Project title:	Sweet peppers: the use of thermal screens for summer shading and their effect on plant growth and fruit quality	
Project number:	PC 269	
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Date completion due:	March 2008	
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Contents

Grower Summary

Headline

Although no commercial benefit was demonstrated through the use of a thermal screen to provide shading, possibly due to poor summer weather, there was no detrimental effect on the crop. This latter conclusion is important as it allays growers' main concerns over the use of shading; that being the potential for increased disease levels and loss of yield.

Background and expected deliverables

The growth and development of any plant can be significantly impeded during periods of high stress. Stress conditions are commonly associated with high greenhouse temperatures with high humidity deficit, and high light intensities. The impact is so great that on some crops (for example ornamentals) moveable screens designed to provide as much as 75% shading are used.

Shading does not come without its risks, however. Knock-on effects include higher relative humidity's which have the potential to increase disease levels and less light received by the plants can reduce yields.

This project was therefore commissioned to examine the practical risks and benefits and evaluate sensible control boundaries for the use of thermal screens applied to crop shading.

Specific objectives were:

- To quantify the effect of summer shading using a thermal screen on the yield, quality and disease levels in a commercial sweet pepper crop.
- To develop a shading screen control strategy to reduce the occurrence of stress inducing conditions.
- To identify the aerial environment that causes plant stress (indicated by stomatal closure and reduced transpiration) in a commercial sweet pepper crop.
- To validate the use of water uptake, measured as volume applied minus drain volume, in relation to light as an indicator of plant stress.

Results

Research method

The project was undertaken at Valley Grown Nursery, Nazeing, Essex in a 15,000m^2 greenhouse built in 1999. A permanent (moveable) thermal screen using Ludvig Svensson SLS10 Ultra Plus material was installed.

The thermal screen in one block was used to provide shade during the summer months. The aerial environment and crop performance in this block was compared with an adjacent block where shading was not used.

A range of measurements were taken to help identify periods of plant stress and the aerial environment associated with them. These measurements included:

- Photosynthesis - taken manually at key stages in the project.
- Sap flow - recorded at 15 minute intervals for typically two weeks at key stages in the project.
- Water uptake per irrigation round - recorded continuously by the climate control computer.
- Greenhouse aerial environment - temperature, humidity and CO_2 recorded continuously by the climate control computer.

Shading screen set points and operation

Set points

Set points to close the thermal screen and provide shade were implemented in Week 13. The control strategy was developed following consultation with Wim van Wimgerden (GreenQ Crop Consultant) and fine tuning according to the greenhouse environment achieved.

The screen was opened and closed according to the outside light intensity (W/m^2) as detailed in Table 1 below.

Table 1 – Shading screen control set points

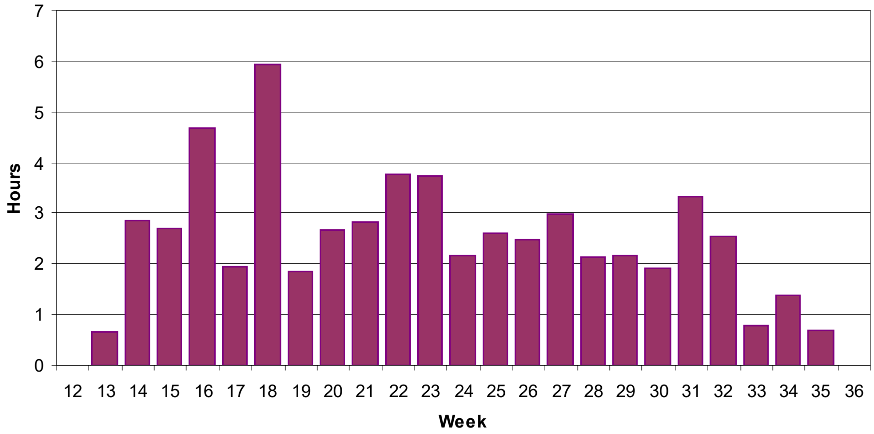
Description	Set point
Time period	10:00 – 18:00
Screen closed	650W/m^2
Screen open	550W/m^2
Maximum screen position	75%

Screens were closed as soon as the light intensity exceeded 650W/m^2 as rapidly rising light levels were expected to be a plant stressor. The screen was not allowed to open again until the light level dropped to below 550W/m^2 for more than 30 minutes. This was to avoid excessive ‘hunting’ of the screen and to ensure that the screen continued to provide shade during highly variable light conditions; another expected cause of plant stress.

A maximum screen position of 75% was used to ensure adequate natural ventilation.

The screen was not allowed to close before 10:00am as extreme greenhouse temperature and humidity conditions were uncommon before this time even when light intensity exceeded 650W/m^2. Figure 1 below shows the effect of these set points on the average number of hours that the screen was closed to provide shade each day during 2007.

Figure 1 –Average shading hours per day



Greenhouse environment

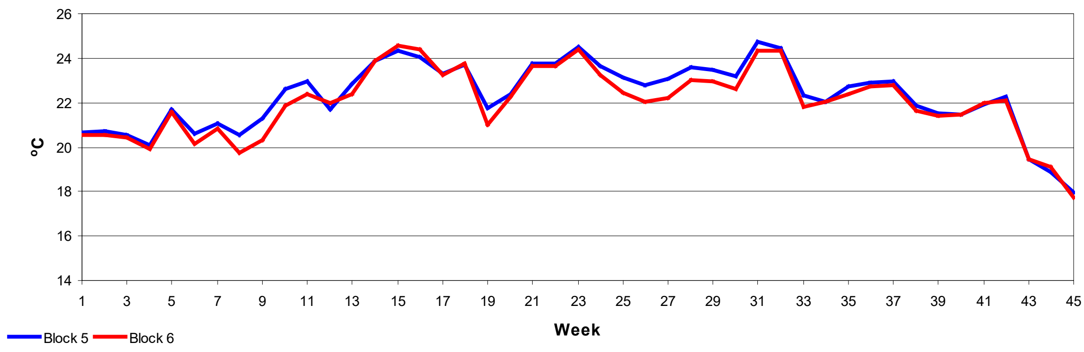
The following data analysis is based upon the daytime period only which therefore highlights the underlying effects during shading periods.

Temperature

A comparison of data from 2006 when shading was not used showed that there was very little difference between temperatures recorded in the greenhouse compartments.

In 2007 when shading was used in Block 5 (see Figure 2 below) temperatures were on average 0.5^{o}C warmer in this block for Weeks 23-31. This suggests that the reduction in natural ventilation caused by the screen being 75% closed had a greater effect on increasing temperature than the shading effect had on reducing temperature.

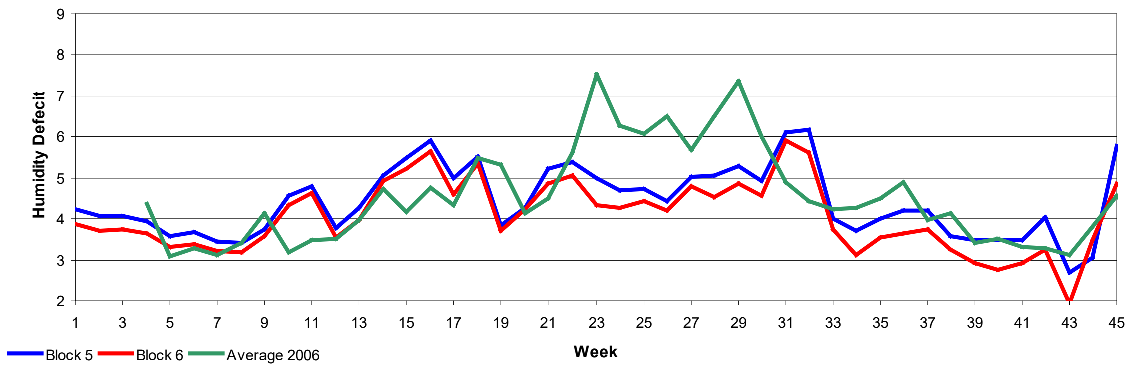
Figure 2 –Average daytime greenhouse temperature 2007



Humidity

A comparison of data from 2006 when shading was not used in either compartment showed that the humidity deficit in Block 5 was on average 0.5g/m^3 higher than in Block 6. In 2007 when shading was used in Block 5 (see Figure 3 below) a similar difference was recorded.

Figure 3 – Average daytime humidity deficit 2007



Comparing the average humidity deficit in the two blocks in 2006 with the humidity in 2007 showed that the average daytime HD was consistently above 6.0g/m^3 between Weeks 21-31 in 2006. During the same period in 2007 it rarely exceeded 5.0g/m^3.

CO_2

The CO_2 level in the shaded block tended to be higher during the summer than in the unshaded block. However, the relative CO_2 level in each block varied even when shading was not used. As a result it was not possible to prove this with any degree of confidence.

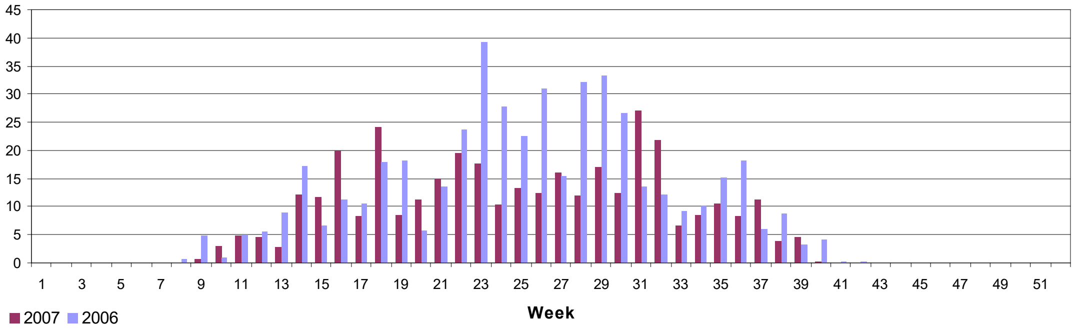
In summary considering all environmental measurements, the use of thermal screens for shading during the summer of 2007 had little effect on the greenhouse environment compared to an adjacent compartment where shading was not used.

Weather conditions

High greenhouse temperatures and humidity deficits during the summer are driven largely by outside temperature and light intensity. A comparison of the outside temperature and light levels during the summer (Weeks 23-35) of 2007 with those during 2006 showed that:

- Outside temperature was on average 2.2°C lower in 2007.
- Ambient light intensity was above 600W/m^2 for 120 hours less in 2007 than in 2006 (Figure 4 below).

Figure 4 – Hours above 600W/m^2



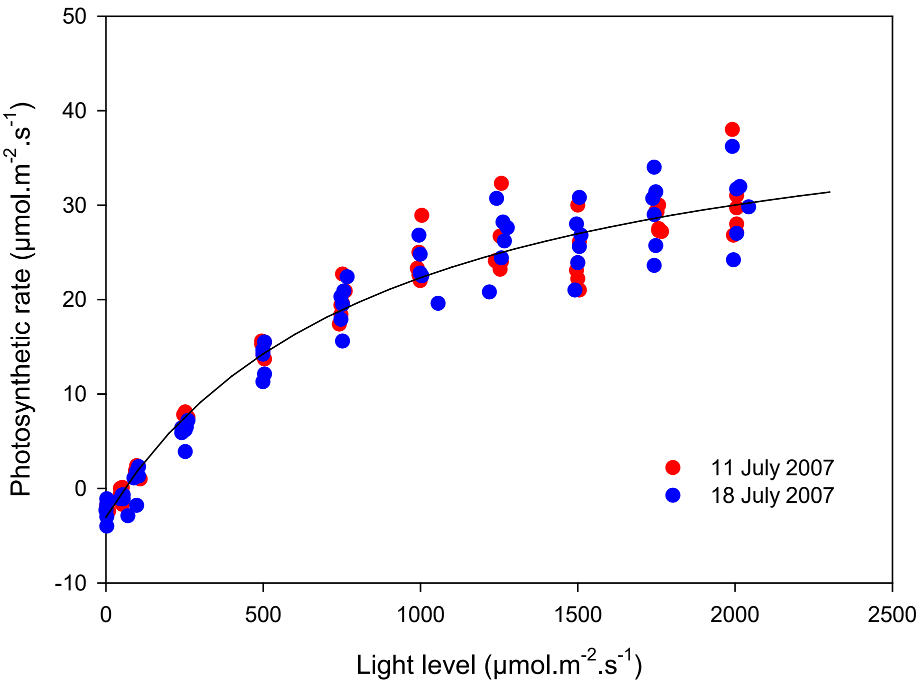
In summary with lower temperatures and light levels, the weather conditions in the summer of 2007 were less likely to cause plant stress than those in 2006.

Plant measurements

Photosynthesis

An underlying objective of this project was to make sure that photosynthesis was maximised by reducing stomatal closure during periods of high greenhouse temperature and humidity deficit. A CIRAS-1 portable photosynthesis system was used to measure these parameters. Figure 5 below shows the relationship between photosynthesis and light intensity for young leaves at the top of the canopy lit with an artificial light source. The data were recorded at an average CO_2 level of 528ppm when the temperature and humidity were not considered to be limiting.

Figure 5 – Light response curve for sweet pepper plants



As a guide, 1,100µmol.m^{-2}.s^{-1} is equivalent to an outside light intensity of approximately 600W/m^2. From this it is clear that where factors such as temperature and humidity are not limiting a sweet pepper plant is able to utilise light intensities equivalent to 1,200W/m^2.

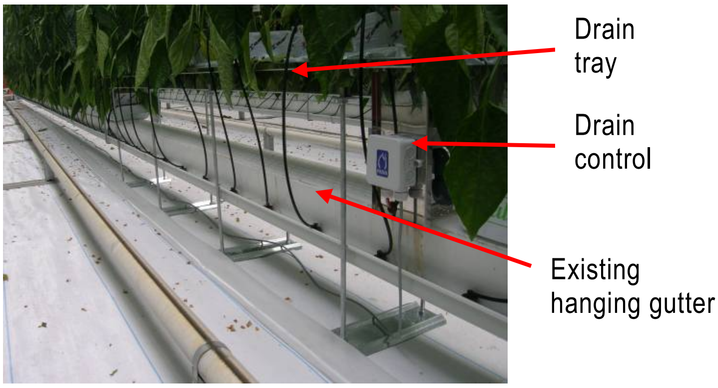
This information provided the benchmark against which photosynthetic activity was used to identify 'high stress' conditions.

During the period of the tests, in spite of regular site visits and monitoring, it was not possible to identify any period when the photosynthetic activity of the plants was significantly below this line. As such there was no indication of stress. It is important to note that it does not follow that plant stress does not occur in commercial greenhouse systems in the UK. As previously discussed, the conditions experienced in the summer of 2007 were not typical and were somewhat kind from a plant stress point of view.

Sap flow and water uptake

The objective of this part of the project was to determine whether water uptake was reduced at times as a result of stress causing stomatal closure. We also wanted to assess whether uptake measured as applied volume minus the volume of drain water, was sufficiently comparable to direct measurements of sap flow to allow its use as an indicator of plant stress.

Figure 6 - Drain measurement



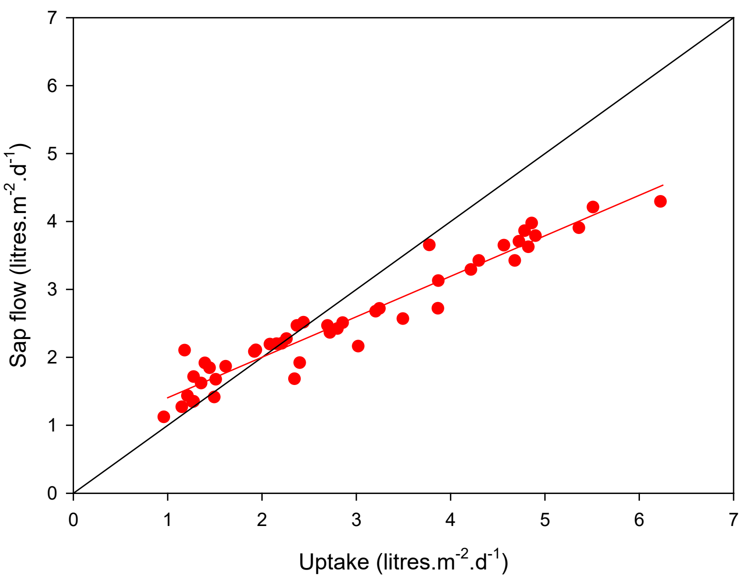
measurement

Figure 7 - Sap flow

Sap flow data, recorded every 15 minutes, showed good correlation with the light intensity measured by the climate control computer. However, we were unable to identify periods of stress where water uptake was reduced.

The comparatively infrequent irrigation rounds, even when water use was high, combined with the time required for drain water to percolate through the growing media slab meant that it was not possible to use drain measurements as a real-time indicator of sap flow. However, the total amount of water used per day compared favourably with the average sap flow as shown in Figure 8 below. Overall shading had little or no effect on water uptake in 2007.

Figure 8 - Comparison of daily water uptake estimated via drain measurements and sap flow. The black line indicates the line of identity on which points would fall if there were perfect agreement.



Yield and disease

Yield

The yield from the shaded block was 24.3kg.m^{-2} compared with 24.4kg.m^{-2} from the unshaded block. Plant growth records including length and flowers set also showed very little difference.

Overall there was no significant yield or plant performance difference between shaded and unshaded treatments.

Disease

Very few fruits were recorded as unmarketable due to external damage during Weeks 12-25. However, this increased from Week 26 onwards with 7% of the fruit rejected in the worst week. A small proportion of fruit was unmarketable due to severe blossom end rot. The nursery manager estimated that around 70% of the fruit that was rejected was due to Fusarium fruit rot. Over the 10 week period (Weeks 26-35) the percentage wastage in the unshaded Block 6 was 2.9% compared to 2.6% in the shaded block. In a second block where shading was also used the wastage was 3.4%. It was therefore concluded that shading had no significant impact on Fusarium fruit rot.

The examination of visibly healthy fruit in the laboratory over a similar period recorded internal infection on 8.5% of the fruit from the shaded block compared to 8.3% in the unshaded block. The difference was statistically insignificant.

No other diseases of any significance were observed.

Financial benefits for growers

Benefit

The use of thermal screens to provide shading over a commercial sweet pepper crop had no significant effect on yield or disease levels in 2007. In more extreme summer weather conditions, an increase in marketable yield may have been apparent.

With only variable costs to cover (harvesting and marketing) had an increase in yield been apparent this would have been worth £0.30 per m^2/kg of extra fruit produced.

Cost

Thermal screens are now commonplace on edible crop nurseries and the capital required can be justified on energy saving alone. Using a thermal screen to provide shade does incur some extra maintenance and depreciation costs in addition to those resulting from normal energy saving operations. Shading increases the number of open / close cycles and exposes all of the material to UV light rather than just the upper edge of the packed material. Therefore, there is little doubt that using a thermal screen to provide shade will reduce the life of the material. However, there is no commercial data available to quantify the actual cost of this.

An estimate of the cost of using a thermal screen for shading follows:

- Thermal screen materials are expected to last for at least 6 years.
- The cost of replacing the material including labour is currently around £2.00/m^2.
- Therefore the screen material replacement cost is £0.33/m^2 p.a.

If the life of the thermal screen material reduced to five years due to using them for shading, the cost would increase to £0.40/m^2 - an increase of £7,000/Ha per year.

Based on these assumptions using thermal screens to provide summer shade would need to deliver an increase in marketable yield of 0.23kg/m^2 to break even.

Conclusions

- Closing a thermal screen to 75% to provide shade at outside light intensities greater than 600W/m^2 had no detrimental effect on yield or disease in 2007.
- None of the data collected indicated that photosynthesis was limited by extremes of temperature or humidity in the greenhouse in 2007.
- Weather conditions in the summer of 2007 were relatively mild compared to 2006 and the incidence of high temperature and high humidity deficit in the greenhouse was significantly less as a direct result.
- Sap flow can provide a real-time indication of plant ‘health’ and can be use in a commercial situation if it can be reliably and easily measured.
- Water uptake although simple and reliable to measure does not provide sufficiently frequent data to allow real-time application to identify plant stress and trigger screens to close.
- Water uptake is a useful indicator of plant health / activity when viewed as the total per day and compared with the light received.

Action points for growers

- Investigate the ability of their climate control computer to control screens for shading and learn how to use it.
- Consider conducting shading trials using the control strategy employed in this project knowing that these settings are unlikely to cause any losses or disease problems with the crop.

Science Section

Introduction and background

The growth and development of any plant can be significantly impeded during periods of high stress. Extremes in the aerial environment such as high light and temperature and low relative humidity are common causes. The benefits of providing shade to sensitive ornamental crops like bedding plants and orchids are so great that screen materials specifically designed to block out light are installed. The widespread use of thermal screens in edible crop production to save energy offers the opportunity to provide some summer shading (20% light reduction) without the need for any further capital investment. The potential benefits of shading to edible crop growers include:

- Increased photosynthesis by reducing stomatal closure during high stress conditions.
- Improved yield and quality by reducing extremes of temperature and humidity.
- Increased CO_2 levels as a consequence of reducing the ventilation requirement for cooling.
- Improved crop management through better control of stress events and their impact on the vegetative / generative balance of the crop.

Cucumber growers routinely use thermal screens to provide summer shade when a new crop is planted and until the plant canopy is sufficiently developed. Some pepper and tomato growers have also used thermal screens to provide shade during the summer. However, benefits have been far from consistent and in some cases an increase in fungal disease has occurred. As a result, few edible crop growers use thermal screens to shade a fully developed crop. Specific associated issues include:

- The possibility of increased disease levels.
- The possibility of reduced yield.
- A lack of knowledge about when to provide shade for edible crops.
- A lack of reliable commercially proven benefits.

This project was commissioned to investigate all of the above points. Sweet peppers were chosen as the trial crop because of the need to retain good plant balance through the cyclical fruit set / yield pattern.

Objectives

This project was commissioned to examine the practical risks and benefits when using thermal screens for crop shading and evaluate sensible control boundaries.

Specific objectives were:

- To quantify the effect of summer shading using a thermal screen on yield, quality and disease levels.
- To identify the aerial environment which causes plant stress (indicated by stomatal closure, reduced transpiration and increased leaf temperatures) in a commercial sweet pepper crop.
- To develop a shading screen control strategy to reduce the occurrence of stress inducing conditions.
- To validate the use of water uptake, measured as volume applied minus drain volume, in relation to light as an indicator of plant stress.

Research method

Overview of location facilities and cropping

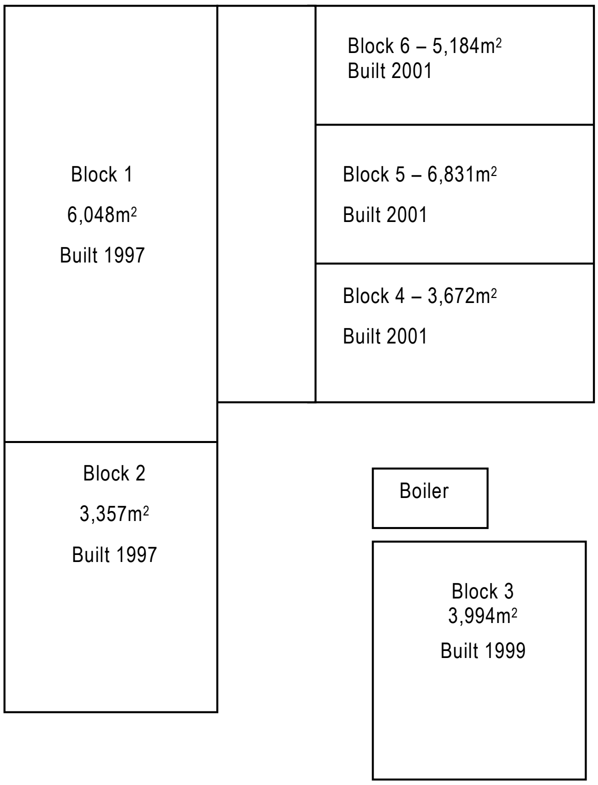
The glasshouse facilities were located at Valley Grown Nurseries, Nazeing, Essex. Data collection and analysis was carried out at FEC Services Ltd, Stoneleigh Park, Warwickshire and by Warwick HRI, Wellesbourne. Routine on-site data collection, meter readings and crop recordings were carried out by Gary Taylor, Managing Director, Valley Grown Salads Ltd.

Greenhouse

The layout of the nursery and the size of each greenhouse block are shown in Figure 9 below. Blocks 4-6 include a permanent thermal screen (Ludvig Svensson SLS10 Ultra Plus).

Summer shading was applied in Block 5 with the thermal screens and Block 6 was used as the control.

Figure 9 – Valley Grown Nursery site layout



Environmental control

Each greenhouse block had its own independent heating and ventilation system, thermal screen and separate measuring box containing standard wet and dry bulb sensors. The climate control computer was a Priva Integro version 724.

Crop

All plants were grown in hanging gutters in mineral wool growing media. The variety Special was grown in both treatments.

Data collection

Greenhouse environment and weather data

Greenhouse internal environment and weather data were recorded using the site climate control computer. Data was downloaded via broadband connection by FEC consultants.

Data collected and analysed included:

- Greenhouse set points and equipment operation:
  - Set points – heating and ventilation temperature.
  - Heating pipe temperature.
  - Vent position.
  - Screen position.
- Greenhouse environment:

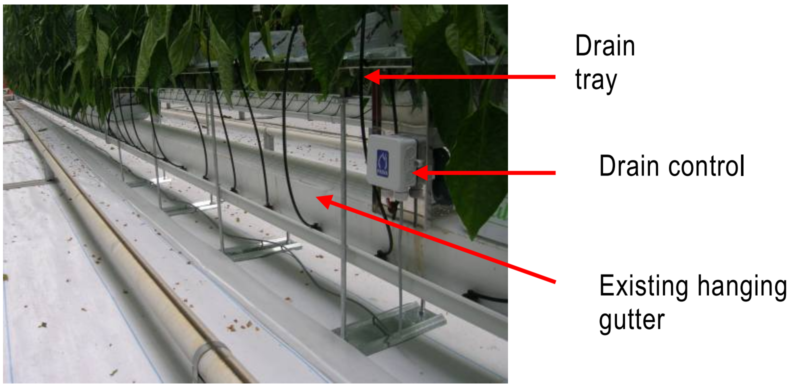
- Temperature.
    - Humidity deficit.
    - CO_2.
- Temperature and humidity deficit were measured at two locations:
    1. 30cm below the top of the crop. These measurements were used by the climate control computer to control the heating, ventilation and screens.
    2. 30cm above the growing media. These measurements were recorded to provide more detailed information on the conditions experienced by the crop.
- Weather data:
    - Temperature.
    - Solar radiation.

Figure 10 – Low level measuring box

Irrigation data

The volume of water applied was recorded by the climate control computer which also controlled the irrigation system. A ‘tipping spoon’ drain tray was added to record the volume of drain (run off) from two growing media slabs. This allowed water uptake to be calculated.

Figure 11 – Drain measurement



This data was recorded on the computer at five minute intervals. This allowed the water uptake between each round of irrigation to be determined and compared with the light intensity during the same period.

Photosynthesis measurement

A CIRAS-1 portable photosynthesis system was used to measure leaf photosynthesis. Measurements were made at ambient temperature. The CO_2 concentrations in the chamber were controlled to avoid fluctuations caused by CO_2 dosing in the glasshouse. In addition to ambient light an LED light source (1000 or 2000μmol.m^{-2}.s^{-1}) was used to expose leaves to high light levels.

Figure 12 - Photosynthesis measurement

Sap flow measurement

Sap flow was measured using a heat balance method with commercially available gauges (SGA10, SGA13, SGB16; Dynamax Inc). The outputs from these gauges were scanned every 60 seconds and the mean value was logged every 15 minutes by a Campbell CR 10X data logger and an AM416 multiplexer.

*Figure 13 - **Sap** flow sensor without weather shield attached to a pepper plant*

Crop data

Nursery staff carried out weekly crop recording based on a sample of 20 stems in each greenhouse block. Note was taken of:

- Growth – cm.
- Total plant height – cm.
- Fruit set each week.
- Number of fruit on each plant.
- The number of new flowers produced each week.
- The number of fruit picked each week.

Yield data was recorded daily by nursery staff.

Disease levels, principally Fusarium, were assessed at key stages of the season by Dr Tim O'Neill, ADAS Consulting Ltd.

Comparisons with previous years

Data for the 2006 cropping season was used as a comparison to allow the relative performance of Blocks 5 and 6 to be determined whilst operated in the same way. This included:

- Greenhouse temperature and humidity deficit.
- CO_2 levels.
- Yield.

Results

Literature review

While there are a number of published studies concerning shading in sweet peppers, many of these are associated with the use of fixed screens in countries where the climate is more stressful when compared to that of the UK.

A number of trials have been conducted in Israel. Aloni *et al*. (1994) showed that although shading (~50%) decreased photosynthetic rates, the total yield was actually increased with shading due to the fact that this treatment extended the fruiting period. Rylski and Spigelman (1986a) concluded that in the north western Negev desert, 12-26% shade was optimal in terms of marketable yield. Shading increased plant height, number of flower nodes and leaf area, however, it reduced the number of side shoots. Shading also reduced the number of sun-scalded fruit from 36% with no shade, to 2.5% under 47% shade. Similarly trials in the Arava Valley (Rylski and Spigelman, 1986b) showed that yields were increased (and delayed) in screen houses (25% shade) when compared with crops grown in the field. Shading of plants once they had well developed fruits was shown to enhance quality, but did not increase yields. Shading was also shown to decrease water use (Möller and Assouline, 2007).

As one would expect the results from trials in other countries vary depending on the prevailing weather conditions. Roberts and Anderson (1994) showed that in Southern Oklahoma, marketable yields of sweet pepper grown in the field could be increased through the use of shading with spunbonded polypropylene row covers. Jaimez and Dada (2006) showed that 40% shade (on passion-fruit vines) could be used in Venezuela for shading without a yield loss, while workers in Japan demonstrated a reduction in sweet pepper yield with just 25% shade (Jung *et al.,* 1994). Similarly workers in Korea showed that sweet pepper yields decreased as the level of shading increased from 0 to 70% (Jeon and Chung, 1982).

While the authors are aware of pepper shading trials in the Netherlands the results have not been published in international journals. In summary there was little information of direct relevance to this project in the public domain.

Shading screen control

Set points

Set points used to close the thermal screen to provide shade were implemented in week 13. The control strategy was developed following consultation with Wim van Wimgerden (GreenQ Crop Consultant) and fine tuned according to the greenhouse environment achieved.

The screen was opened and closed according to the outside light intensity (W/m^2) as detailed in Table 2 below.

Table 2 – Shading screen control set points

Description	Set point
Time period	10:00 – 18:00
Screen closed	650 W/m^2
Screen open	550 W/m^2
Maximum screen position	75%

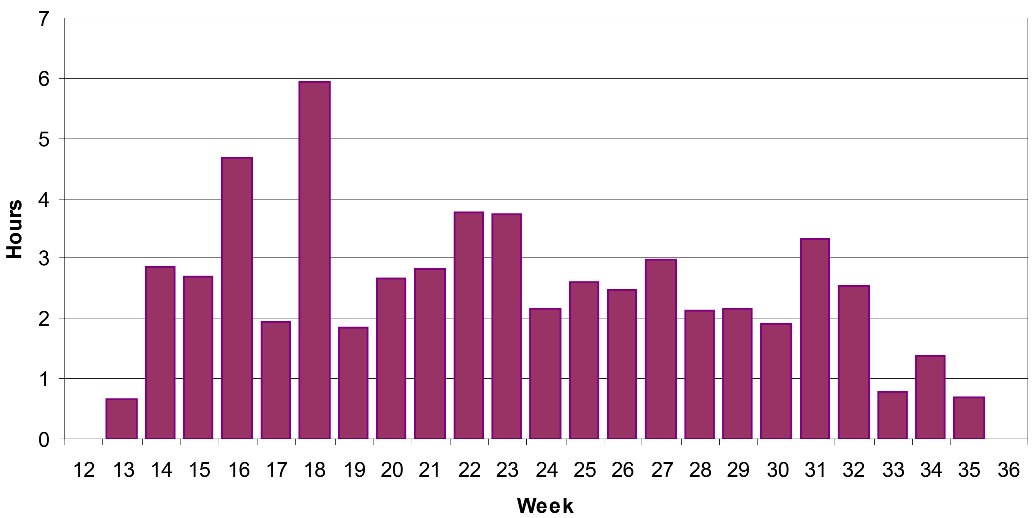
The screen was closed the moment light levels of 650W/m^2 were exceeded as high light levels were expected to be a plant stressor. However, the screen was not allowed to open until the light level dropped below 550W/m^2 for 30 minutes. This helped to avoid excessive 'hunting' of the screen and to ensure that the screen continued to provide shade during variable light conditions as these were also expected to be a plant stressor.

The maximum screen position for shading was limited to 75 % to ensure adequate ventilation. Allowing the screen to fully close (100%) would have severely restricted ventilation causing high temperatures and poor humidity.

The time period shown in Table 2 was that typically used for mid-summer. The screen was not allowed to close before 10:00 as extreme greenhouse temperature and humidity conditions rarely occurred before this time. It also ensured that the crop had the opportunity to completely dry out following the morning warm up period where condensation events were most likely. These set points remained fundamentally unchanged throughout the trial period.

Figure 14 below shows the average number of hours that the screen was closed to provide shade each day under this regime.

Figure 14 – Shading hours

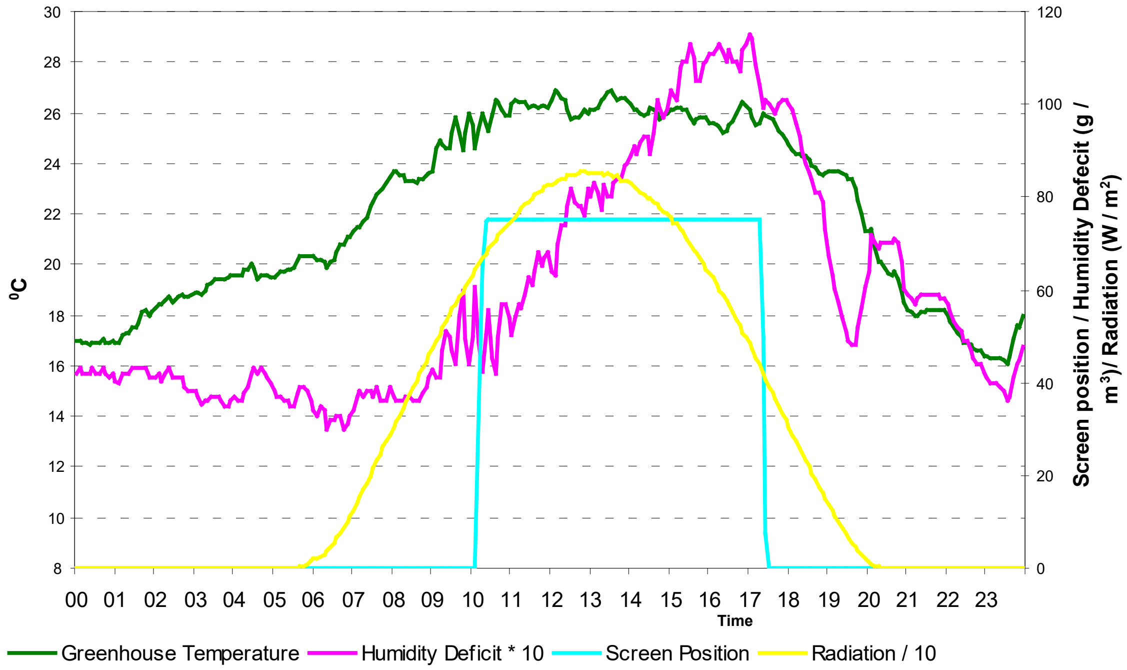


Typical days

The following graphs help to demonstrate the operation / impact of the shading set points applied.

Sunny cloudless day

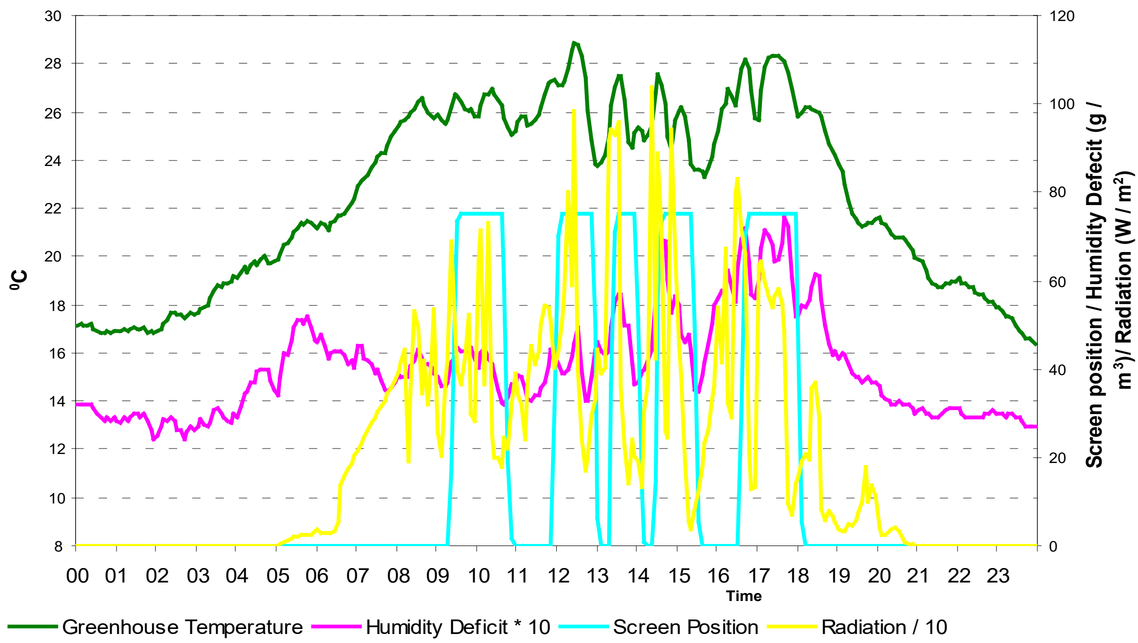
Figure 15 – Screen operation on a perfect light day



Screen closure was triggered at 650W/m². However, the rapid increase in light intensity combined with the relatively slow speed at which screens move meant that the light intensity exceeded 680W/m² by the time the screen had reached 75%.

Broken cloud day

Figure 16 – Screen operation on a broken cloud day



At the first screen opening, the 30 minute time delay following the trigger point of 550W/m^2 light level meant that the light intensity had actually fallen to 240W/m^2 before the screen opened. This shows how dead-bands and waiting times affect screen operation compared to the use of basic set points.

On a bright cloudless day as shown in Figure 15 such dead-bands and waiting times are unnecessary. However, such days rarely occur and a balance has to be reached between set points that respond quickly to changes in light intensity and those that do not cause excessive hunting on days such as the one shown in Figure 16.

On a day such as the one in Figure 16 it can sometimes be best to manually set the screen to be open or closed all day.

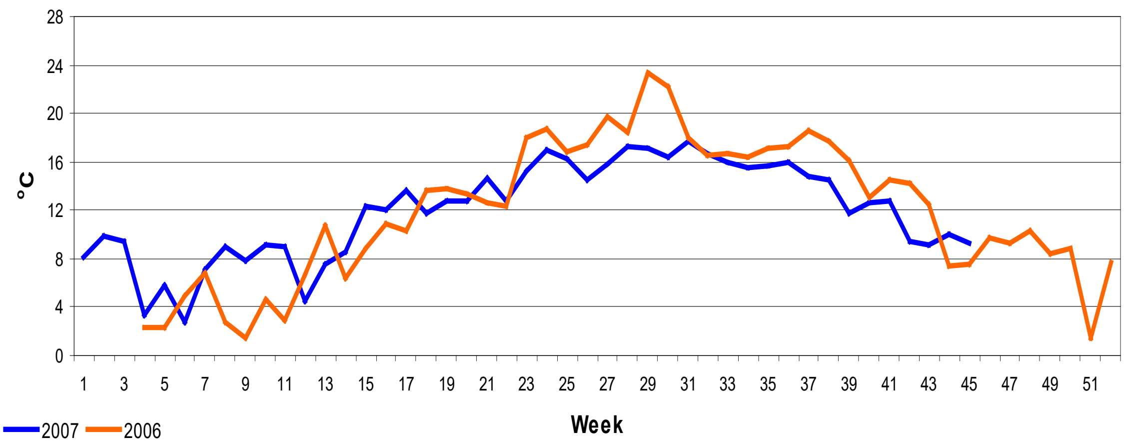
Weather conditions

High greenhouse temperatures and humidity deficits during the summer are a result of high outside temperature and light intensity. The weather conditions during the project (2007) were considered to be colder and less bright i.e. less likely to cause plant stress than in a typical year. The data for 2007 was therefore compared with the previous year (2006).

Outside temperature

Figure 17 below shows the average weekly outside temperature in 2006 and 2007. During the early part of the year (up to Week 17) 2007 was 2.5°C warmer than 2006. However, from Week 23 to Week 35 when the highest outside temperatures are typically reached and plant stress conditions are most common, the average temperature was 2.2°C lower.

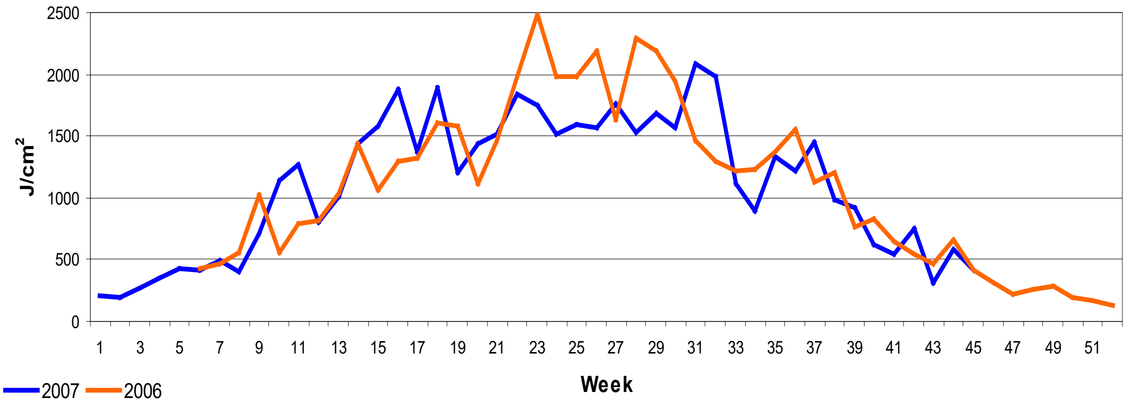
Figure 17 – Outside temperature



Light

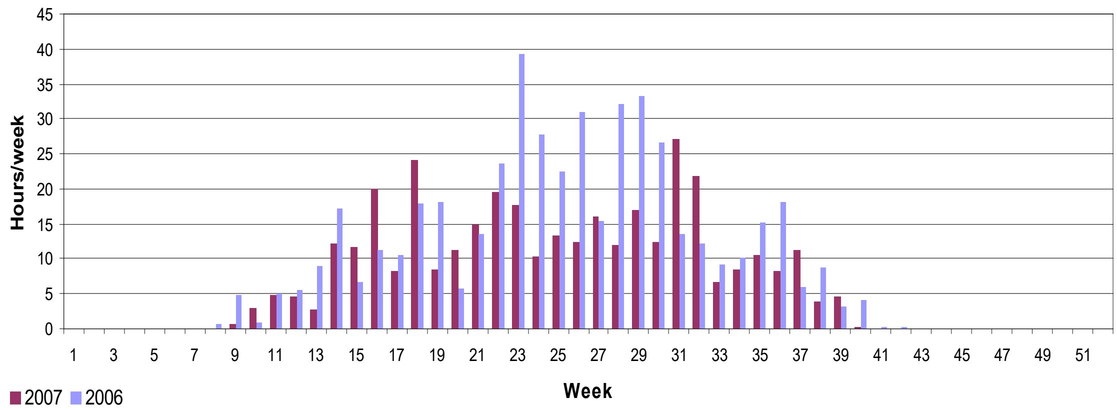
Light levels followed a similar pattern to outside temperature shown in the radiation sum in Figure 18 below.

Figure 18 – Radiation sum



As well as light integral, the instantaneous light intensity (W/m^2) is also important. Figure 19 below shows the number of hours in each week that the light level exceeded $600W/m^2$ in each year. In total, the light level was above $600W/m^2$ for 359 hours in 2007 compared to 479 hours in 2006. Figure 19 also shows that the majority of this difference occurred during the peak summer weeks (23-35).

Figure 19 – Hours above $600W/m^2$



Greenhouse environment

The use of thermal screens for summer shading only has an impact on the greenhouse environment during the daytime. The following data therefore excludes night-time temperatures so that daytime differences are more readily identified.

Temperature

Figure 20 –Average daytime greenhouse temperature 2006

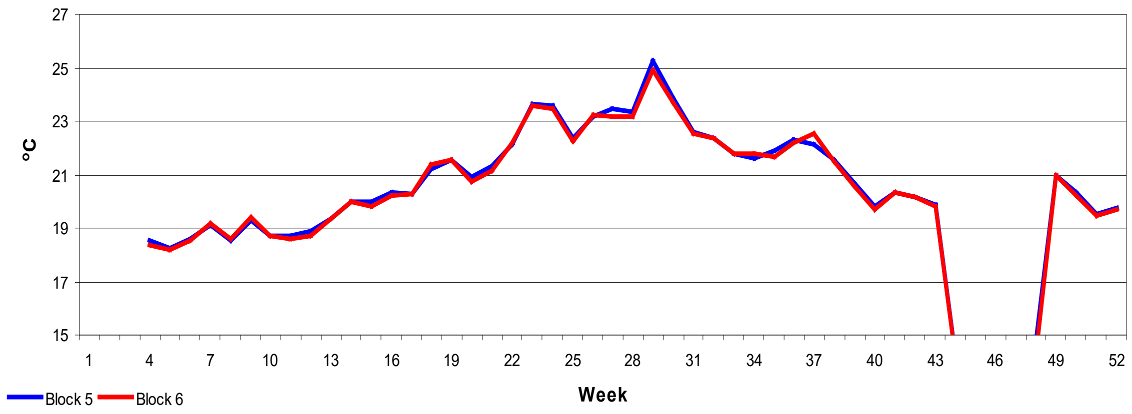
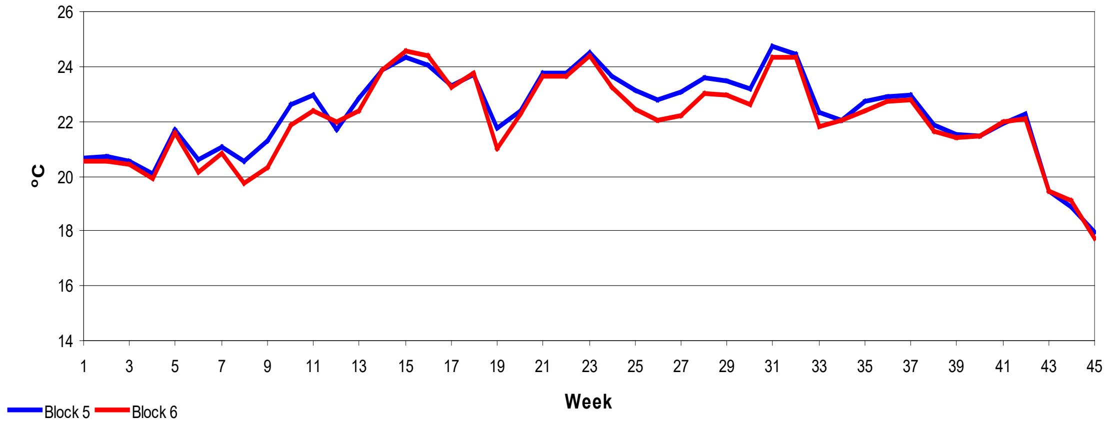


Figure 20 above shows that the average temperature in Block 5 and Block 6 was almost identical throughout 2006.

Figure 21 –Average daytime greenhouse temperature 2007

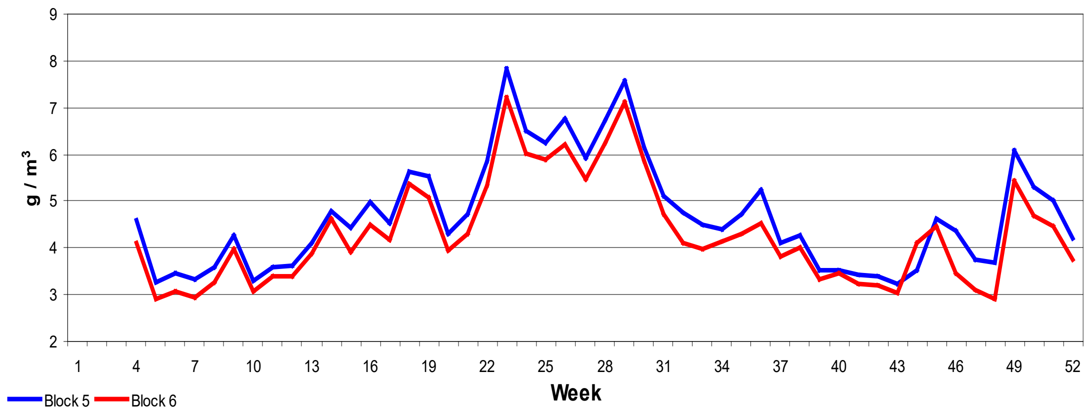


In 2007 (Figure 21) the temperatures were once again almost identical apart from two periods:

1. Weeks 5–11. This was when shading was not used and the reason for the difference is not known.
2. Weeks 23-31. When shading was used Block 5 was on average 0.5°C warmer.

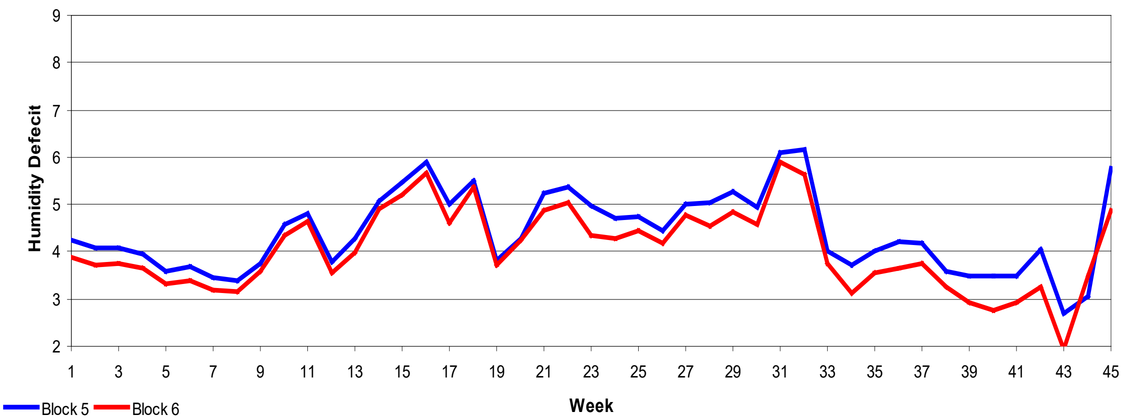
Humidity

Figure 22 – Average daytime humidity deficit 2006



The above graph shows the average daytime humidity deficits throughout the 2006 season. The HD in Block 5 was consistently higher (typically 0.5g/m^3) than Block 6. The same pattern occurred throughout 2007 (Figure 23 below). Another point of note is that during 2007 the average daytime HD rarely exceeded 5.0g/m^3 and only reached an average of greater than 6.0g/m^3 during two weeks. This compares to 2006 when the HD was above 6.0g/m^3 almost every week between Weeks 22-31.

Figure 23 – Average daytime humidity deficit 2007



CO_2

Figure 24 - Average daytime CO_2 levels 2006

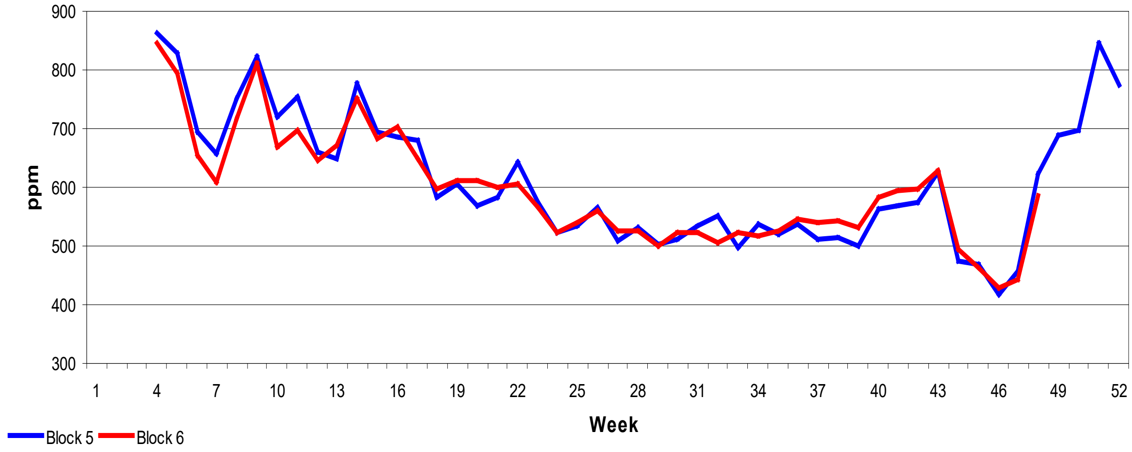
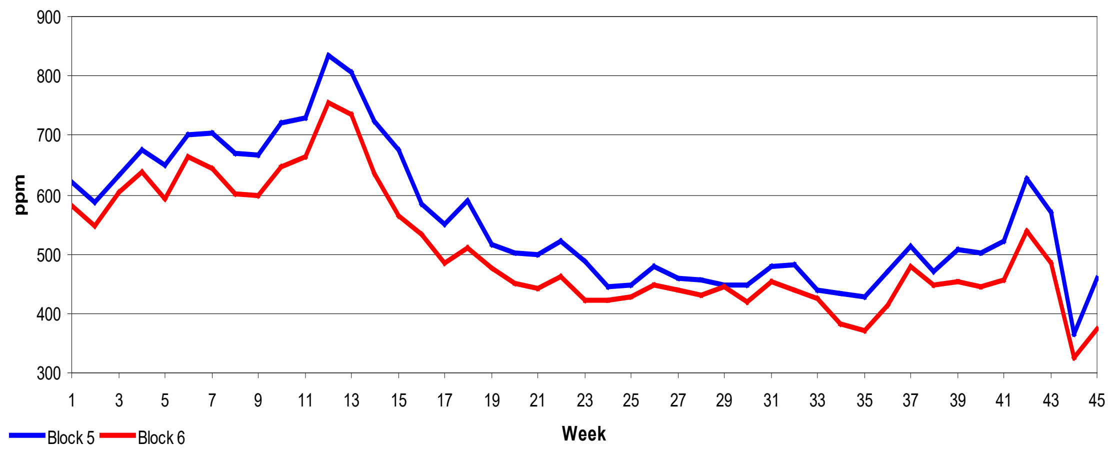


Figure 24 above shows the CO_2 levels achieved in both blocks in 2006. There was some variation at each end of the cropping season. However, during the mid-summer period CO_2 levels were very similar.

In 2007 (Figure 25 below) the CO_2 level in Block 5 (shaded) was consistently higher than in Block 6 (unshaded). The difference was greatest during the times of year when shading was not used (week 1-13). This could have helped to offset any yield penalty cause by using shading. However, the reason for the higher CO_2 levels is unknown. From week 1-13 in particular the temperature in block 5 was higher than block 6. As the same ventilation set points were used more ventilation would therefore have been required in block 5. Finally, both blocks were served by a single CO_2 enrichment system and no modifications were made between 2006 & 2007. Taking all these factors into account a lower CO_2 level in block 5 might have been have been expected rather than a higher one especially when there was no shading. Although it remains unproven the most likely explanation for this difference is measurement error.

Figure 25 - Average daytime CO_2 levels 2007



Plant measurements

The work described in this section of the report was carried out by Dr S. Adams and Dr V. Valdes of Warwick HRI.

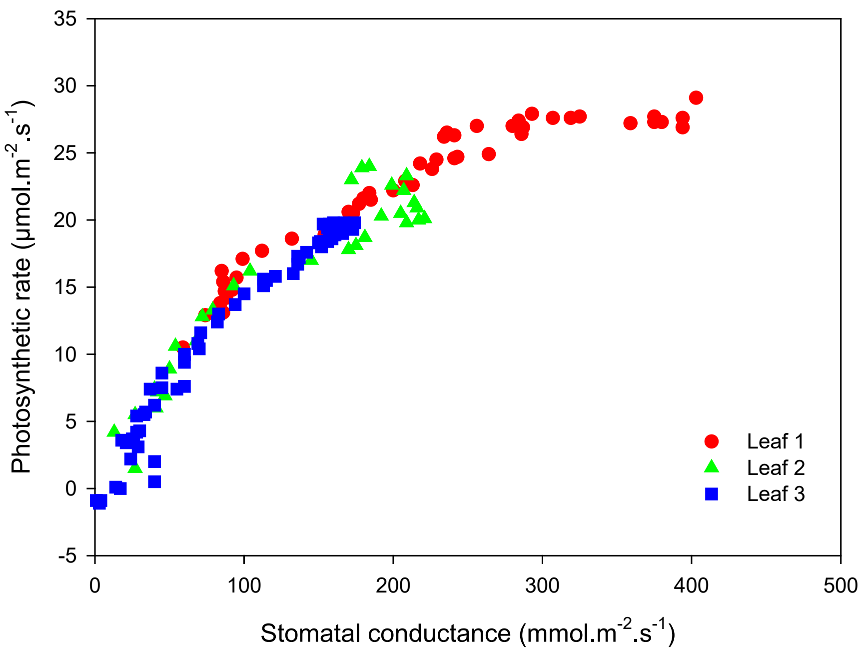
Photosynthesis and transpiration

Method

Most of the data were collected from the first fully expanded leaf from the top of the plant. These leaves were expected to have the highest photosynthetic rates. Measurements were made at ambient temperatures and the CO_2 concentrations in the chamber were controlled so as to avoid fluctuations caused by CO_2 dosing in the glasshouse. The mean CO_2 concentration in the chamber was 528ppm (with a standard deviation 22.4ppm).

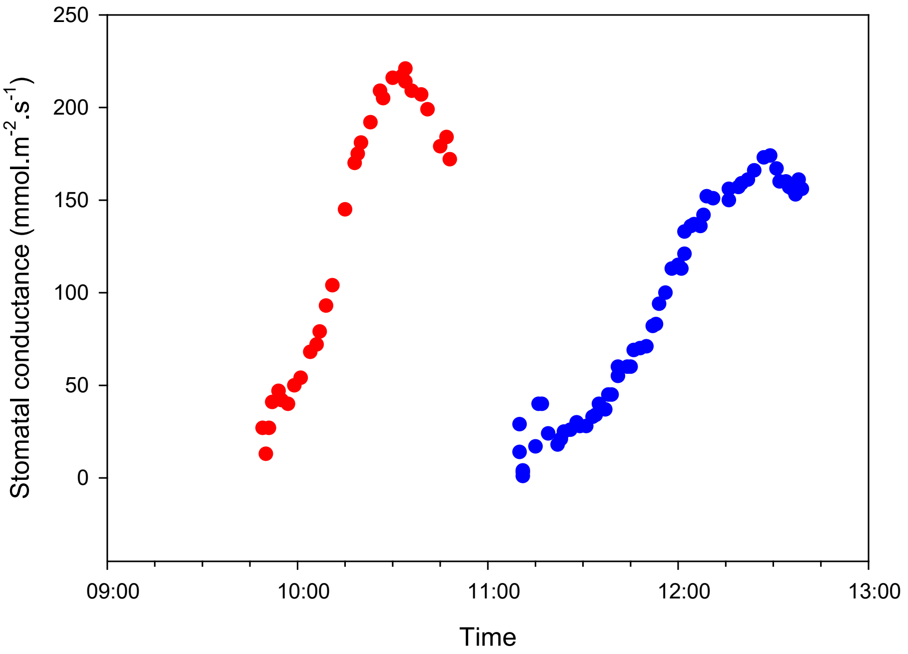
Before detailed measurements were made comparing shaded and unshaded blocks, the relationship between stomatal conductance and photosynthesis was examined. Individual leaves were covered for a number of hours so that the stomata shut due to the dark. These leaves were then exposed to high light levels using an LED light source (1000 or 2000μmol.m^{-2}.s^{-1}). The fact that the stomata were initially closed limited the leaf photosynthesis; photosynthesis then increased as the stomata slowly opened (Figure 26). Once the stomatal conductance reached around 250-300mmol.m^{-2}.s^{-1} there was no further increase in photosynthetic rate indicating that the stomatal aperture was no longer a limiting factor at these light levels.

Figure 26 - The effect of stomatal conductance in limiting leaf photosynthesis. Leaves were kept in the dark and then exposed to 1000 (leaf 2) or 2000μmol.m^{-2}.s^{-1} (leaves 1 and 3) of light.



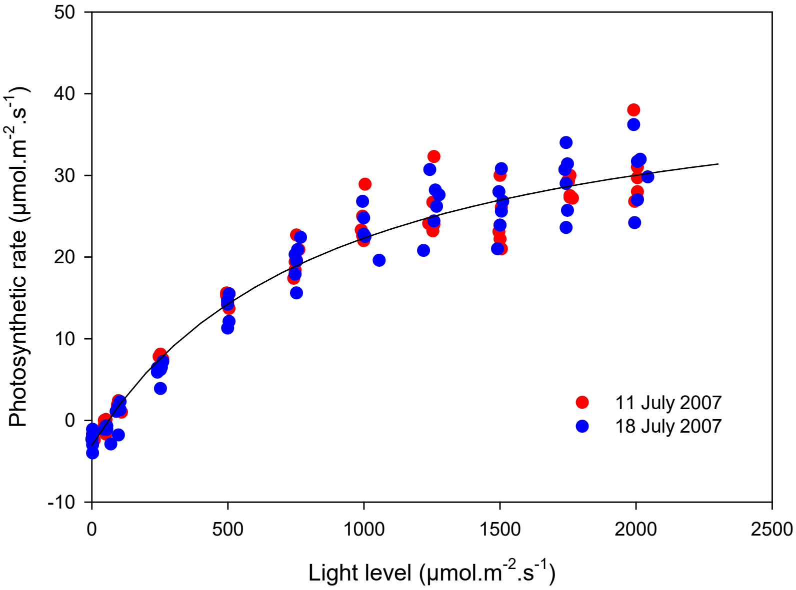
Therefore, we aimed to wait for stomatal conductance values over 250mmol.m^{-2}.s^{-1} when producing a light response curve. However, this was not always easy to achieve. Figure 27 shows the increase in stomatal conductance over time for leaves that were previously in the dark. On this occasion the stomata opened relatively slowly and then began to close again, as a result stomatal conductance was probably always limiting photosynthesis. Measurements indicated that lower leaves were even less responsive, and therefore had very low photosynthetic rates, even when high light levels were provided using an artificial light source.

Figure 27 - The slow increase and then decrease in stomatal conductance over time for leaves held in the dark and then exposed to either 1000 (red) or 2000μmol.m^{-2}.s^{-1} (blue) of LED light



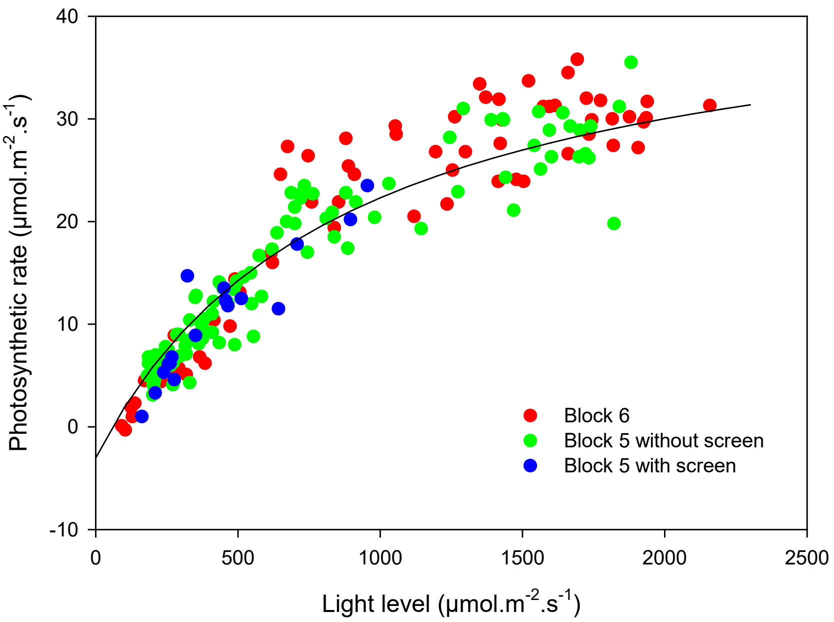
To investigate the relationship between light and leaf photosynthesis (produce a light response curve), leaves were exposed to a range of light levels (0 to 2000μmol.m^{-2}.s^{-1}). Leaves were initially exposed to high light levels to encourage stomatal opening. A total of six leaves were examined on the 11 July 2007 and a further six leaves were recorded on 18 July 2007 (Figure 28). These data were used to fit a light response curve using a rectangular hyperbola.

Figure 28 - A light response curve for leaf photosynthesis. This was produced by exposing leaves to a range of light levels using an LED light source.



Measurements of photosynthesis under ambient conditions in the shaded and unshaded blocks were then compared with the light response curve, the aim being to identify periods of stress when leaves were under performing. It was also intended to assess whether the shaded plants outperformed those without shading for a given light level. Seven visits were made throughout the summer, despite this there were only a few occasions when the shades were closed during the visits.

Figure 29 - Leaf photosynthesis recorded under ambient light conditions in Block 6 (unshaded) and Block 5, both with and without the screen in use. The line represents the response curve from the Figure 28. Data shown were collected on 24 May, 2 August and 4 September 2007.



The photosynthesis data collected under ambient light levels showed a very similar response to light when compared to the light response curve fitted under artificial light (Figure 28). There was no evidence to suggest that leaves in the two blocks (shaded and unshaded) responded differently. Furthermore, despite the earlier problems in getting the stomata to open under an artificial light source, there was little evidence to suggest that stomatal conductance was limiting photosynthesis under ambient light levels for young leaves at the top of the canopy.

Figure 29 also highlights the speed of screen operation when light conditions were constantly changing. Data were collected from the shaded block at very high light levels before the screen came across. For comparison 600W.m^{-2} (total solar radiation) outside would equate to around 1,100μmol.m^{-2}.s^{-1} (assuming that 50% of the radiation is photosynthetically active radiation and that there is 80% light transmission into the glasshouse). When the screen did come across the outside light level quickly fell and very low light levels were recorded under the screen. These data were analysed and when the shade was in use the photosynthetic rate was shown to be reduced due to the light loss because of the screen. This highlights the risk that shading could reduce light interception and cause a small yield penalty. Having said that when the light loss is estimated by considering the recorded screen positions and assuming an 88% light transmission (the manufacturers claimed value for direct light), the light loss is only predicted to be 3.7% between Weeks 21 and 31. Over the whole season the light loss will be even less than this and so the effect on yield is likely to be minimal, especially when it is considered that the relationship between light and photosynthesis is non-linear (Figure 29) and shading is only used at high irradiances.

Water uptake

Water uptake (transpiration) was also used as a potential indicator of plant stress. If plants were experiencing summer stress it was possible that stomata would close reducing transpiration. Two methods for measuring water uptake were compared; sap flow and drain records.

Sap flow

Sap flow was measured for over 60 days during the period from 3 - 18 May. Four sensors were attached to 12-16mm diameter stems in the shaded block and four were used in the unshaded block. The sensors were attached to the bottom of the shoots, usually just above the V. Sensors were positioned on sections of stem that were relatively straight and cylindrical. The sheath conductance (Ksh), which was needed for sap flow calculations, was estimated by looking at minimum values at night. While this would give a reasonable approximation, the plants would have still been transpiring at night, and so this would tend to result in a slight underestimate of sap flow. The best way of obtaining an accurate calibration under glasshouse conditions is to cut the stems at the end of the experiment and measure the sheath conductance with zero sap flow, although this is clearly undesirable in a commercial crop.

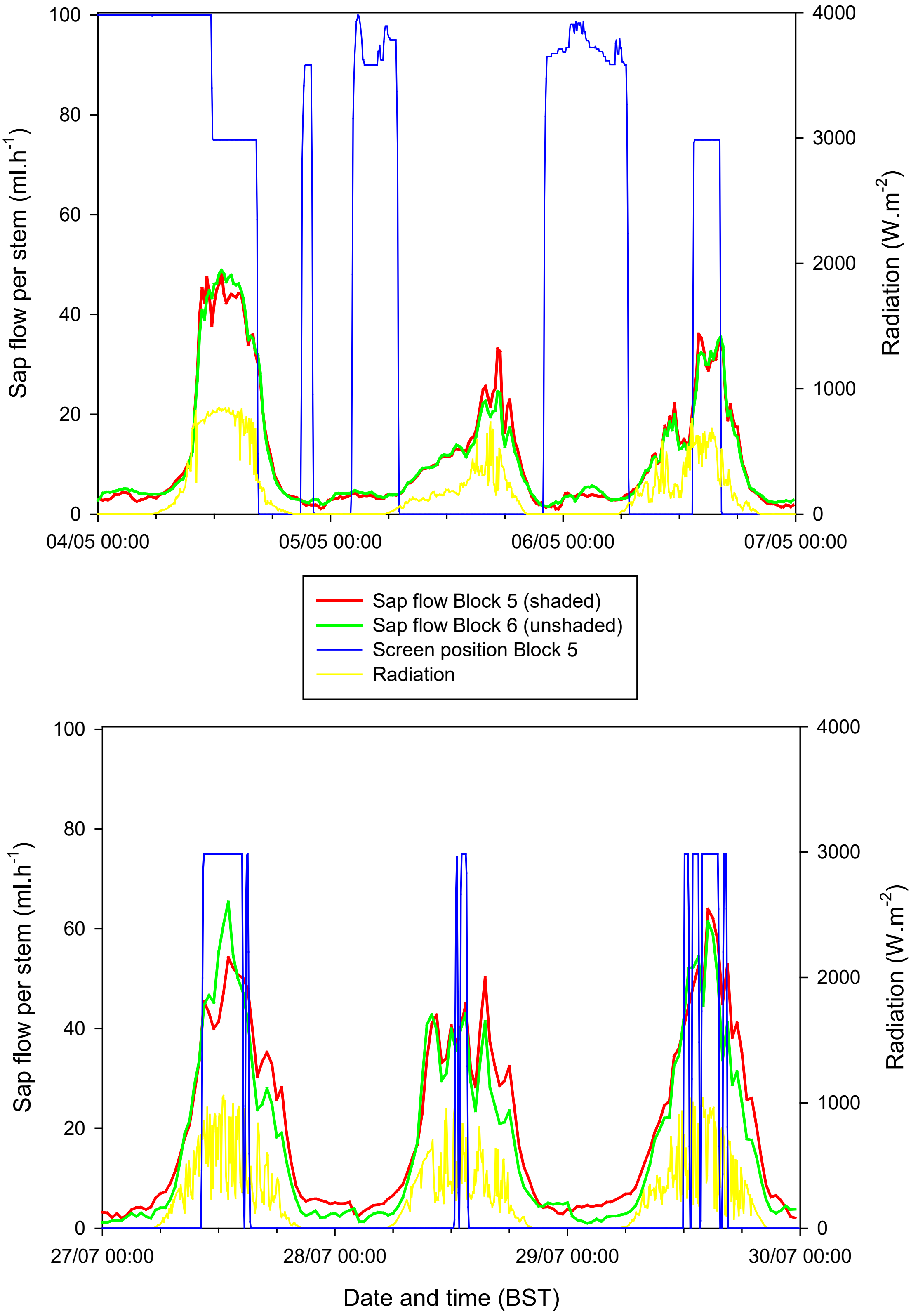
To improve thermal contact an electrical insulating compound (silicon grease) was initially applied to the area of the stem to be covered by the gauge as recommended by the manufacturers. Gauges were covered with the manufacturer's weather shield and a number of layers of aluminium foil to reduce temperature fluctuations through solar radiation. However, after a couple of weeks these plants were wilting and the stems were found to be infected with *Fusarium oxysporum* (Figure 30). The use of electrical insulating compound was found to be the primary cause, even though it has been successfully used for a number of other species including tomatoes; it presumably damaged the stems by preventing gas exchange. Therefore, this compound was not used in the subsequent measurements. As a result the data were a little more variable due to poor stem contact.

Figure 30 - Damage caused as a result of the electrical insulating compound.

As one would expect the sap flow over the course of each day closely followed solar radiation levels (Figure 31). However, the sap flow data are smoothed slightly by the fact that the data are based upon averages over the previous 15 minutes. There was little or no evidence for a decrease in sap flow with high irradiance which would have indicated stomatal closure due to stress. At times there were differences in the average sap flow recorded in Blocks 5 and 6. However, these differences were greater when the electrical insulating compound was not used and was largely due to variation between sensors rather than any consistent difference between the two blocks. This is supported by the fact that differences sometimes occurred when the screen was not in use.

There were also slight differences as a result of whether shoots were on the east or west side of the double rows. In Figure 31, the screened data (Block 5) comprises of two stems facing west and one facing east, while the unscreened data comprises one stem facing west and two facing east (the other sensors were not contacting properly at the time). As a result, the screened area with a higher proportion of stems facing west gave higher values in the afternoon.

Figure 31 - Comparison of the average sap flow recorded in the shaded and unshaded block, together with the outside solar radiation and the position of the screens in Block 5.



Comparison of sap flow and drain data

Figure 32 below shows irrigation water application and drain volume data exported from the climate control computer for a typical day. The beginning of each dosing round is indicated by the step increase of the dose line. The end of each round is indicated by line becoming horizontal again. A similar pattern occurs with the drain volume albeit with a slight time delay due to the time it takes for the water to percolate though the growing media. Analysis of these data allowed water uptake by the plant between each round of irrigation to be determined (Figure 33) and compared with the photosynthesis and sap flow measurements.

Figure 32 – A daily profile of irrigation applied and drain volume

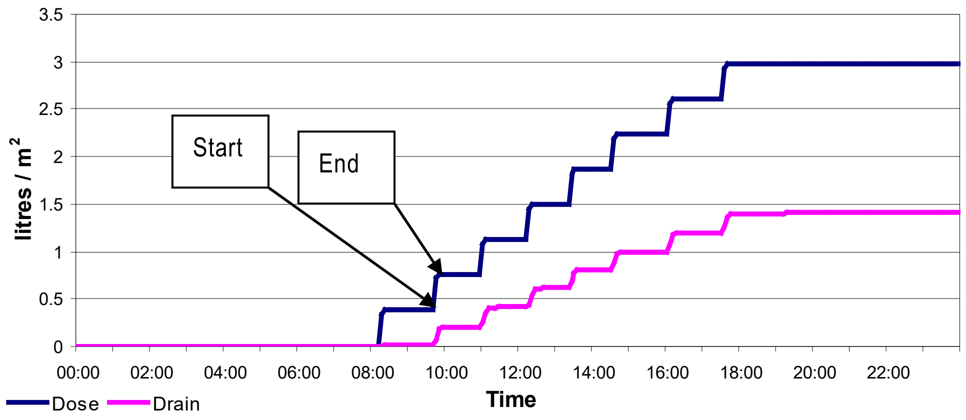
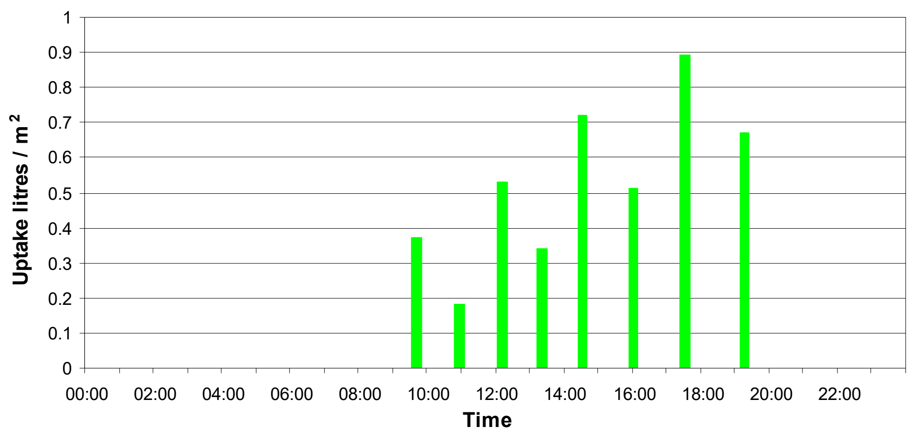


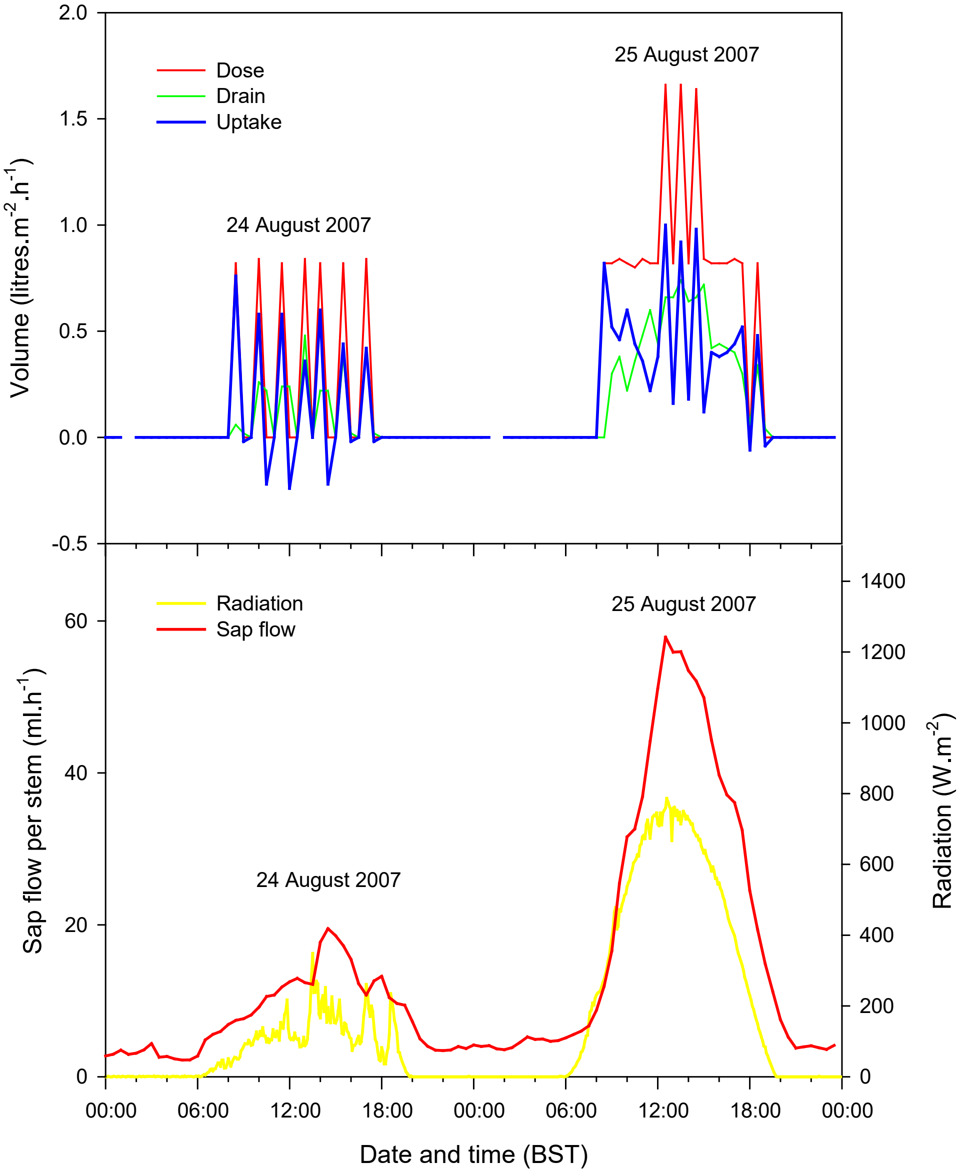
Figure 33 – Uptake per irrigation round



The daily pattern of water uptake is very different when sap flow and the estimates via drain measurement are compared (Figure 34). The drain measurements showed no uptake at night and erratic uptake during the day. The difference is greater on dull days (e.g. 24 August) when the irrigation frequency is reduced. This is because of the time lag between irrigation and drain. Also the calculations do not take into account the drying of slabs at night or their wetting up in the morning. The sap flow sensors, measuring water uptake directly, do not exhibit these inconsistencies, and therefore give a far better indication on the pattern transpiration over time.

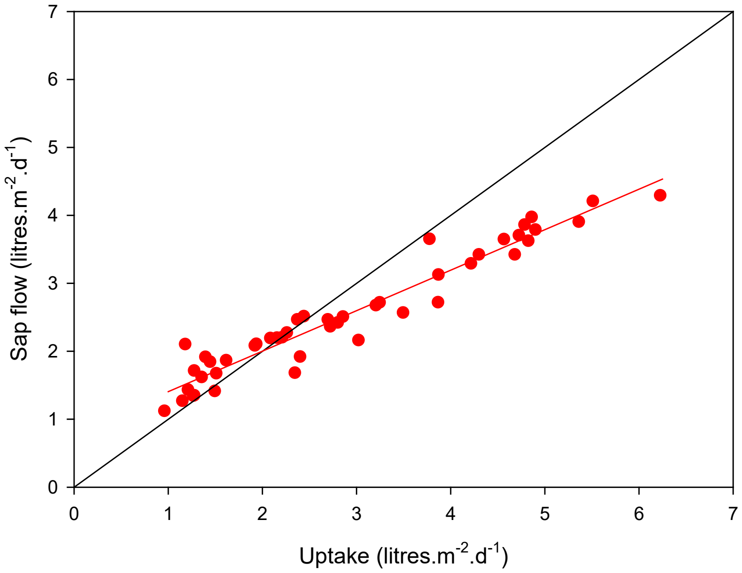
When the average sap flow per day was compared with the uptake calculated using the drain measurements there was a strong positive correlation (Figure 35). However, on dull days when transpiration was low, the sap flow values tended to be higher that those recorded using the drain, and on good days the sap flow sensors gave slightly lower values. This may have been due to problems with thermal contact of the sap flow sensors (caused by not using the electrical insulating compound) and calibration of sheath conductance.

Figure 34 - Comparison of hourly water uptake when measured using sap flow gauges and estimated using dose and drain.



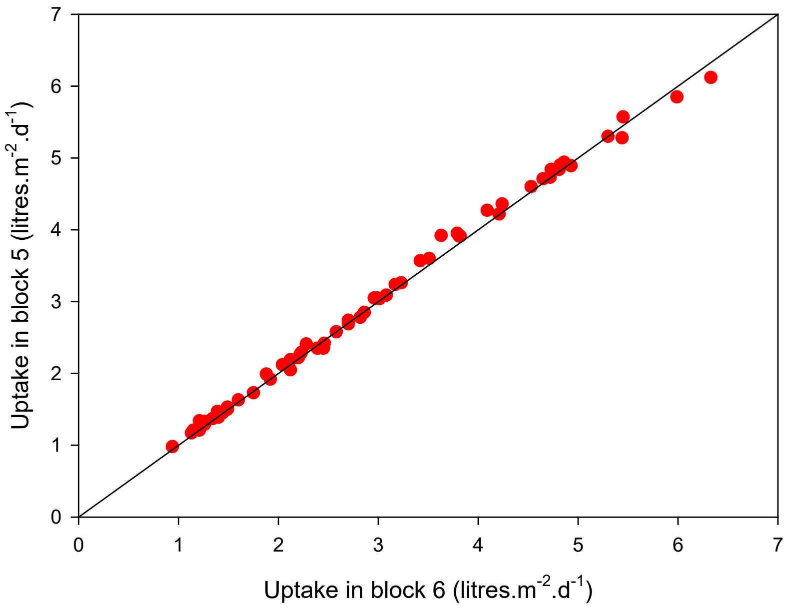
Similarly there would be errors in the estimates using drain, although for daily values the latter would tend to be more accurate.

Figure 35 - Comparison of daily water uptake estimated via drain measurements and sap flow. The black line indicates the line of identity on which points would fall if there were perfect agreement.



The conclusion that there was little difference in the sap flow between the shaded and unshaded blocks is confirmed by the uptake calculated using dosing and drain. The daily uptake was calculated for the two blocks and is compared in Figure 36. The estimated uptake was almost identical in the two blocks.

Figure 36 - Comparison of the water uptake in the unshaded and shaded block when measured using drain measurements. The line indicates where points would fall if the uptake were identical in both blocks.



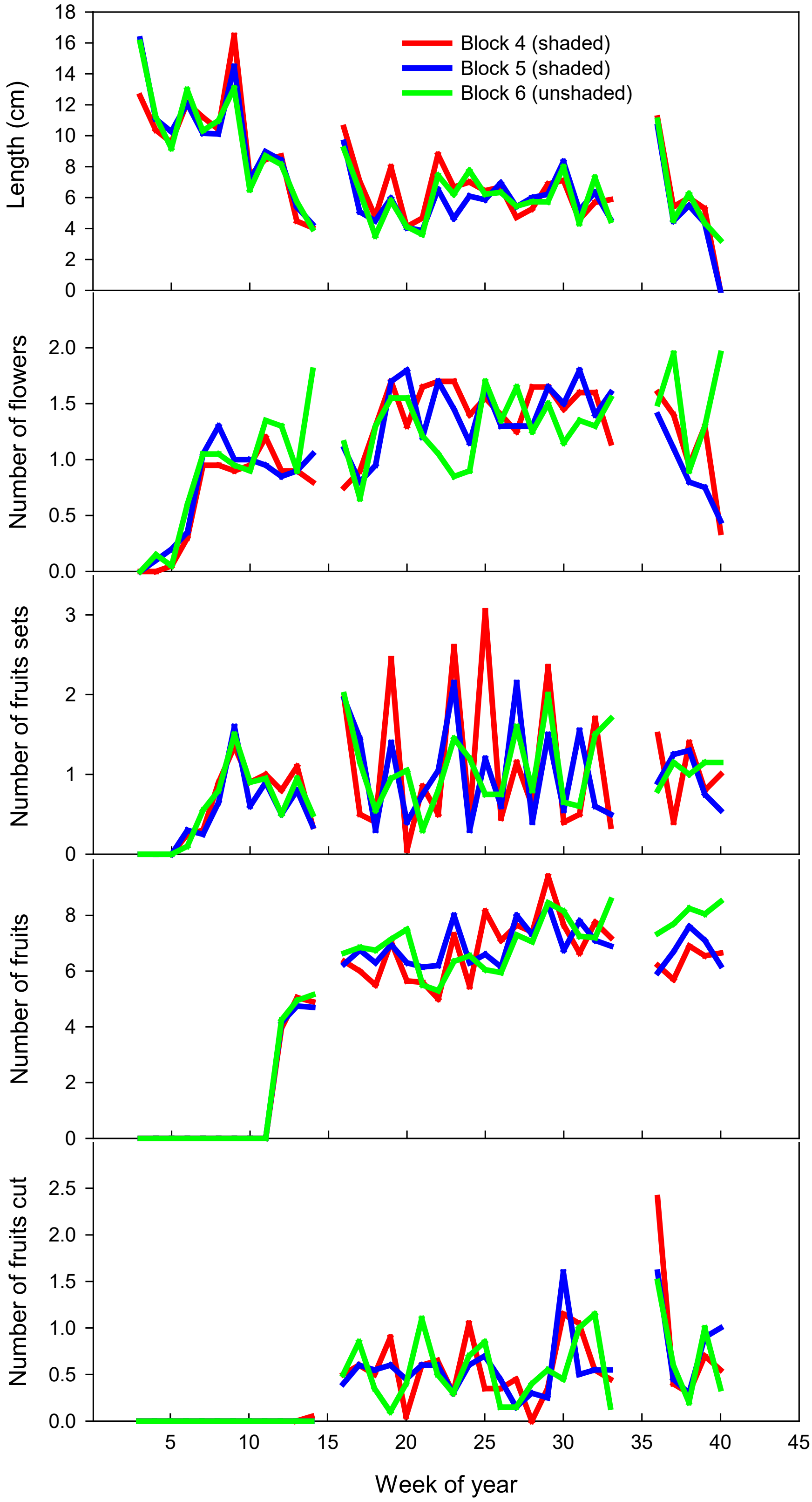
Crop growth and development records

Weekly crop records were taken by the nursery staff, this comprised of 20 stems per block. While the trial was focused on Blocks 5 (shaded) and 6 (unshaded), data from Block 4 was also included in the analysis as this block was also shaded and treated exactly the same as Block 5. The differences between Blocks 4 and 5 were used to indicate the variation between 'identical' blocks to give an indication whether the treatment differences in Block 6 were significant.

When the total stem length, and cumulative set and cuts per stem were compared at the end of the season there was no evidence to suggest that there were significant differences due to shading (P >0.05). The average stem length was 277cm and there was on average 31 fruits set per stem and 13.7 fruits cut.

These data were also analysed on a weekly basis to assess whether there were any effects in particular weeks. These data are summarised in Figure 37. While there were differences between the three blocks, the effect of shading would appear to have been relatively small.

Figure 37 - Weekly increase in stem length, and the number of flowers, fruits set, total number of fruits per stem, and number of fruits cut per week. These data are from 20 stems per block.

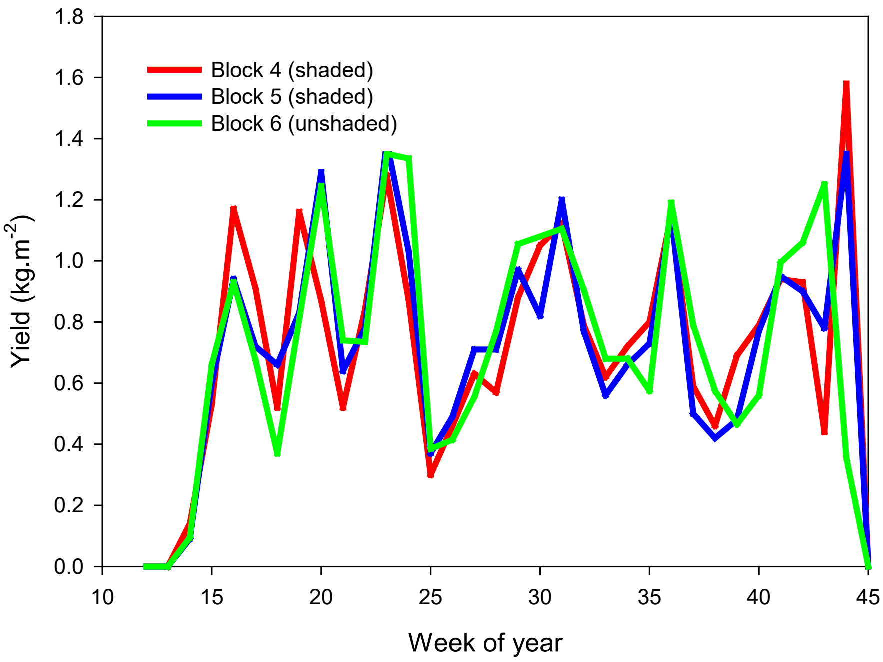


Yields

The yield data were analysed for each worker, although the yields from one worker were excluded as while they were predominantly from Block 5, they also included a few rows in Block 6. This left data for one worker in each of Blocks 4 and 5 and two workers in Block 6. These data were analysed using ANOVA.

The average yield from the shaded blocks was 24.3kg.m^{-2} compared with 24.4kg.m^{-2} from the unshaded block, this difference was not significant (*P* >0.05). These data were also analysed on a weekly basis to assess whether there were any seasonal differences; the yields for each block are summarised in Figure 38. While there were differences between the shaded and unshaded blocks, these were no greater than the differences between Blocks 4 and 5 which were both treated the same. The only significant differences ($P < 0.05$) were at the very end of the cropping season (Week 43) when the yields per worker per day were quite erratic. This was not due to the effect of the treatments.

Figure 38 - Weekly yields recorded from the three blocks.



Disease

This section summarises the work carried out by Dr Tim O'Neill of ADAS Consulting Ltd. A complete version of his report is provided in Appendix 1.

Methodology

Crop assessment

Crops were assessed for disease on 9 May, 2 July, 25 July, 11 September, and just before crop pull-out on 30 October. All plants within a pathway in each compartment, comprising over 250 stems, were inspected for stem lesions.

Fruit testing

On four occasions (Weeks 19, 27, 30 and 37) samples of 50 fruit with no external symptoms of Fusarium rot were taken from crates of produce picked by nursery staff from the shaded and unshaded blocks and assessed in the laboratory.

On all occasions the fruit were Class 2 and some had slight blossom end rot; on one occasion unblemished Class 1 fruit were also assessed. Additionally, the nursery provided records of the total weekly pick, by weight, and the proportion of the pick that was unmarketable due to visible Fusarium rot and/or blossom end rot or other damage.

Results

<u>Fusarium fruit rot - external symptoms</u>

Relatively few fruit was recorded by the nursery as unmarketable due to external damage during Weeks 12-25. However, this increased from Week 26 onwards with 7% of the fruit rejected in the worst week. A small proportion of fruit was unmarketable due to severe blossom end rot, while the nursery manager estimated that around 70% of the fruit that was rejected was due to Fusarium fruit rot.

Over the 10 week period (Weeks 26-35) the percentage wastage in Block 4 (3.4%) was significantly greater than in Block 6 (2.9%), which was itself greater than in Block 5 (2.6%).

<u>Fusarium fruit rot - internal infection</u>

When visibly healthy fruit were examined in the laboratory, growth of Fusarium was observed within samples from shaded and unshaded areas at all five sampling dates. There was no significant difference between the incidence of Fusarium in fruit from the shaded and unshaded areas in any of the samples. The incidence of infection ranged from 2.0% to 15.7% with an average over the season of 8.5% in the shaded block and 8.3% in the unshaded block.

In some fruit, infection by Fusarium was confined to the seed, whilst in others the inner wall, especially at the lower end (flower end), was also affected. Out of the 564 visibly healthy fruit examined, 29 (5.2%) had Fusarium growth on the inner wall. This is greater than the incidence of fruit rejected at picking due to externally visible Fusarium (2.6-3.4%), consistent with the hypothesis that Fusarium fruit rot progresses from the inside of the fruit outwards.

Other diseases

No Botrytis stem rot (*Botrytis cinerea*), Sclerotinia stem rot (*Sclerotinia sclerotiorum*), or powdery mildew *(Leveillula taurica*) were observed in either Block (5 or 6) during the season. The incidence of plant death at the end of the season in both compartments was very low and on 30 October just one stem lesion (botrytis) was found in the monitored row in the unshaded block and one stem lesion (Fusarium) in the monitored row in the shaded block.

Glasshouse climate and Fusarium fruit rot

Examination of glasshouse climate data indicated that between Weeks 13–36, when summer shading was used in Block 5, the day humidity deficit was greater in the shaded than in the unshaded block, by around 0.5g/m^3. Consistent with this, the daily number of hours when relative humidity (RH) was greater than 85% was greater in the unshaded block, often by around 5-10h per day. However, as discussed in section 10.4 this was thought to be due to an inherent climate difference between the two blocks or measurement error and not the effect of shading.

Work on Fusarium stem rot of pepper caused by *F. solani* and *F. oxysporum* indicates stem infection is favoured by high humidity. As such, the small but significantly greater incidence of Fusarium fruit rot in Block 6 (2.9%) compared to Block 5 (2.6%) is consistent with the higher RH recorded in Block 6.

Fusarium fruit rot is believed to develop from the inside of fruit outwards, as evidenced by the occurrence of fruit with internal Fusarium rot and no external symptoms. The fact that a significant difference between the three blocks was found for external Fusarium fruit rot, and not for fruit with only internal Fusarium, is possibly due to the much greater sample size for the former, resulting in a more sensitive comparison.

Discussion

Identification of conditions that cause plant stress

The weather during the summer of 2007 was relatively poor. As a direct result high greenhouse temperatures and humidity deficits rarely occurred. A comparison of weather and greenhouse aerial environment data for 2007 vs 2006 confirmed this was the case.

Such was the impact of this that, in spite of a high level of instrumentation and regular site visits it was not possible to record any instances of plant stress indicated by stomatal closure and / or reduced photosynthetic efficiency.

Impact of shading on the greenhouse environment

Although there were differences between the humidity and CO_2 in the greenhouse compartments similar differences also occurred in 2006 when shading was not used. There were therefore underlying inherent differences between the compartments or differences in sensor calibration which could not be put down to the use of shading.

There was a small increase in average daytime temperature (0.5^{o}C) in the shaded compartment during mid summer. Greenhouse shading impacts temperature in two ways. Reduced light levels promote lower temperatures but restricted ventilation tends to have the opposite effect. In the marginal conditions in 2007 the restriction on ventilation appears to have dominated resulting in temperatures being marginally higher. The screen was only allowed to close to 75% (leaving a 25% gap). Allowing an even greater gap was not expected to deliver significantly better ventilation and would have reduced the level of shade provided to such an extent that it would have given little shading benefit.

One of the biggest concerns of growers when using screens to provide shade is the impact on humidity levels in the greenhouse. The shading strategy used in this project took no direct account of the humidity in the greenhouse. However, as the screen was only closed when light levels exceeded 600W/m^2, the humidity was always above 5.0g/m^3 (<80% RH) too high to be a problem.

Performance of different plant stress related measurements

The primary goal when growing edible crops is to maximise photosynthesis and promote growth. Therefore the most reliable indicator of plant stress is a reduction of photosynthetic activity when the available light (photosynthetic efficiency) is taken into consideration.

The measurements taken using the CIRAS-1 system served as the benchmark for measuring photosynthetic activity.

Practically, on commercial nurseries it remains difficult and expensive to have continuous, reliable and accurate measurements of photosynthesis, hence the need in this project to consider alternative measures like sap flow and water uptake which present simpler and potentially more commercially viable alternatives.

Although there were no occasions when any of these measurements implied that the plants were under stress, it was still useful to compare them to give an indication of their potential.

For the purposes of this project plant stress was defined as a reduction in photosynthesis relative to the light intensity, brought about by a reduction in the stomatal opening. Stomatal restriction reduces the amount of water transpired by the plant, the sap flow and water uptake. On this basis, sap flow would seem to be the most direct measurement to indicate the level of photosynthesis after direct measurement of photosynthesis itself.

The sap flow data recorded showed good correlation with the light intensity and provided a continuous stream of data. In comparison, the water uptake data was heavily influenced by the timing of each round of irrigation. This was particularly problematic when the frequency of irrigation was low. Even when irrigation rounds were more frequent i.e. when stress conditions were most likely, the data produced remained difficult to interpret. This was disappointing as, in comparison to sap flow and photosynthesis, water uptake was a relatively simple and robust thing to measure.

As might have been expected the total water uptake per day compared well with the average sap-flow. Therefore, comparing water uptake with radiation sum would give an indication of the average plant efficiency over a day. However, this information only has retrospective value and could not be used to control shade screens directly. Nevertheless, it could be used to provide some indication of the occurrence of stress in very severe conditions.

Screen control strategy (shading)

As no plant stress events were identified in the unshaded block it could be argued that there was never a need to use shading in the particular year studied. It might have been expected that the seemingly unnecessary use of shading could have affected the yield, but in fact there was no significant effect on yield either positive or negative.

Neither did the use of screens impact on humidity in the greenhouse or disease levels. Both were unaffected.

Overall, although the screen control strategy may have provided shading when it delivered little or no benefit it is important to recognise that it failed to produce any negative effect either. This opens the door to growers who may wish to explore shading themselves. They should be able to apply the same shading strategies (or possibly less) as used in the project, with the confidence that their action will at worst have no detrimental effect on their crop. But in a hotter, sunnier summer they could prove to be beneficial.

Conclusions

- Closing a thermal screen to 75% to provide shade at outside light intensities greater than 600W/m^2 had no effect (positive or negative) on yield or disease on a sweet pepper crop in 2007.
- None of the data collected indicated that photosynthesis was limited by extremes of temperature or humidity in the greenhouse in 2007.
- Weather conditions in the summer of 2007 were relatively poor (lower temperatures and light levels) compared to 2006 and the incidence of high temperature and low humidity deficit in the greenhouse was significantly less as a direct result.
- If sap flow can be reliably and easily measured in a commercial situation it will provide a real-time indication of plant ‘health’.
- Water uptake is easy and reliable to measure. However, it does not provide sufficient ‘real-time’ data to allow it to be used as a control mechanism - e.g. to identify plant stress and trigger screens to close.
- Water uptake is a useful indicator of plant health / activity when integrated over a day and compared with the light received. However, it is limited to assessing the historical performance of a plant and is only likely to indicate the occurrence of prolonged, extreme events.

Appendix 1 – Disease Assessments

Carried out by Dr Tim O'Neil, ADAS Consulting

Summary

Two adjacent areas of a glasshouse crop of sweet pepper, cv. Special, in the Lee Valley, Essex, were regularly assessed for disease during 2007. Between Weeks 13 and 36, thermal screens were applied during the hottest part of the day in one area (Blocks 4 and 5; the 'shaded' area) and not in an adjacent area (Block 6, 'unshaded'). Fusarium fruit rot caused by *F. oxysporum* or a similar species occurred at a relatively high level in both areas. During Weeks 26-35, wastage of fruit, primarily due to Fusarium fruit rot visible at picking, was significantly different between the three blocks but this could not be attributed to the shading treatment. The proportion of affected fruit in the unshaded block (2.9%) was intermediate between the levels in the two shaded blocks (2.6% and 3.4%). No significant difference was recorded between the blocks in the incidence of internal Fusarium fruit rot assessed on four occasions between Weeks 19 and 37. Fusarium stem node lesions were rare and were cut out as they occurred; no girdling lesions were recorded. No other diseases were found.

Introduction

The use of summer shade screens to reduce temperature extremes may lead to an altered glasshouse climate, notably of temperature and humidity. Both may influence the types of diseases that occur and their speed of development in a crop. The objective of this study was to determine and compare the diseases occurring in a crop where one area of a glasshouse used thermal screens to provide summer shade and an adjacent area did not.

Methods

Crops

Two adjacent glasshouse areas growing sweet pepper cv. Special, planted in December 2006 on rockwool slabs in hanging gutters, were examined. The plants originated from Holland. Between Weeks 13 to 36, thermal screens were used to provide sun shade in one area (Blocks 4 and 5) and not in the adjacent area (Block 6). Between Weeks 1-12 and Weeks 36-43, the use of thermal screens was identical in the three blocks. Humidity was measured at 30-50cm below the plant head by FEC. Air-circulation fans were used above the crop in both blocks. Apart from preventative treatment with sulphur no other fungicides were applied.

Disease monitoring

In 2007, crops were assessed for disease on 9 May, 2 July, 25 July and 11 September, and just before crop pull-out on 30 October (Weeks 19, 27, 30, 37 and 44, respectively). All plants within one pathway in Blocks 5 and 6, comprising over 250 stems, were inspected for stem lesions.

Fruit testing

On four occasions (Weeks 19, 27, 30 and 37) samples of 50 fruit with no external symptoms of Fusarium rot were taken from crates of marketable produce picked by nursery staff from the shaded and unshaded areas and assessed in the laboratory. Fruit were cut open and examined within 1 day of collection and examined for sporulation of *Fusarium* species on the seed and internal walls. Fungal growth was identified by microscope examination.

On all occasions the fruit were Class 2 and some had slight blossom end rot; in Week 27, unblemished Class 1 fruit were also assessed. Additionally, the nursery provided records of the total weekly pick, by weight, and the proportion of the pick that was unmarketable due to visible Fusarium rot and/or blossom end rot or other damage.

Data on Fusarium fruit rot were examined by calculation of standard deviations assuming a binominal distribution; 95% confidence limits were calculated to determine if the levels of Fusarium fruit rot in shaded and unshaded blocks differed significantly.

Results and discussion

Fusarium fruit rot - external symptoms

Relatively few fruit was recorded by the nursery as unmarketable due to external damage during Weeks 12-25. However, from Week 26 onwards a relatively high incidence of fruit was unmarketable (Table 1). A small proportion of fruit was unmarketable due to severe blossom end rot, while the nursery manager estimated that around 70% of the fruit that was rejected was due to Fusarium fruit.

The total weight of fruit picked from each block during this period was in excess of 25 tonnes. There was significant variation between blocks from week to week in fruit wastage due to Fusarium rot. Over the 10 week period (Weeks 26-35) where increasing large losses were recorded, the proportion of fruit unmarketable was significantly different between the three blocks, with the unshaded block suffering losses at a level intermediate between the two shaded blocks. The percentage wastage in Block 4 (3.4%) was significantly greater than in Block 6 (2.9%), which was itself greater than in Block 5 (2.6%) (P=0.05).

Fusarium fruit rot - internal infection

When visibly healthy fruit were examined in the laboratory, growth of Fusarium was observed within samples from shaded and unshaded areas at all five sampling dates. There was no significant difference between the incidence of Fusarium in fruit from the shaded and unshaded areas in any of the samples (P>0.05) (Table 2). The incidence of infection ranged from 2.0% to 15.7% with an average over the season of 8.5% in the shaded block and 8.3% in the unshaded block. There was no evidence that the level of fruit infection was associated with crop age.

In some fruit, infection by Fusarium was confined to the seed, whilst in others the inner wall, especially at the lower end (flower end), was also affected (Table 3). Seed infection alone might be overlooked by consumers but Fusarium growth on the inner wall was usually associated with a brown rot, likely to develop to an external rot, and more likely to have led to complaints. Out of the 564 visibly healthy fruit examined, 29 (5.2%) had Fusarium growth on the inner wall (Table 3). This is greater than the incidence of fruit rejected at picking due to externally visible Fusarium (2.6-3.4%), consistent with the hypothesis that Fusarium fruit rot progresses from the inside of the fruit outwards.

Other diseases

No Botrytis stem rot (*Botrytis cinerea*), Sclerotinia stem rot (*Sclerotinia sclerotiorum*), or powdery mildew *(Leveillula taurica*) were observed in either block (5 or 6) during the season. The incidence of plant death at the end of the season in both compartments was very low and on 30 October just one stem lesion (botrytis) was found in the monitored row in the unshaded block and one stem lesion (Fusarium) in the monitored row in the shaded block. Botrytis fruit rot was found on occasional over-mature attached fruit in both blocks.

Glasshouse climate and Fusarium fruit rot

Examination of glasshouse climate data provided by FEC indicated that between Weeks 13–36, when summer shading was used in Block 5, the day humidity deficit was greater in the shaded than the unshaded block, by around 0.5g/m^3. Consistent with this, the daily number of hours when relative humidity (RH) was greater than 85% was greater in the unshaded block, often by around 5-10h per day (Figure 1).

At first examination these results might suggest that the use of summer shade screens has increased the humidity deficit beneath the screen. However, between Weeks 36 - 43, when there was no difference between the two blocks in the use of shade screen, the humidity deficit in Block 5 remained around 0.5g/m^3 greater than in Block 6, indicating the difference between the two blocks is not due to the use of shade screens. It is more likely to be an inherent climate difference between the two blocks. Examination of climate data for 2006 collected by FEC also revealed the humidity deficit to be consistently greater in Block 5 than in Block 6.

Block 6 had a greater occurrence of high humidity periods than Block 5 (Figure 1). Block 6 also had a small but significantly greater incidence of Fusarium fruit rot (2.9%) than Block 5 (2.6%). Work on Fusarium stem rot of pepper caused by *F. solani* and *F. oxysporum* indicates stem infection is favoured by high humidity. Further work would be required to determine if the apparent association of a higher level of Fusarium fruit rot in pepper grown in a house with a higher humidity, as found in this study, is causal.

Fusarium fruit rot is believed to develop from the inside of fruit outwards, as evidenced by the occurrence of fruit with internal Fusarium rot and no external symptoms. The fact that a significant difference between the three blocks was found for external Fusarium fruit rot, and not for fruit with only internal Fusarium, is possibly due to the much greater sample size for the former, resulting in a more sensitive comparison.

Further work is needed to determine factors influencing infection of pepper flowers and fruit by *Fusarium* spp. and the development of Fusarium fruit rot. Work elsewhere suggests that fruit infection may originate via infection of the flowers and a comparison of surface wetness duration on flowers in shaded and unshaded compartments might be useful.

Table 1: Occurrence of unmarketable pepper fruit due to external damage at picking (primarily Fusarium rot) in three adjacent glasshouse blocks

	Unmarketable pepper fruit (% total pick by weight)		
Week number	Shaded (block 4)	Shaded (block 5)	Unshaded (block 6)
26	5.5 (0.56)	4.2 (0.46)	2.2 (0.32)
27	4.4 (0.43)	3.0 (0.33)	5.7 (0.43)
28	5.1 (0.48)	2.8 (0.32)	2.5 (0.24)
29	2.8 (0.29)	2.1 (0.24)	2.2 (0.20)
30	2.1 (0.23)	1.4 (0.21)	2.4 (0.20)
31	1.5 (0.19)	1.2 (0.16)	1.9 (0.18)
32	3.0 (0.31)	1.8 (0.25)	1.7 (0.19)
33	3.3 (0.37)	4.3 (0.44)	3.7 (0.32)
34	5.5 (0.44)	5.0 (0.44)	4.9 (0.36)
35	4.1 (0.73)	2.3 (0.58)	7.0 (1.00)
Total (weeks 26-35	3.39 (0.11)	2.58 (0.10)	2.88 (0.09)

( ) – standard deviation

Table 2: Effect of summer shade screens on occurrence of internal Fusarium rot in harvested pepper fruit - 2007

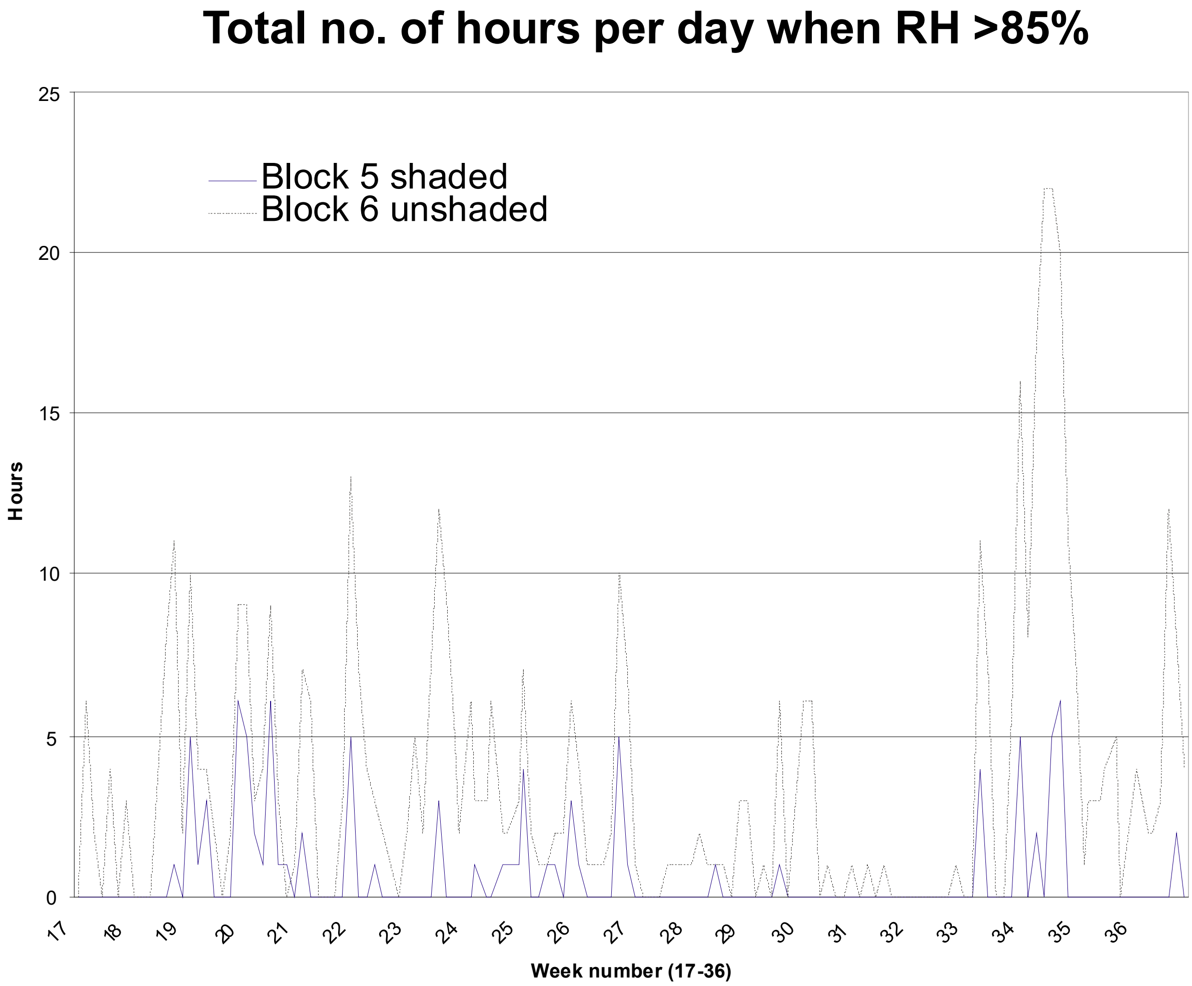
Week	Class of	Shaded (Block 5)		Unshaded (Block 6)	
Number	Fruit	No. fruit examined	% fruit with internal Fusarium	No. fruit examined	% fruit with internal Fusarium
19	Class 2	81	12.4 (3.6)	81	9.9 (3.3)
27	Class 1	50	4.0 (2.7)	51	5.9 (3.3)
27	Class 2	50	12.0 (4.6)	50	8.0 (3.8)
30	Class 2	50	10.0 (4.2)	50	2.0 (1.9)
37	Class 2	50	4.0 (2.7)	51	15.7 (5.1)
Means			8.5		8.3

( ) – standard deviation

Table 3: Location of Fusarium sporulation within pepper fruit lacking external Fusarium rot symptoms – 2007

Week	No. fruit	% fruit with Fusarium		
Number	examined	On seed only	Inside wall only	Seed and wall
19	162	2.5	3.7	4.9
27	101	0.9	0.9	3.0
30	200	3.5	2.5	2.0
37	100	5.9	2.9	1.0
Mean		3.2	2.5	2.7

Figure 1 - Occurrence of high RH periods (>85%) at head of pepper plants in shaded and unshaded areas between weeks 17-36.



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