS

Jones, H.G., Drew, R.L.K., and McBurney, T. (1995). Improving irrigation by infra-red thermometry. ***The Grower***, March 30, pp. 32-33.

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



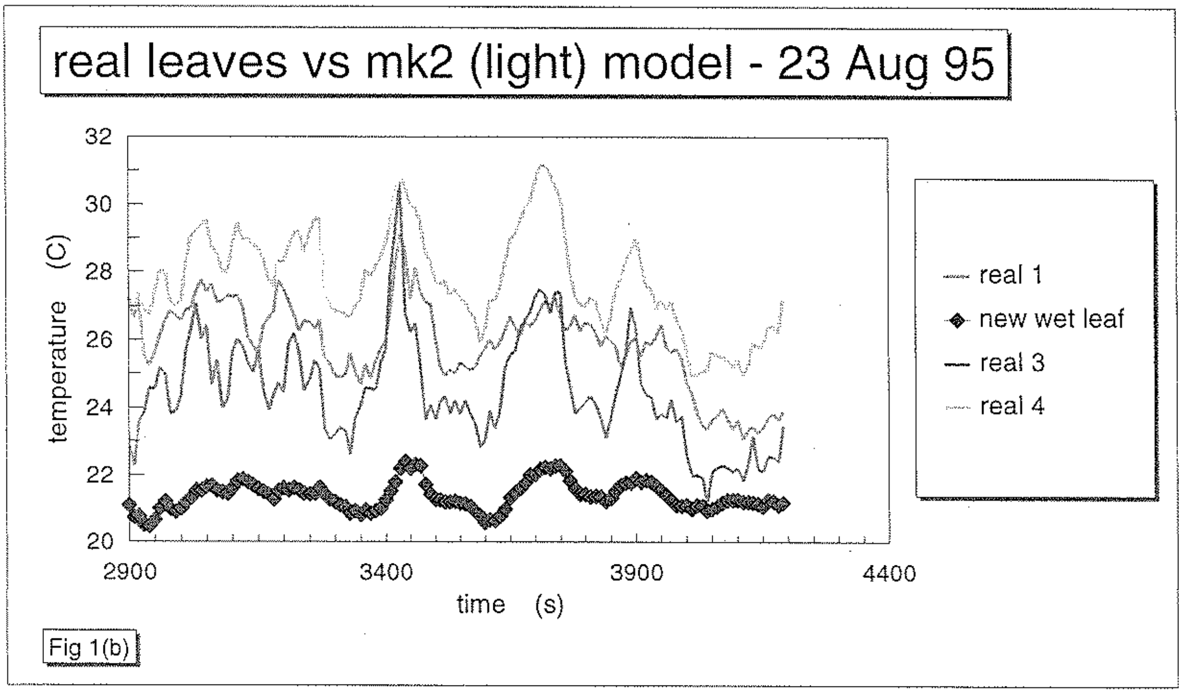


Figure 1: Illustration of the time response of the temperature of real leaves and of the original (a) and the newer (b) model leaves in response to fluctuating windspeed and radiation in the field.

It is clear from these traces that the model leaves respond more slowly than do real leaves and that the amplitude of their response is significantly damped in comparison with that of the real leaves, though the lag is much reduced with the lighter mark 2 leaf.

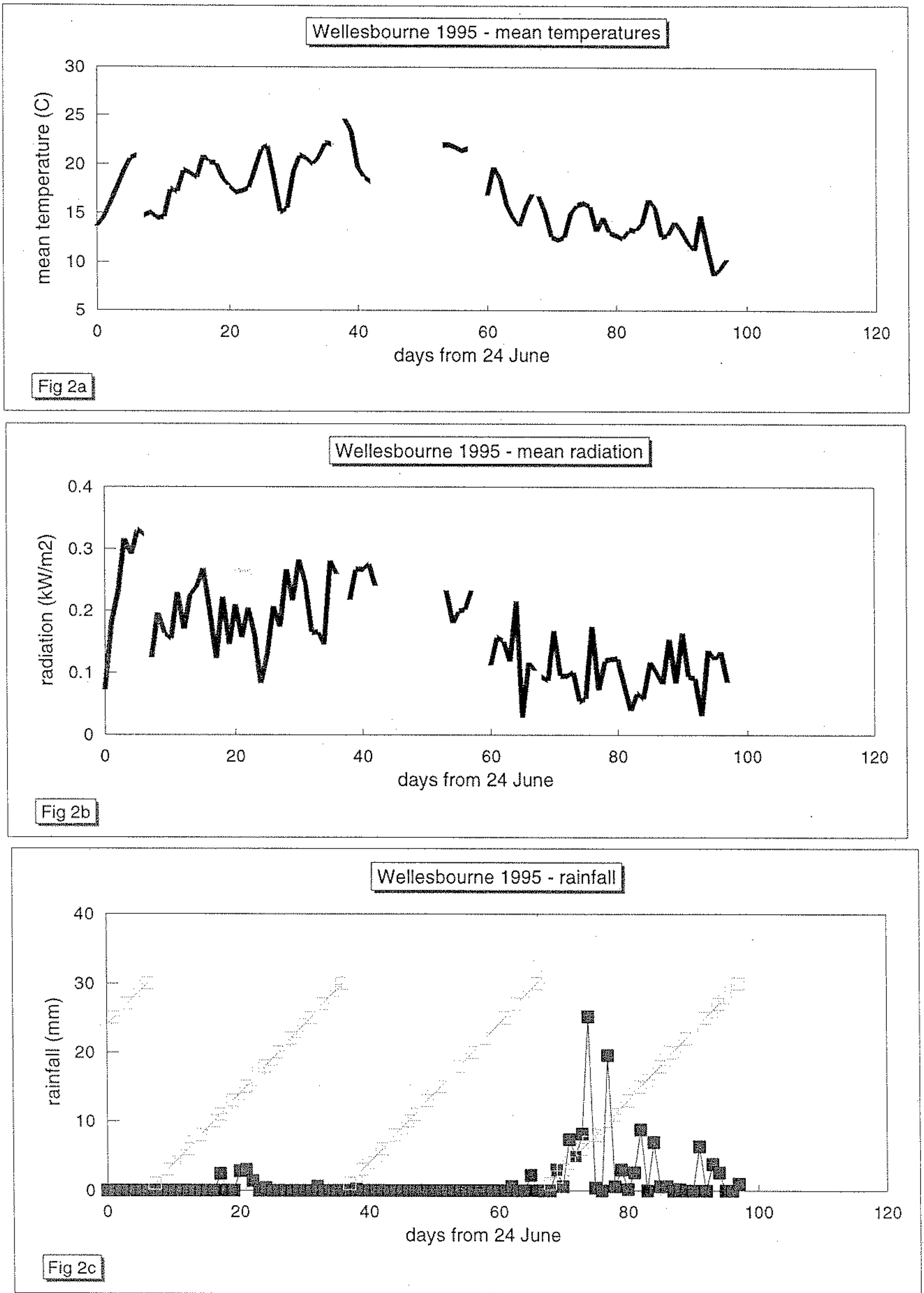
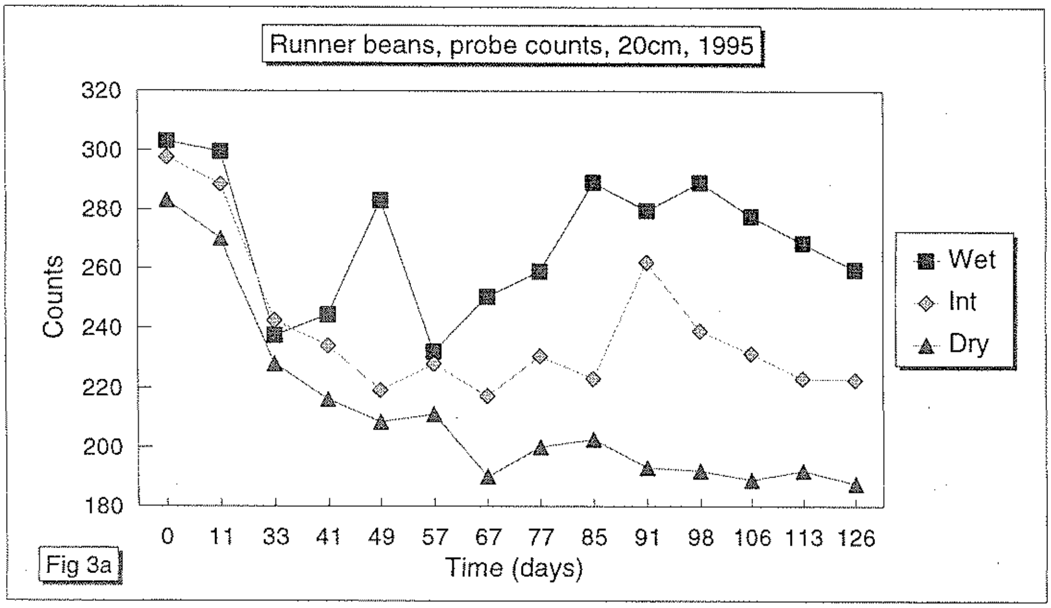
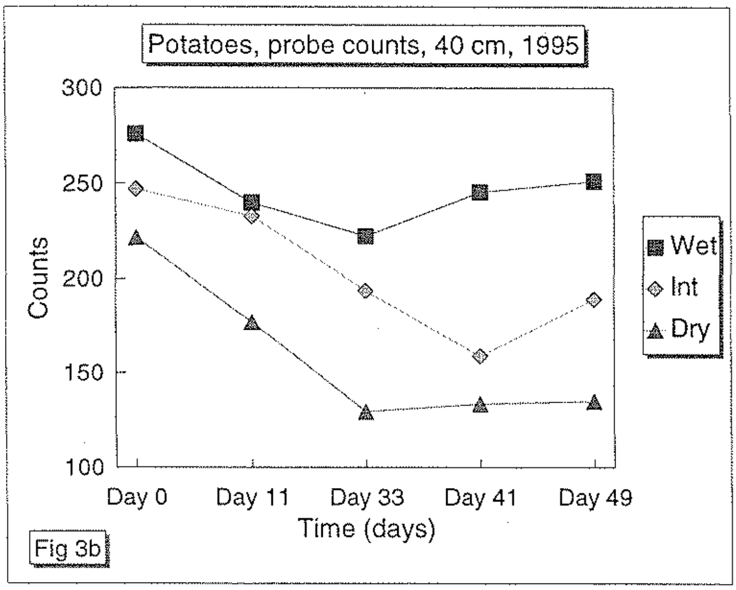


Figure 2. Seasonal means of temperature, incident radiation, and daily rainfall in the field at Wellesbourne during 1995. Dates are expressed from 24 June, the lines in (c) indicate months





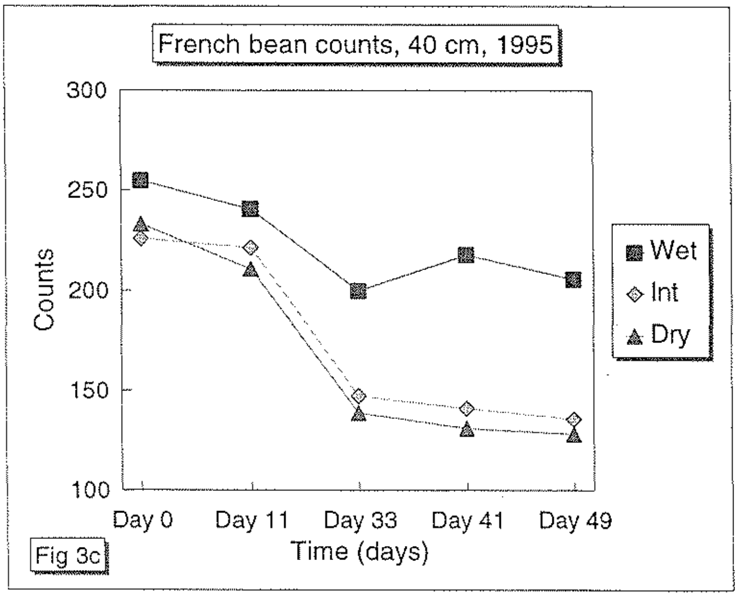


Figure 3: Seasonal trends in neutron probe counts for (a) runner beans, (b) potatoes, and (c) French beans at Wellesbourne during 1995.

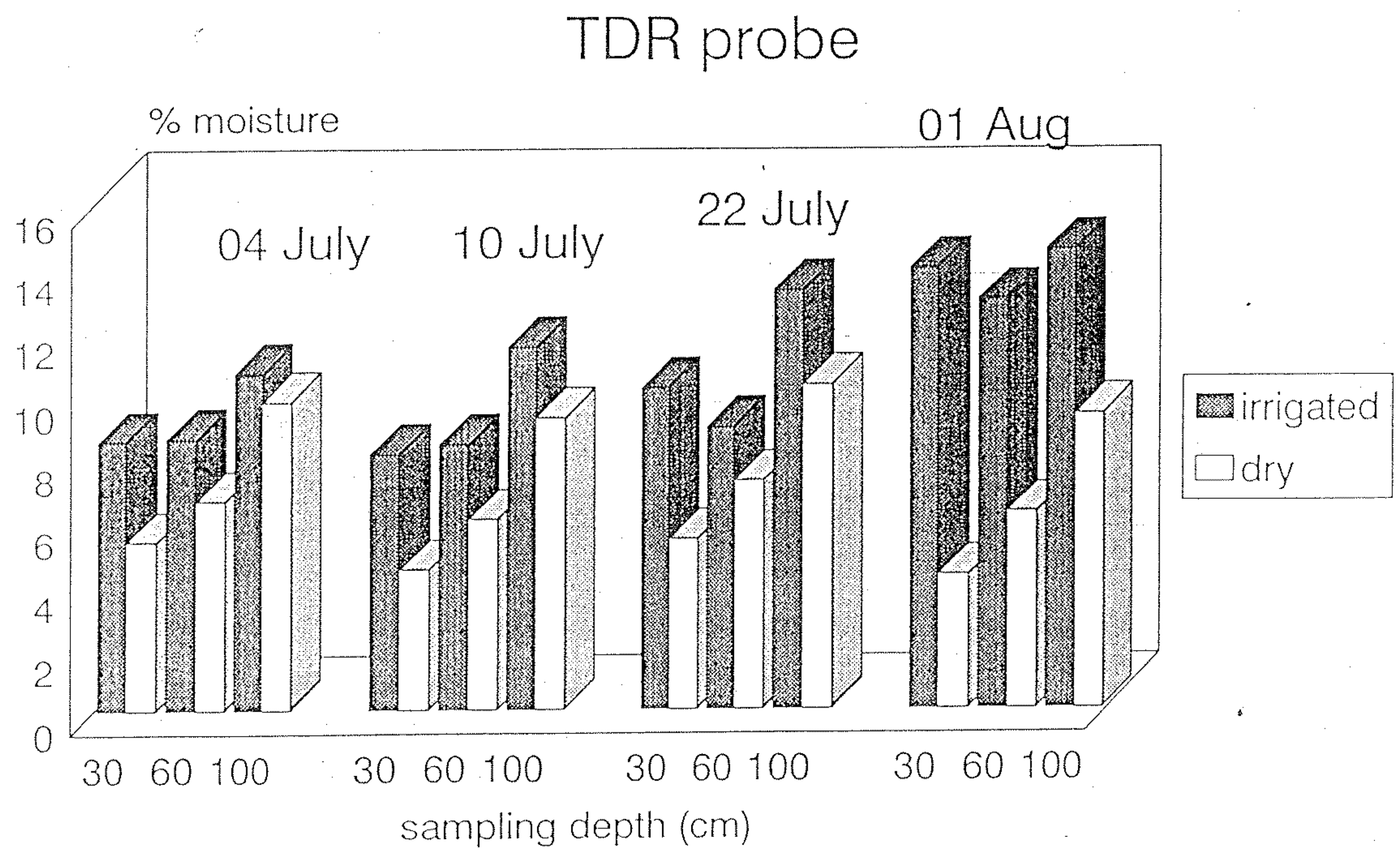


Figure 4. Soil moisture measurements under runner beans during July 1995 at Top Barn Farm obtained using Time Domain Reflectometry. On all occasions there was significantly greater soil drying under the droughted than under the irrigated runner bean plots, especially at shallower depths.

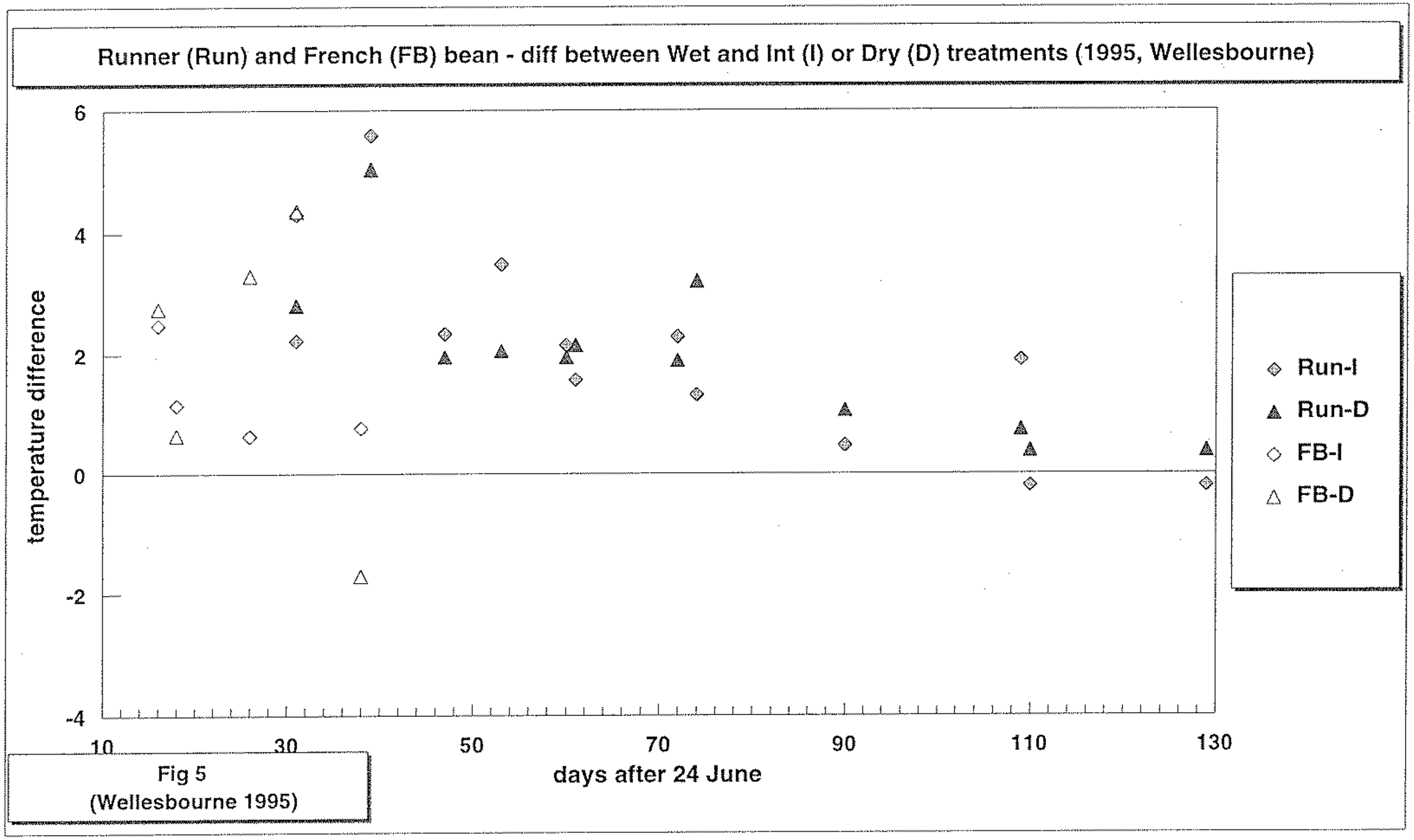


Figure 5: This figure shows the temperature differences on different days during the 1995 growing season between leaves from the Intermediate (I) and dry (D) treatments and the well watered controls. In general the leaves from the dry treatments were warmer than well watered controls.

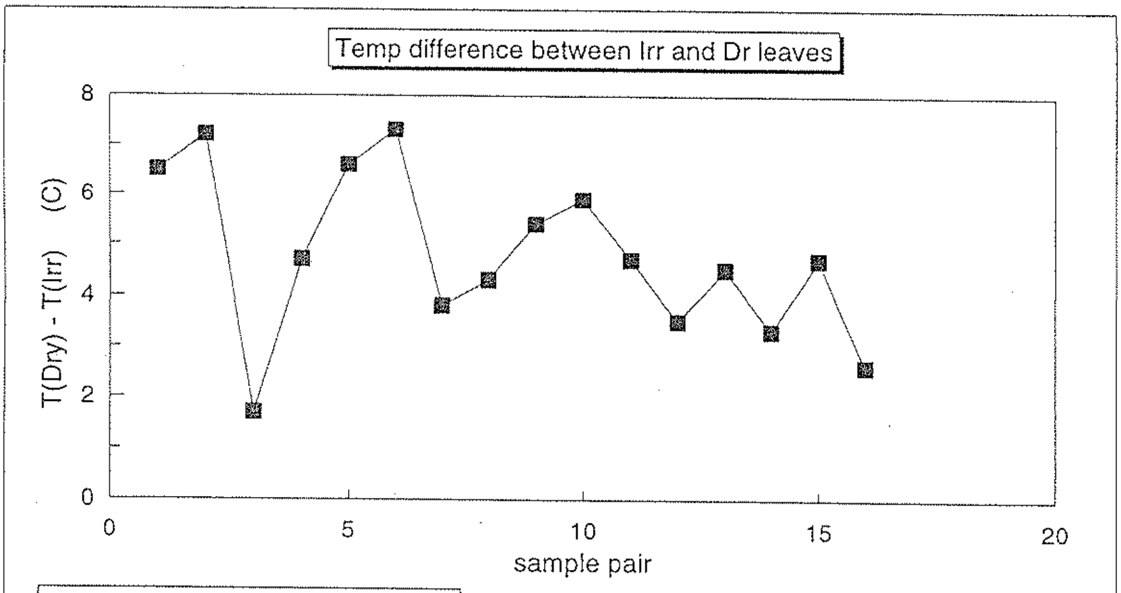


Fig 6a (Top Barn Farm, Jul 3 1995)

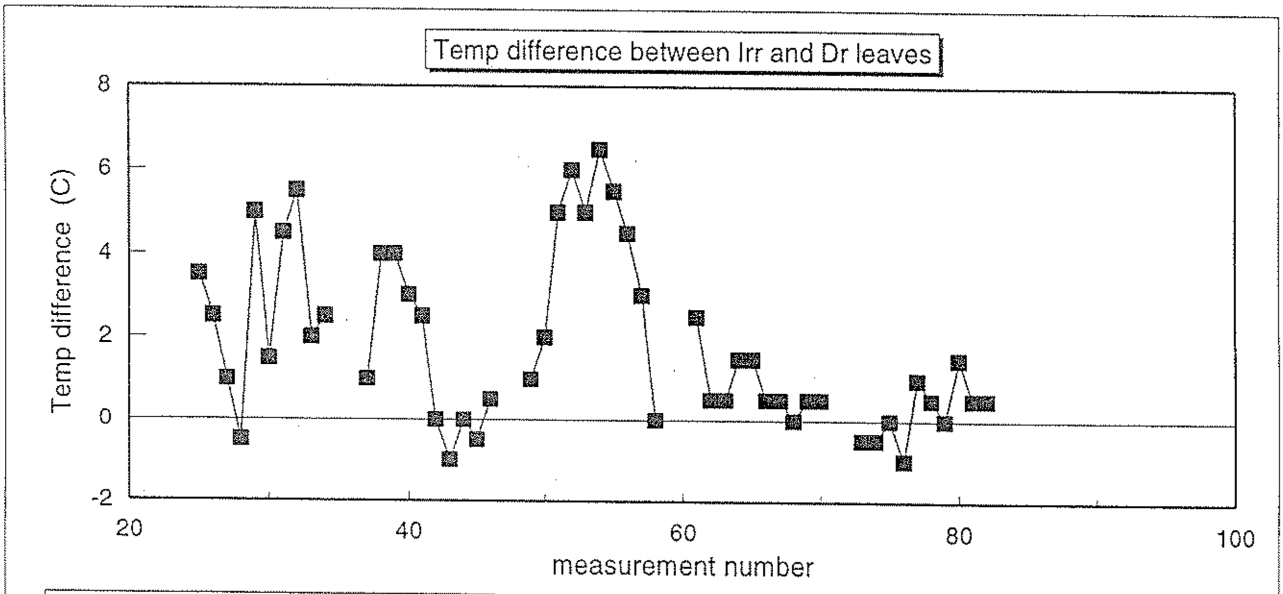
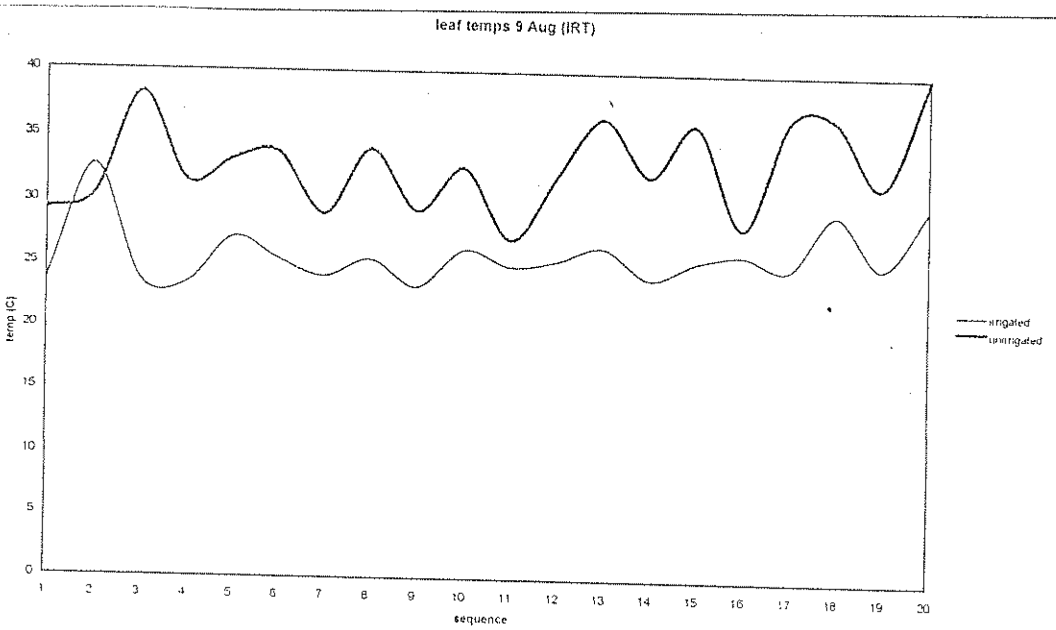
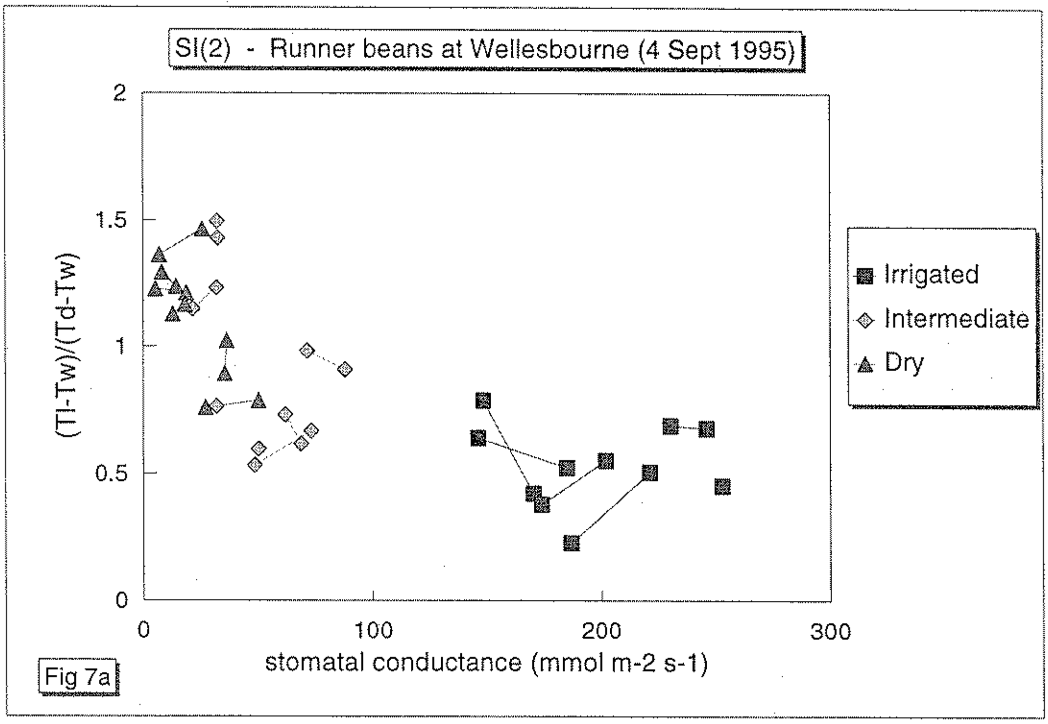


Fig 6b (Top Barn Farm, Aug 17 1995)



6c.

Figure 6: Some detailed examples of individual measurements of paired sequential comparisons between irrigated and drought plots of runner bean at Top Barn Farm. (a) and (b) show two examples of the variability that can occur in the difference, while (c) shows the strong tendency for the absolute temperatures of wet and dry plots to vary together.



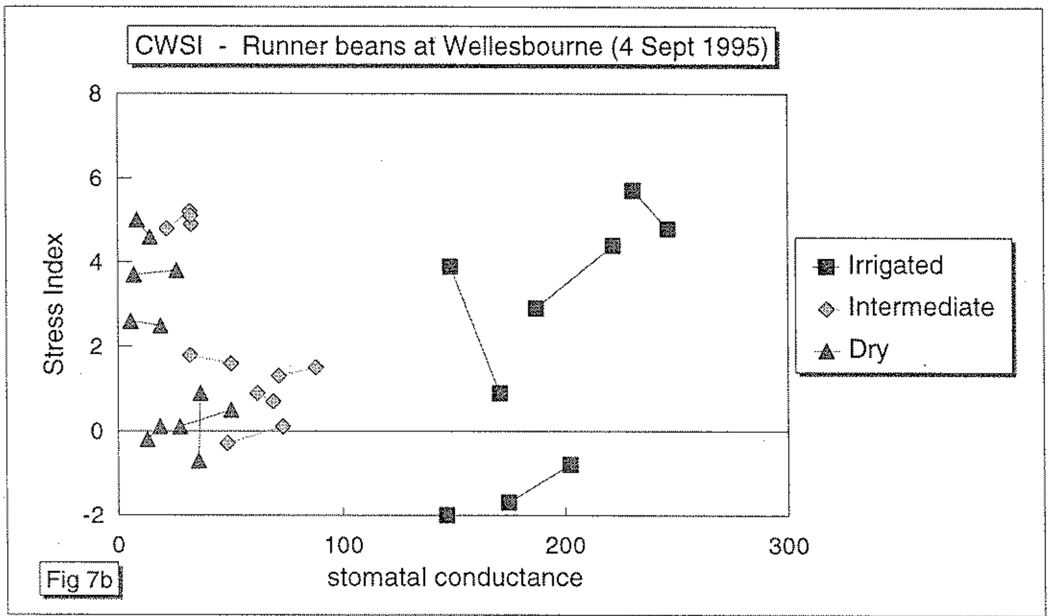
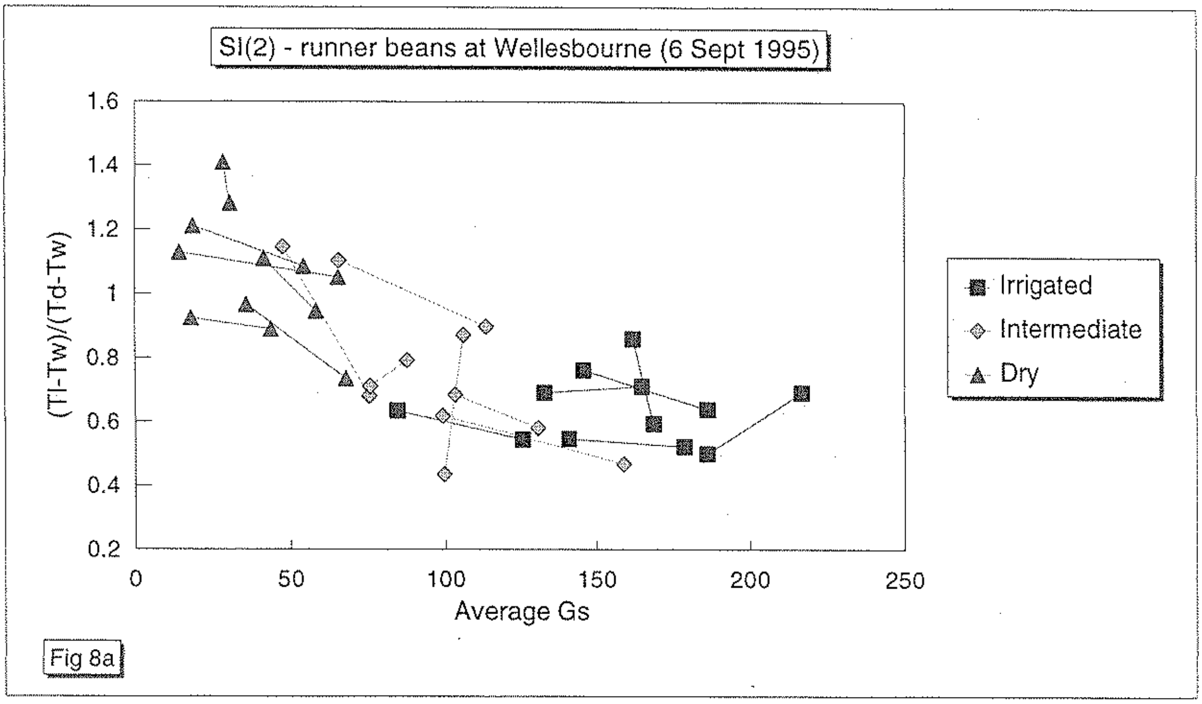


Figure 7: An example for one day (4 Sept 1995) showing how (a) the new stress index SI(2) can be much better than the 'Scheduler' CWSI (b) at distinguishing treamtents. The water status of the three treatments was clearly distinguished by stomatal conductance as shown on the abscissa.



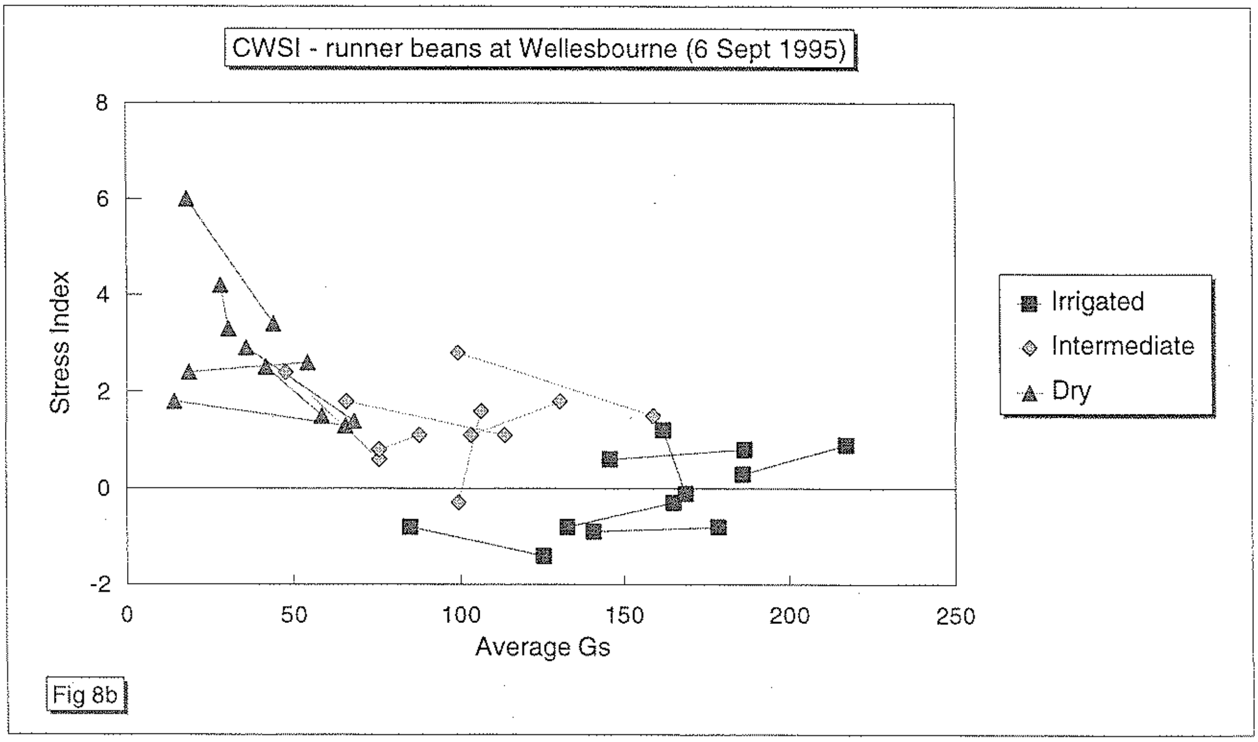
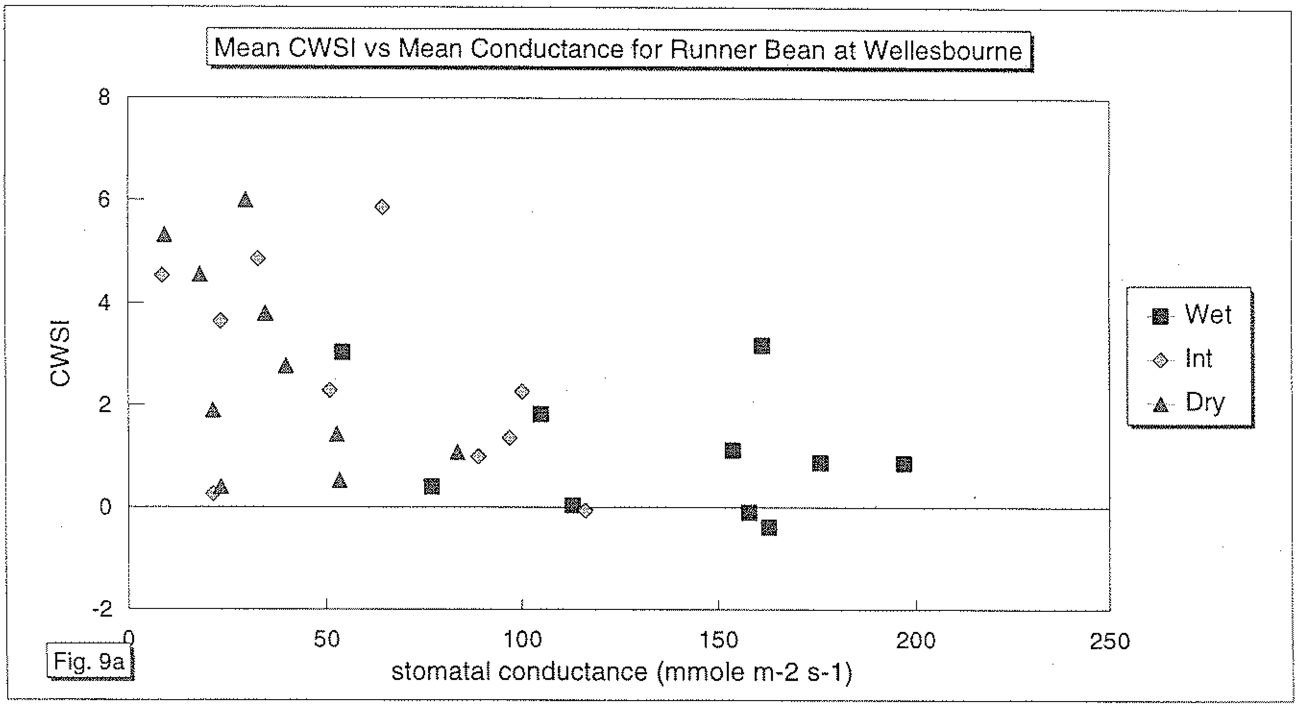


Figure 8: Another example showing the relationship between stomatal conductance on the abscissa and either (a) the new stress index SI(2), or (b) CWSI obtained with the 'Scheduler'



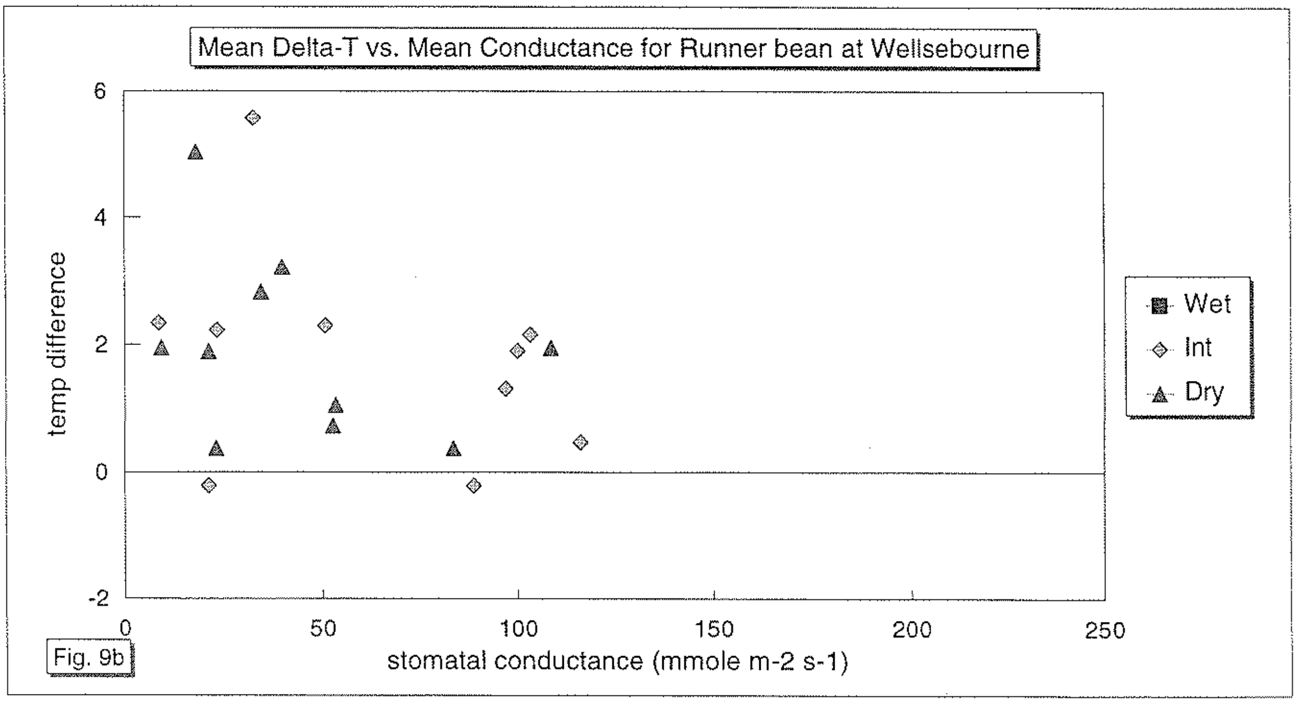
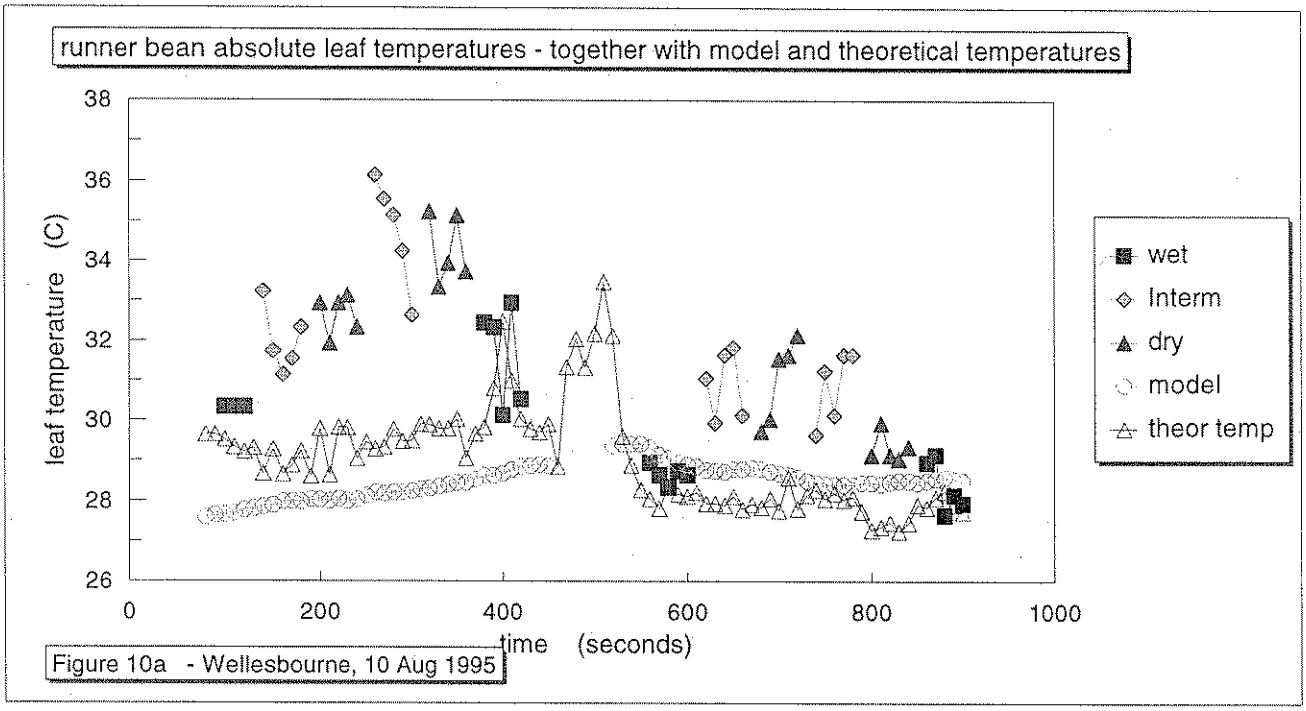


Figure 9: Daily means of (a) CWSI or (b) temperature difference between droughted and irrigated leaves, plotted against mean stomatal conductance for the 1995 runner bean data at Wellesbourne.



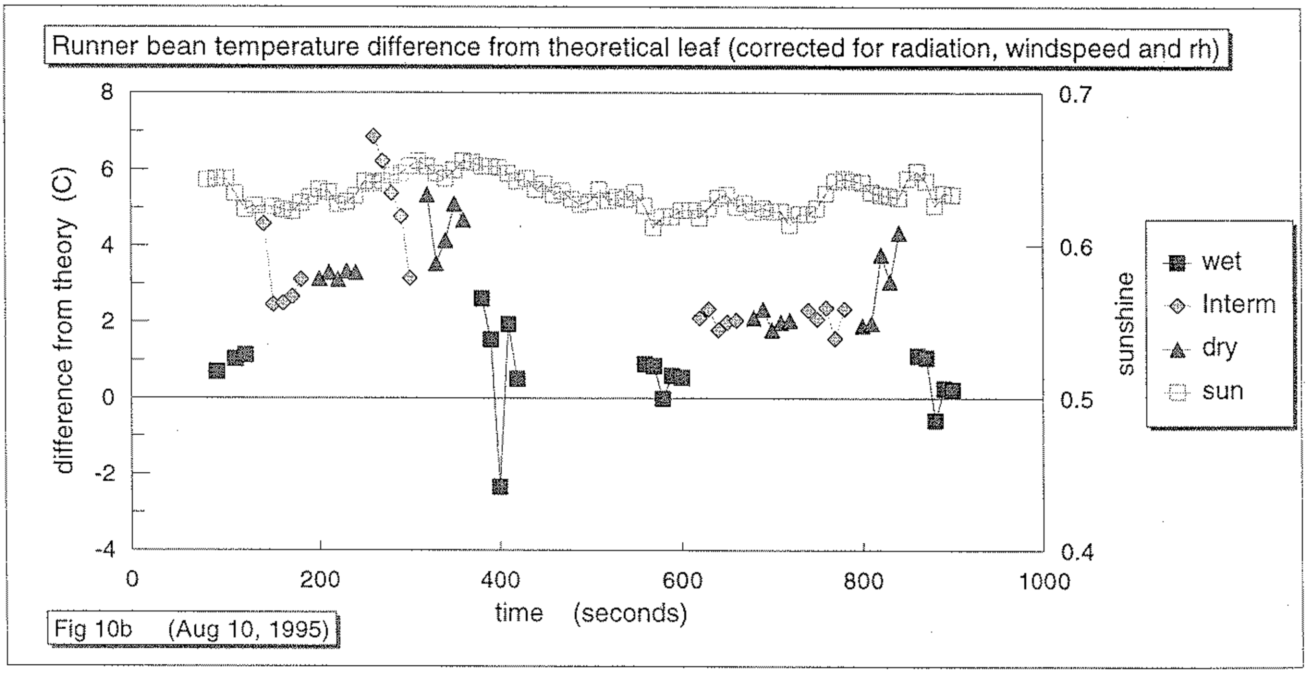


Figure 10: (a) shows how the temperatures of leaves from different treatments change over quite short time periods, such that they can mask even quite large treatment differences. Also shown in this figure is the corresponding temperature fluctuation for one of the original (Al cored) model leaves (very slow) and the theoretical fluctuation in temperature for a leaf with a constant conductance. (b) shows that using the theoretical temperature as reference can greatly improve the ability of the technique to separate treatments.

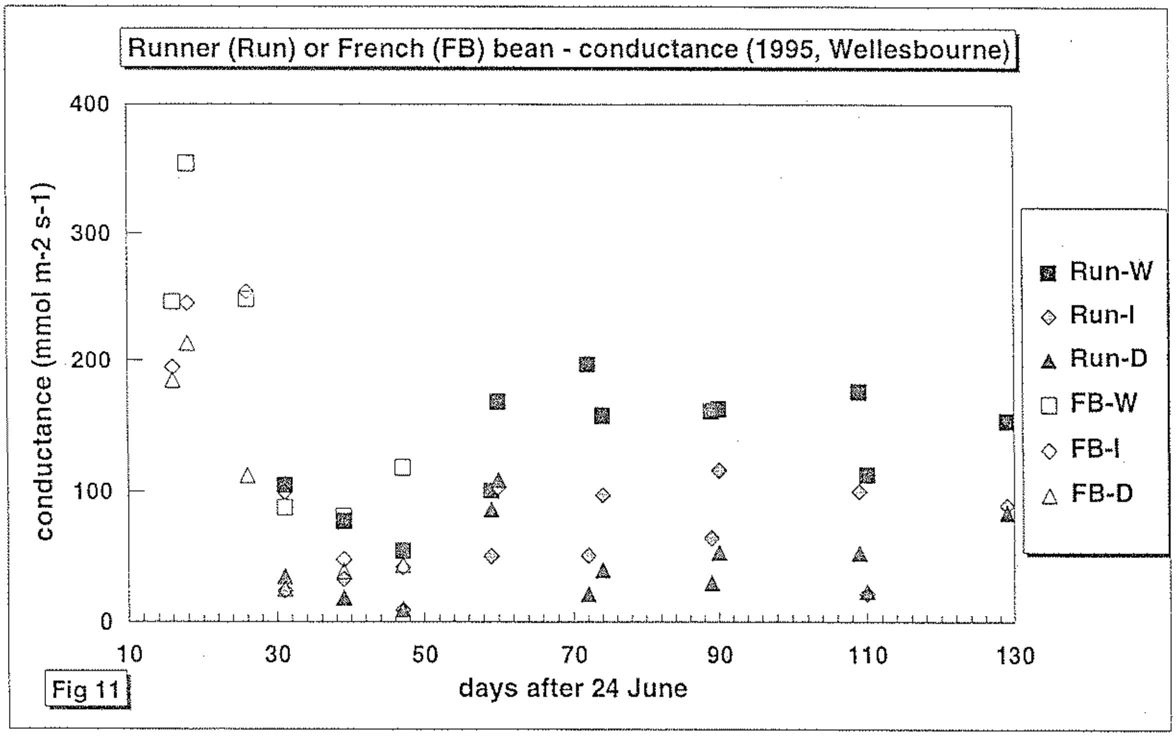
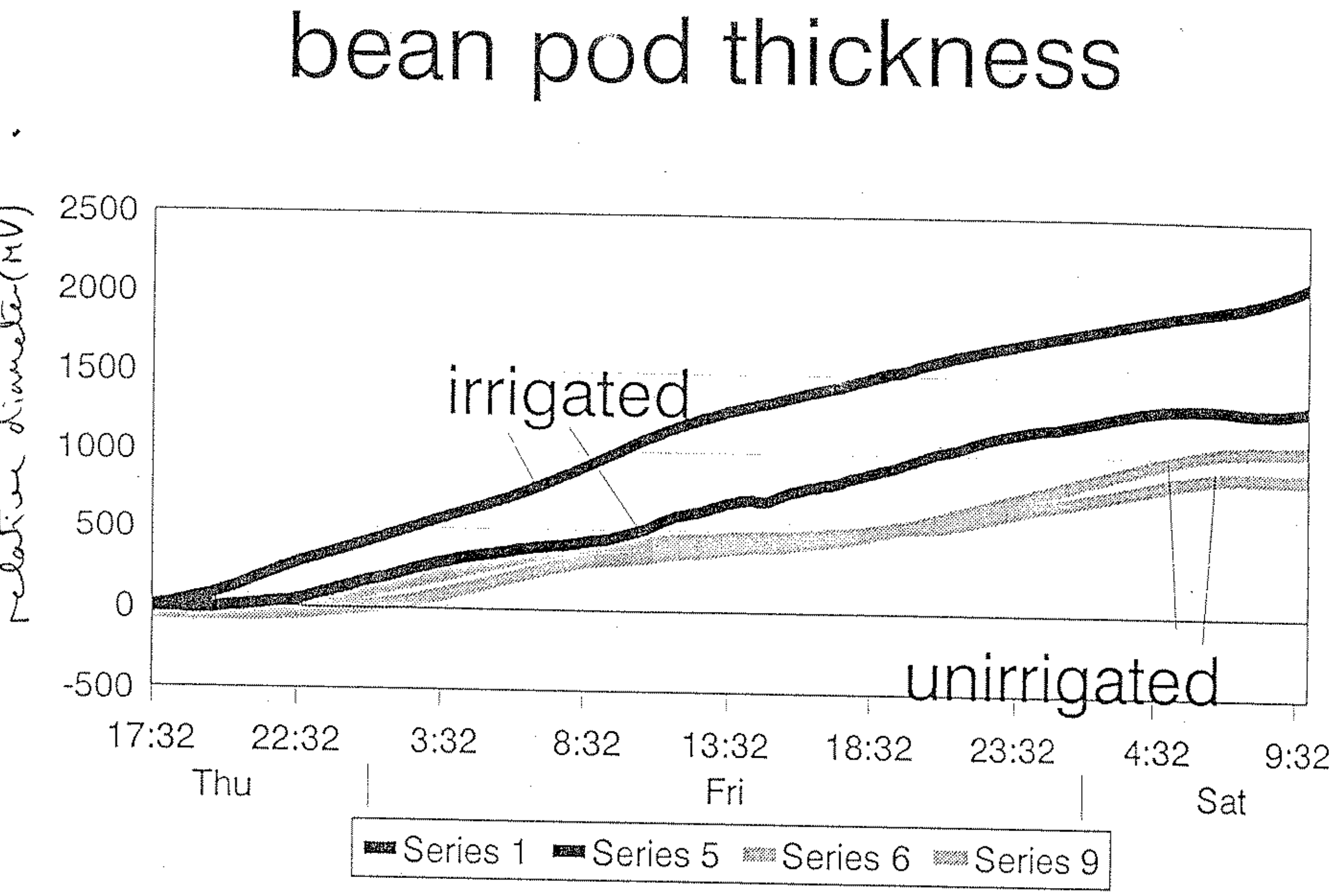


Figure 11: Seasonal changes in stomatal conductance as measured with a portable porometer (PP Systems) at Wellesbourne on runner beans or French beans

A.



B.

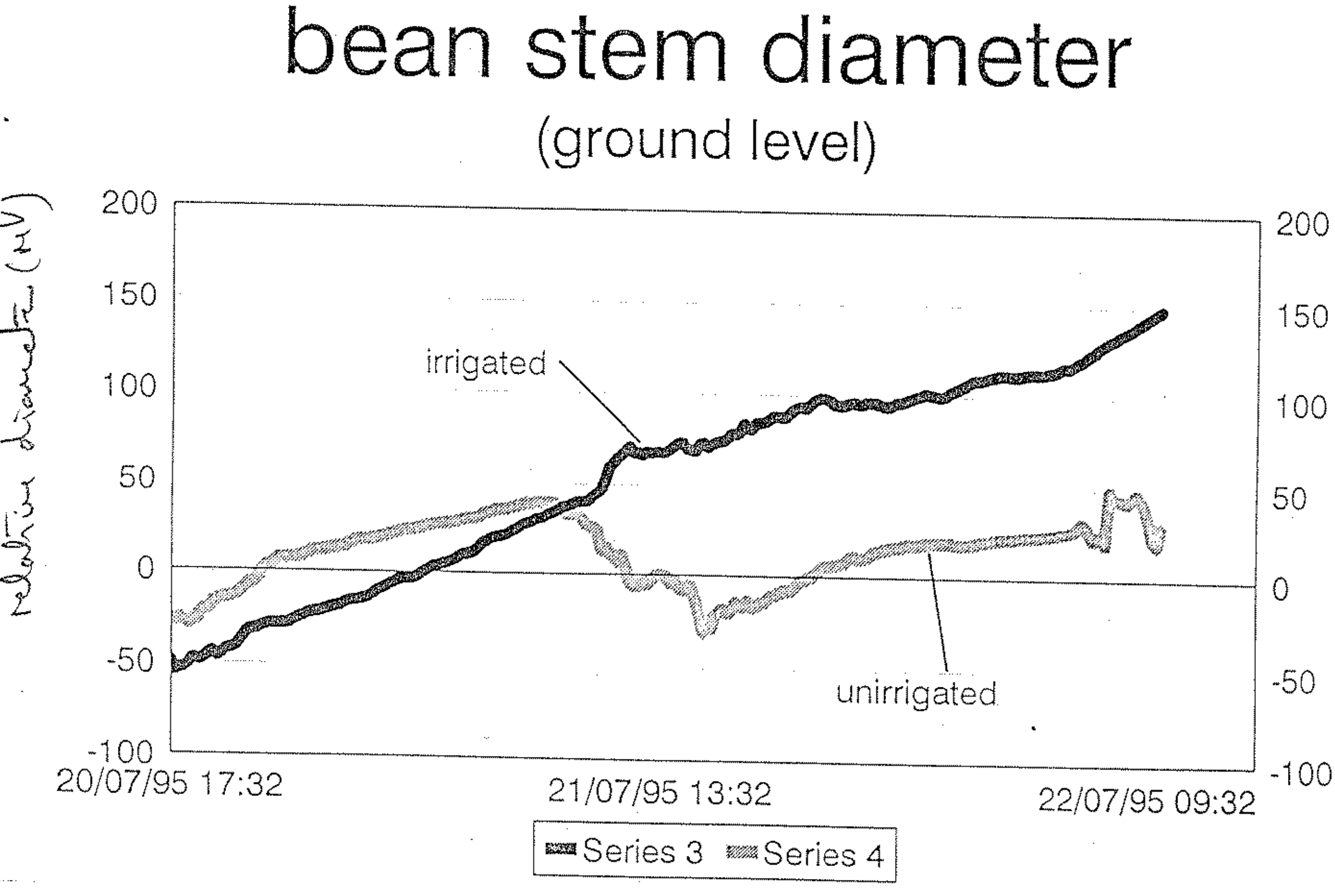


Figure 12: Diurnal variation in (a) bean pod thickness or (b) bean stem diameter measured at ground level. This figure illustrates that drought both reduces the rate of growth (the mean slope of the lines), and also tends to enhance the diurnal amplitude of the fluctuations (see especially b).

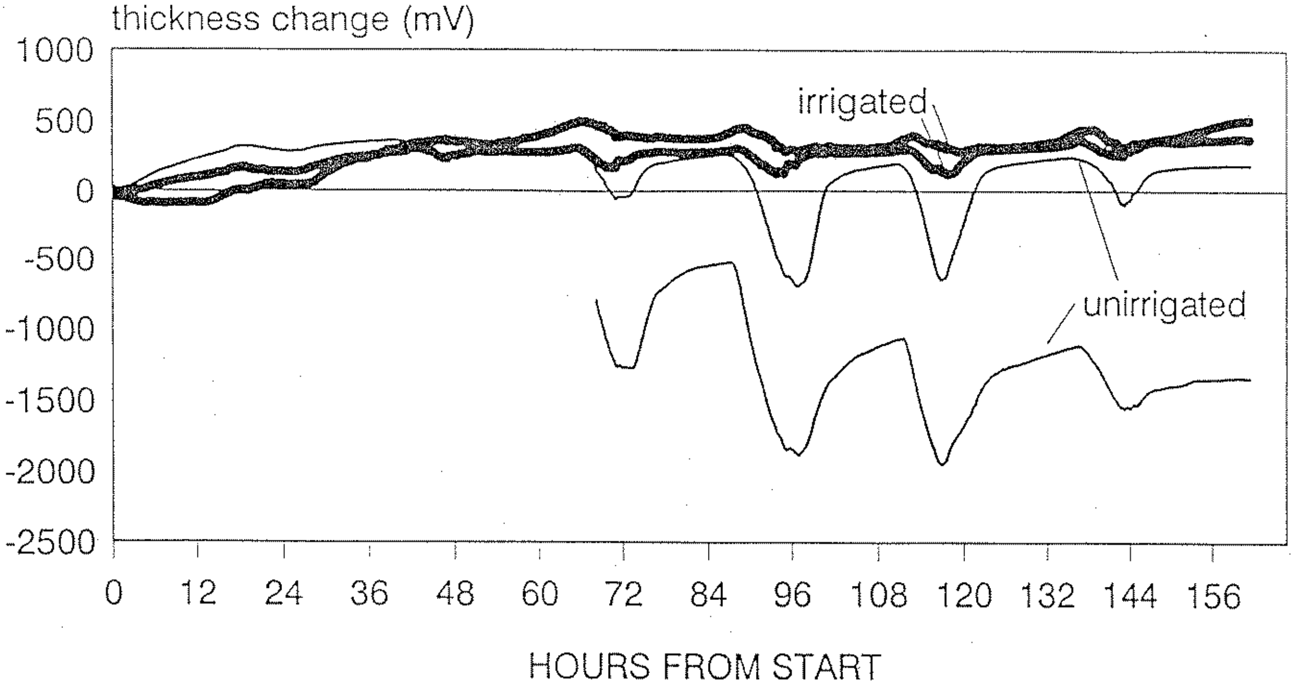


Figure 13: Changes in bean pod thickness over a six-day period after withdrawing irrigation. Again the major effect of developing drought is to increase dramatically the amplitude of thefluctuations.

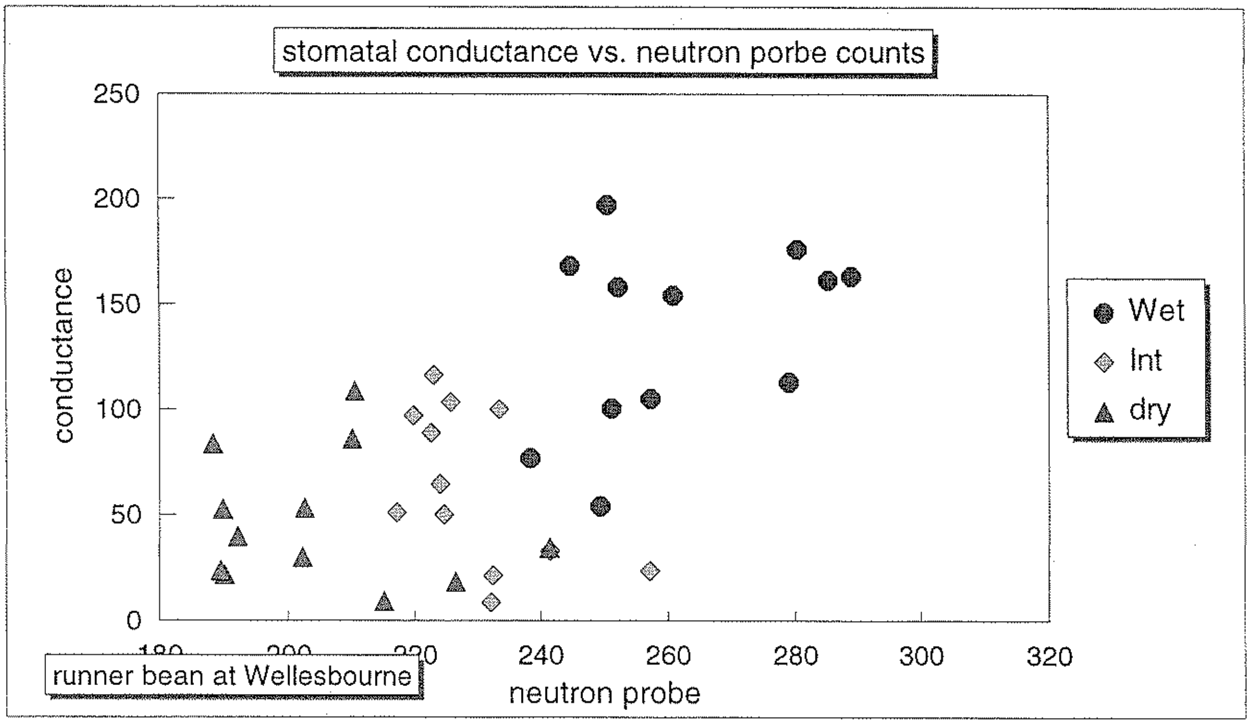


Figure 14: The relationship between stomatal conductance of runner bean at Wellesbourne and soil moisture content at 20 cm (as obtained by simple extrapolation between neutron probe readings).