Project title:	Targeting of humidity control, through the use of stem temperature measurements, to reduce stem botrytis and save energy in tomato production.
Project number:	PC 301
Project leader:	Tim Pratt, FEC Services Ltd
Report:	Final Report, April 2011
Previous report:	None
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Location of project:	Warwick HRI (Warwicks), FEC Services Ltd (Warwicks), Red Roofs Nursery Ltd (E. Yorks), Mill Nurseries Ltd (E. Yorks), Wight Salads Group Ltd (Isle of Wight).
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Date project commenced:	1st July 2009
Date project completed (or expected completion date):	31st March 2011

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Tim Pratt
Technical Director
FEC Services Ltd

Signature .... Date ....

Report authorised by:

Andrew Kneeshaw
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Grower Summary

Headline

Tomato stem temperature sensors can be used to fine tune glasshouse humidity control, helping to cut energy costs and prevent condensation/stem Botrytis development.

Background

Suppression and control of high humidity in glasshouses is important as it helps to prevent condensation on plants which may lead to fungal disease. It also promotes crop transpiration and growth. However, humidity control comes at a price and estimates suggest that heat energy used in the process accounts for 30% of the total required to grow crops such as tomato. Therefore, any improvement in the management of humidity control and related diseases has the potential to deliver significant energy savings and/or yield/quality benefits.

Currently, the main tool used to control humidity and predict condensation events is based around the sensing of general air humidity. However, air-humidity sensing is a rather 'blunt' instrument when it comes to avoiding condensation as it fails to consider the dew point and the 'micro' environment at the plant/air interface. It also fails to recognise the spatial differences in conditions both in the horizontal and vertical planes. Consequently, humidity control set points used commercially are lower e.g. under 85–90 % than would be necessary to prevent general condensation - and more heating energy is used than is strictly necessary. In addition, there are times when air-humidity sensing fails to predict condensation and disease occurs.

Sensing plant temperature and dew point at the plant/air interface itself, rather than relying on air-humidity sensing, can allow closer and more accurate control to be exercised, cutting heating energy costs and reducing disease risk.

One main problem to the adoption of this practice is the necessary adaption of sensing equipment to effectively measure plant surface temperature and the interpretation of the output by the climate control computer. Challenges include the selection of the right sensing technology (infra-red or contact sensors), accuracy, sensor attachment methods, assessing the speed of response of sensing systems and selecting the best place for sensing and number of points necessary for good control.

This project was commissioned to explore and evaluate these issues and recommend some better commercial solutions.

Summary

Stem temperature sensing can be carried out using either a contact or infra-red (IR) sensor type. Contact systems are likely to prove to be the best option in most cases as they are sufficiently accurate, relatively cheap, and less affected by external influences when compared with IR types.

Experiments showed that new patch-type contact sensors, which cost about £15 per sensor, provided acceptable accuracy and speed of response. An heat conducting compound, applied between the sensor and the stem, improved responsiveness of sensors although this is not expected to give measureable benefits in this application. The use of Velcro straps to secure sensors led to a small reduction in response speed, but this was within acceptable limits for the application. Bead type sensors were less accurate and slower to respond. Thermistor and platinum resistance type sensors were tested and were found to be equally good. The decision on which one to use depends on how easily they can be connected to an individual site's climate computer.

Infra-red sensing is more expensive and is instant in response. However, its accuracy and use was adversely affected by heat given off by sensor heads and the need to keep sensors trained on the plant stem.

Stem temperature can be measured at different levels the see Figure below:

The trial looked at measurement at the top of the crop, at the de-leafing level and at the bottom of the crop. Top positions could be heavily influenced by solar radiation and at least weekly repositioning would be required. Top sensors were also prone to disturbance during plant work. The de-leaf level was similarly affected although the influence of solar radiation was a little less. The bottom of the crop measurement was easier to manage because of lower solar influence and less disturbance. There were only marginal differences between the de-leaf height and the bottom sensor temperature results, so it is recommended that only bottom sensing is necessary in practice for condensation control. Although top sensors are more challenging from a practical point of view, they offer further insight into temperature in relation to crop development.

The micro-environment at the plant stem was shown to vary across the crop. Therefore, it is recommended that if stem temperature is to be monitored, then it should be taken at four positions in the row; with sensors positioned suitably well away from the walls and central passage.

Integration of sensors into climate control system computers is not straightforward, as sensors may not be accepted as plug-and-play items. However, they can be integrated into a simple DC amplifier to produce a 0–5 V signal which can be interpreted by the climate control computer.

Financial Benefits

Financial benefits and returns from using stem temperature monitoring as a method of controlling glasshouse humidity is not simple to evaluate, as specific benefits will be dependent on the ability of the grower to interpret and act on the results available.

The capital cost of systems is likely to be relatively low, with sensors being quite cheap. With money also being required for wiring and integration of the information into the glasshouse control system, and possibly receiving the necessary training to enable information from the system to be interpreted correctly and acted upon, a cost of £3,000 per hectare is realistic.

Potential benefits in terms of energy savings are significant, especially in terms of the necessary investment required to implement this type of control. With humidity control related heating costs averaging say £15,000 - £45,000 per hectare per annum, a conservative 3 % saving in this per year would give a simple payback on investment of three years. Added to this would be savings from avoidance of plant disease — which would depend very much on the current performance of the site before modifications.

Action Points

Stem temperature monitoring and associated humidity control are clearly a significant step forward compared with reliance on control driven by general air humidity sensing. This project identifies that the hardware required can be acquired at reasonable costs and can be adapted to work satisfactorily if care is taken with positioning, attachment and interpretation of outputs.

For growers who consider themselves to have a good technical grasp of the conventional components of humidity control and how their climate controller interprets sensor input, then adoption of stem temperature monitoring and humidity control would be a good step forward. It will allow them to employ a degree of control and access to information which would not be available from simple air humidity monitoring. For those who may be less sure about some of the finer points of humidity control, adoption of stem temperature based systems might prove to be challenging.

In either case, growers should consider an exploratory approach to this technology by partial adoption and initial monitoring before any move to integrate the outputs into the glasshouse environmental control system.

The following steps might be considered for those who are interested in exploring the opportunities for stem temperature based monitoring/humidity control.

- Select an easily monitored compartment or area where an installation might be suitable.
- Investigate the practical issues of installing sensors to a crop row with sensors at four positions down the row, plus an extra measuring box positioned a low level.
- Measuring temperature at the bottom of the crop is most important. De-leafing level sensing gives little more information than the bottom sensor and top sensing is of greatest interest from a crop development point of view.
- Talk to your control system supplier/technician about what needs to be done to enable the interface of sensors to the climate control computer.
- Choose a good quality and thermally light, patch type platinum resistance or thermistor sensor, as it will give the best accuracy. Paying a few pounds more for accuracy will be worth it.
- Position sensors on the northeast side of the stem to minimize radiant heating effects from the sun.
- Set up the climate computer graphs to compare measured stem temperature with dew point temperature.
- Note the times and conditions when stem temperatures get near or go below dew point temperatures and make adjustments as necessary. Similarly note when condensation events are observed in the crop and check the data of the graphs.
- After you know and understand the interaction between stem temperature, dew point and the operation of heating and ventilation, you might consider using the stem measurements to influence how the heating and ventilation work.

Science Section

Introduction

Suppression and control of high humidity in glasshouses is important as it helps prevent fungal disease and promotes crop transpiration and growth. However, humidity control comes at a price and estimates suggest that heat energy used in the process accounts for 30 % of the total required to grow crops such as tomato. Therefore, any improvement in the management of humidity control and related diseases has the potential to deliver significant energy savings and/or yield/quality benefits. Although this project focuses on tomato, the results are applicable to many other crops.

Botrytis stem rot, the most damaging form of tomato Botrytis, continues to be a significant problem in protected tomato production. The risk of infection is increased by the presence of condensation, which tends to occur in high humidity conditions.

Condensations occurs when air is cooled below its dew point (relative humidity of 100 %). causing water-vapour in the air to be released as a liquid and deposited on cool surfaces (potentially the crop).

Humidity control systems in glasshouses are mainly based on air-humidity sensing equipment, which measures the general or ‘macro’ air humidity in the greenhouse. As such, air-humidity sensing is a rather ‘blunt’ instrument when it comes to avoiding condensation as it fails to consider the dew point and the ‘micro’ environment at the plant/air interface. Consequently, humidity controls used commercially are set lower (e.g. under 85 – 90 %) than would be necessary to prevent general condensation and more heating energy is used than is strictly necessary.

Adams (2008) looked at this subject and suggested the position at which the relative humidity (RH) is measured is a key issue. In 2007, an experiment at Warwick HRI looked at the potential of targeting humidity control more precisely, using the higher of either air or plant RH. This work was prompted by interest in temperature integration (TI); a technique that saves energy by exploiting the plants ability to thrive within a band of acceptable temperature, rather than at a range of fixed temperatures. TI, although effective in reducing energy use also tends to demand more accurate and sophisticated humidity control as the potential for condensation is greater.

With TI, set-points were chosen which pushed the night time RH typically 5 % higher than would be accepted in conventionally controlled compartments. This increased the energy saving from TI, compared to a conventional climate control strategy, from 10 % to 18 %, but also increased the risk of condensation. As a consequence particularly careful humidity control was necessary in the mornings as stem temperatures tended to increase more slowly than that of the surrounding air. Targeting humidity control in this way reduced the occurrence of Botrytis.

Key to this tighter and more active control of humidity was the use of infra-red sensors to measure the stem temperature. However, these are relatively expensive and up to this point only proven in a research greenhouse. This project was therefore commissioned to explore and evaluate these measurement techniques and recommend better commercial solutions.

Materials and Methods

In deriving better techniques for dew point measurement, the project involved the following work packages:

- Laboratory assessment of different sensor types and methods of attaching them to the plant/stem.
- Short-term (three weeks) commercial trials to validate the conclusions from work package 1.
- Long-term (March – October 2010) monitoring of commercial crops.

A fourth work package, to apply the knowledge gained to a commercial crop in 2011 and determine the savings delivered, was not undertaken following a project review meeting in November 2010. The reasons for this are discussed later in this report.

Work package 1

Laboratory assessment of sensors

Sensor types

Adams (2008) used an Exergen SmartIRt/c.3 infrared temperature sensor - a non-contact sensor relying on infrared radiation emitted from the plant.

The sensor proved to be effective, although relatively expensive (circa £350 per unit, excluding installation). Its major practical drawback was the difficulty in keeping it targeted on the plant stem.

Contact based sensors were also considered as a cheaper alternative to the infrared, which also had the advantage of not relying on the targeting of a potentially moving stem. Table 1 below lists the contact sensors identified that met the following criteria (in order of priority):

- Physical package that offered low thermal inertia and good contact with the stem.
- Commercially available.
- Easily integrated with current glasshouse control systems.
- Low cost.

Table 1. Contact sensor types tested

Name (used within this report)	**Sensor type**	**Sensor package**	**Manufacturer**	**Supplier**	**Typical cost**
Thermistor bead	10kΩ thermistor	Bead	Fenwall Electronics	Skye Instruments	£3.00
PT100 chip	100Ω platinum resistance	Miniature printed circuit	Unknown	RS Components	£5.00
Thermistor patch	10kΩ thermistor	Silicone rubber patch	Minco (www.minco.com under 'thermal ribbon')	Carel Components	£15.00
PT100 patch	100Ω platinum resistance	Silicone rubber patch	Minco (www.minco.com under 'thermal ribbon')	Carel Components	£15.00

In all cases, listing of a manufacturer and/or supplier does not imply an implicit recommendation. The bead type sensors in particular are widely available. Availability of the patch sensors is more limited.

Sensor attachment methods

As well as different sensor types, attachment methods were also evaluated (Table 2).

Table 2. Sensor attachment methods

Type	Notes
Elastic - no thermal contact compound	Elastic accommodates expansion/contraction of the stem whilst maintaining positive contact pressure
Elastic – with thermal contact compound (silicone grease)	Silicone grease should improve the response time but could cause damage to the stem*
Velcro – no thermal contact compound	Velcro provides a degree of insulation thereby shading the sensor from direct heating from the sun. However, it also affects the response time and the underlying temperature of the stem.
Velcro – with thermal contact compound (silicone grease)	As above

* Similar compounds have been previously used with sap flow sensors on tomato with no problems. However, with sweet pepper they can contribute to the development of Fusarium stem rot.

Testing method

All the sensors were calibrated prior to the following tests.

To test the response time, effect of attachment method and use of silicone grease, the sensors were attached to a 15 mm diameter copper pipe, through which water could be circulated (Figure 1 and 2). Two water baths were used, one at 13°C and the other at 26°C. These allowed rapid switching between each temperature to test the sensor response time. The water temperatures were chosen as being representative of practical plant temperatures. The surrounding air temperature was 20°C. The sensors were connected to a data logger and temperature reading recorded every five seconds.

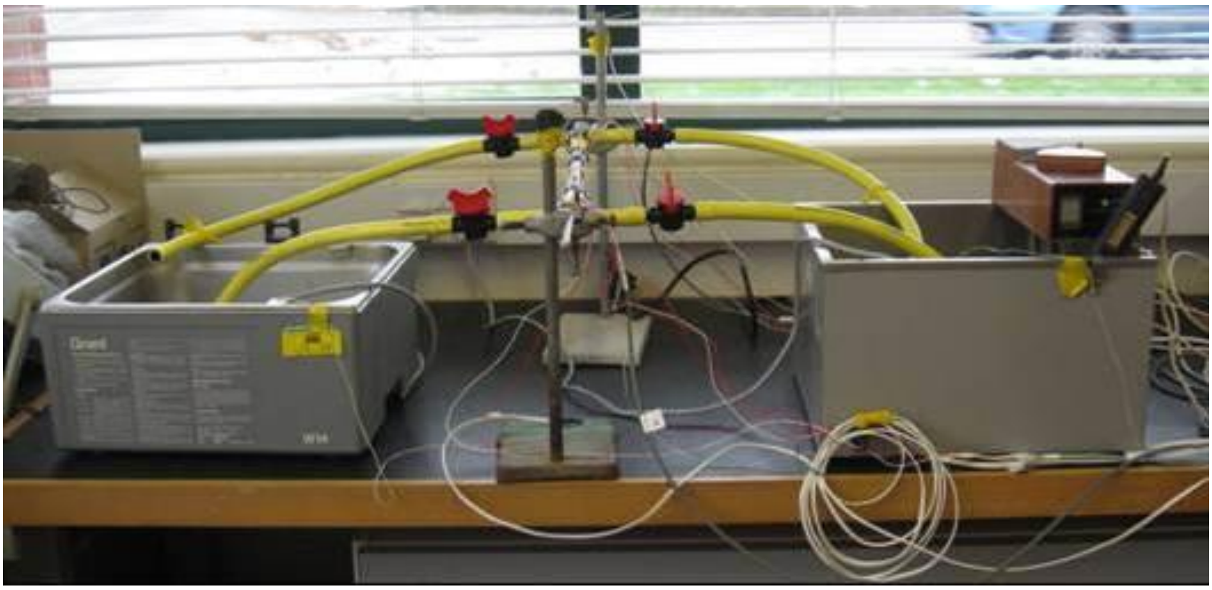

Figure 1. Sensor test rig

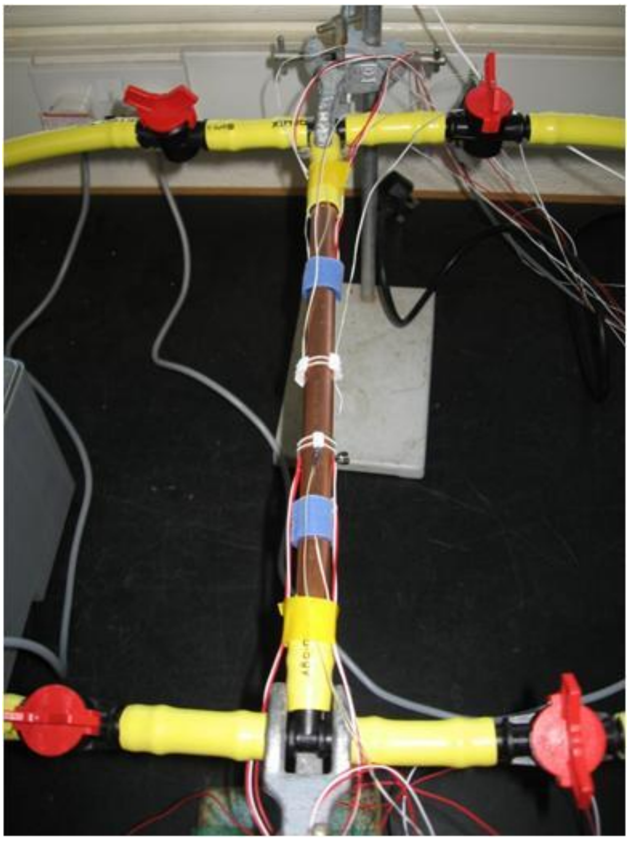

Figure 2. Close up of the copper pipe with sensors

Infrared camera calibration

A hollow cone painted matt black on the inside was immersed in a water bath point down. The IR sensor was aimed at the inside of the cone through holes in a covering plate. Calibrated thermistors were attached to the outside of the cone to give cone surface temperatures over the area viewed by the IR sensor. The temperature of the water bath was set to 15, 20, 25 & 30°C. At each calibration point the temperature of the cone was left to stabilise for a minimum of 15 minutes before measurements were taken.

Two IR sensors were tested:

- The IR sensor used in DEFRA Project HH3611SPC (Old IR).
- An equivalent model from the same supplier, as the original one was no longer available (New IR).

Work package 2

Short-term commercial trials

The sensors tested in the laboratory were transferred to Red Roofs Nurseries Ltd's Northmoor site; a commercial glasshouse, and tested on a crop of tomatoes. Tests began on 06/10/2009. Sensors were attached to plants without insulating compound. Two IR sensors were used at the de-leafing height and one at the top.

Table 3. Sensors, attachment and position in the crop

Contact sensors	**Attachment**	**Position**
Thermistor patch	Velcro	At de-leafing level
Thermistor patch	Elastic	At de-leafing level
Thermistor bead	Velcro	At de-leafing level
Thermistor bead	Elastic	At de-leafing level
PT100 patch	Velcro	At de-leafing level
PT100 patch	Elastic	At de-leafing level
PT100 chip	Velcro	At de-leafing level
PT100 chip	Elastic	At de-leafing level
Thermistor bead	Velcro	Top
Thermistor bead	Elastic	Top
IR sensors		**Position**
Old IR	n.a.	At de-leafing level
New IR	n.a.	At de-leafing level
New IR	n.a.	Top
Other sensors		
Skye Instruments wetness sensor	Wetness of an electronic membrane suspended within the crop, not on the plant itself.	At de-leafing level
Skye Instruments wetness sensor	Wetness of an electronic membrane suspended within the crop, not on the plant itself.	Top
Vaisala humidity and temperature sensor	Stevenson screen type enclosure (measured air condition, not plant measurement)	At de-leafing level
Vaisala humidity and temperature sensor	Stevenson screen type enclosure (measured air condition, not plant measurement)	Top

All the sensors were connected to a data logger. Readings were taken every five minutes (Figure 3-7).

Loggers were downloaded on 21/10/2009 and the position of the sensors checked. The IR sensors had shifted from their original position and read between 3 – 9°C higher when a hand was placed behind the portion of stem where the IR sensors were pointing. They were placed in the correct position, at 7 – 8 mm from the stem. The two PT100 bead sensors were replaced, as one had broken. At the end of the testing period (03/11/2009) the IR sensors were inspected again and found to have maintained the correct position. No problems were encountered with the patch type sensors.

Figure 3. General view of sensors in the crop

Figure 4. Attachment with elastic; PT100 patch sensor (top) and PT100 chip (bottom).

Figure 5. Attachment with Velcro (Thermistor patch)

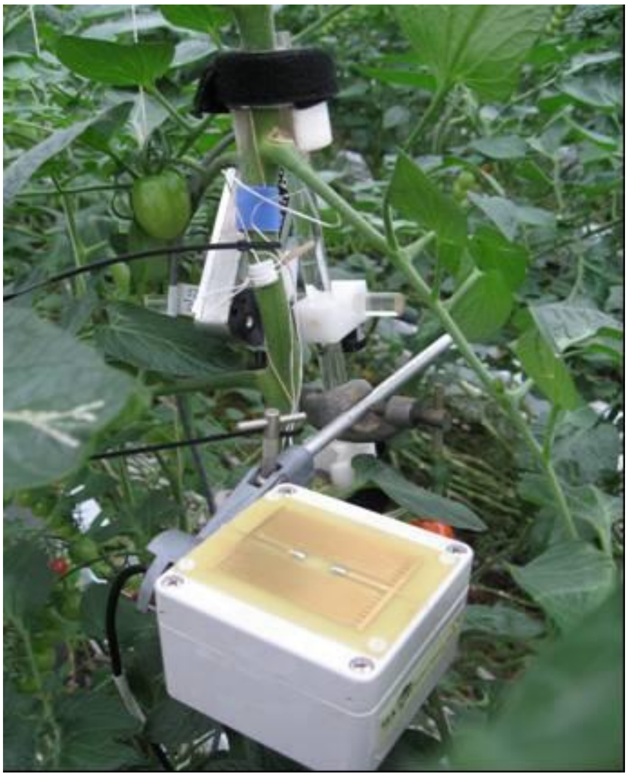

Figure 6. Infra-red and condensation sensors

Figure 7. Vaisala RH and temperature sensors in screen

Work package 3

Monitoring of commercial crops in 2010

The objectives of this work package were to:

- Understand any practical considerations/problems associated with using contact sensor based plant temperature measurement.
- Determine the spatial variation of the climate within commercial greenhouses in relation to the incidence of condensation events.
- Identify any underlying factors which cause condensation events and how they might be avoided by alternative/improved humidity control strategies.

Table 4. Nurseries monitored in 2010

Location	Greenhouse characteristics	Crop	Monitoring period
Mill Nurseries Ltd East Yorkshire CMP14	Approx. 5 m to the gutter, thermal screens, hanging gutters, roof fans but no ‘under gutter’ fans	Encore	March – October (Season long)
Mill Nurseries Ltd East Yorkshire CMP12	Approx. 5 m to the gutter, thermal screens, hanging gutters, Priva Optimiser fans (PC 278)	Encore	June – July (Short-term)
Red Roofs Nursery Ltd Northmoor site East Yorkshire CMP3	Approx. 5 m to the gutter, thermal screens, hanging gutters, roof fans but no ‘under gutter’ fans	Cheramy	March – October (Season long)
Wight Salads Group Ltd Margaret Nursery Block C	Approx. 5 m to the gutter, thermal screens, hanging gutters, roof fans but no ‘under gutter’ fans	Jack Hawkins	March – October (Season long)
R&L Holt Hornsfield Nursery Evesham CMP4	Approx. 5 m to the gutter, thermal screens, hanging gutters, under gutter fans & ducts (no heat or outside air mixing)	Piccolo	September (Short-term)
Buckland Garden	Approx. 3.5 m to the gutter, no thermal screens, grown on the floor, no fans	Elegance	August (Short-term)

All the sensor monitoring was done using Delta T data loggers. All sensors were calibrated before they were installed. General air temperatures and relative humidity were logged using conventional aspirated measurement boxes. Light levels were also measured.

Data collected

Table 5. Standard dataset

<table>
<tr><th>Sensor</th><th>Position on plant</th><th>Position in greenhouse</th></tr>
<tr><td>2 x Thermistor patch</td><td>Top — 30 – 60 cm below the growing point where the stem had reached its final diameter</td><td>Typically 4 m apart either side of the climate computer measuring box</td></tr>
<tr><td>2 x Thermistor patch</td><td>De-leaf — just above the second remaining leaf on the plant</td><td>Typically 4 m apart either side of the climate computer measuring box</td></tr>
<tr><td>2 x Thermistor patch</td><td>Bottom — within the stem bundle</td><td>Typically 4 m apart either side of the climate computer measuring box</td></tr>
<tr><td>1 x Infrared</td><td>De-leaf — as above</td><td rowspan="5">Close to the climate computer measuring box</td></tr>
<tr><td>1 x Wetness sensor</td><td>Close to the de-leaf thermistor patch sensors</td></tr>
<tr><td>1 x light sensor</td><td>Crop wire height</td></tr>
<tr><td>1 x air temperature & humidity</td><td>Close to the top thermistor patch sensors</td></tr>
<tr><td>1 x air temperature & humidity</td><td>Close to the de-leaf thermistor patch sensors</td></tr>
</table>

All the plant temperature sensors were attached with a light smear of silicone grease between the sensor and the plant and a thin piece of Velcro.

The standard dataset was collected on all the greenhouses monitored (long and short-term). In addition, the following was collected as part of the short-term monitoring:

- 18 thermistor bead sensors.
- Four additional air temperature and humidity sensors.

The additional sensors were used to investigate the spatial variation in temperature along and across rows.

Climate computer data

In addition to the data above, the following was exported from the climate control computers at the season long sites. This included:

- Weather data — temperature, wind speed and light intensity.
- Greenhouse equipment status — heating pipe temperatures, thermal screen and vent position.
- Aerial climate data — temperature, RH, dew point.
- Calculated plant temperature — determined by software based models.

Results

Work package 1

Laboratory assessment of different sensor types

Figures 8 and 9 show the performance of the sensors with and without heat transfer compound.

Contact type temperature sensors

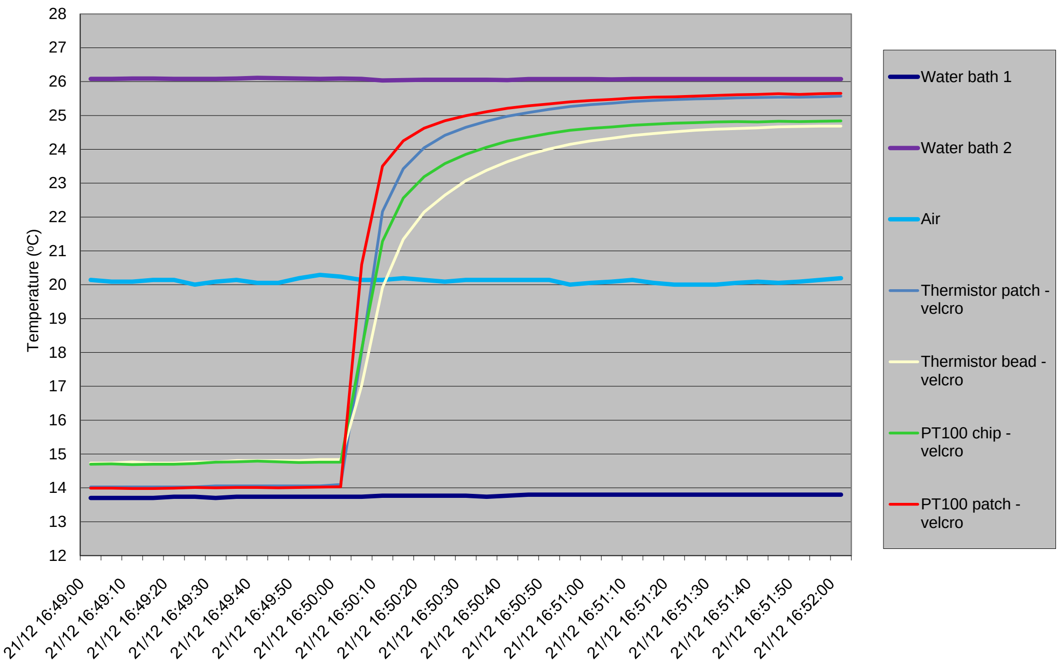

Figure 8. Comparison of sensors without heat transfer compound

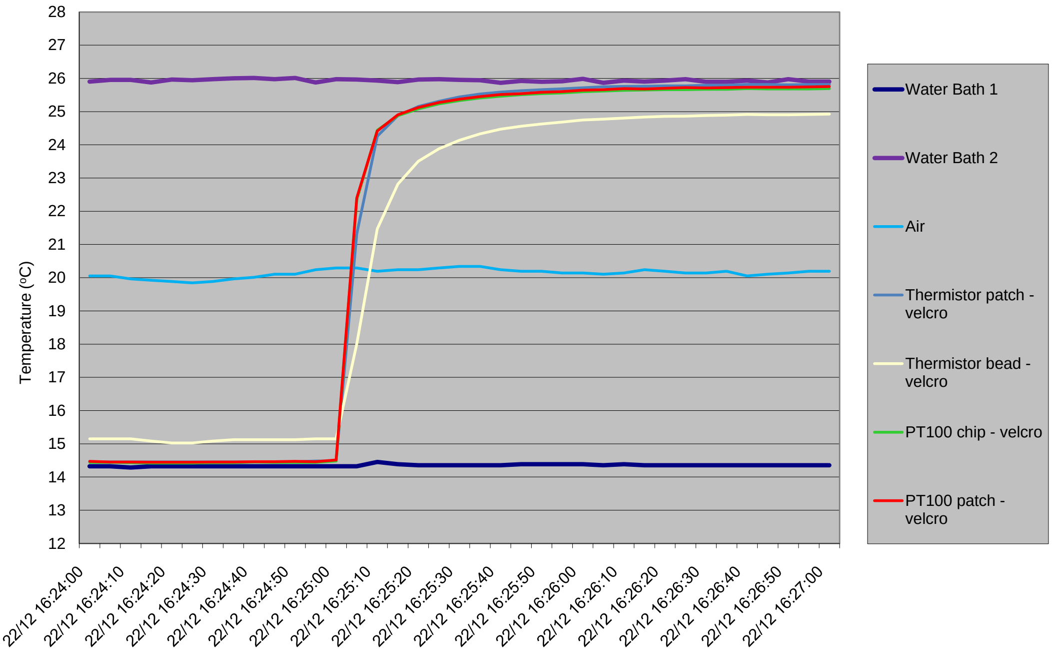

Figure 9. Comparison of sensors with heat transfer compound

Two issues revealed by the graphs are:

- The response of the sensor — how quickly the sensor responds to a step change in temperature.
- The steady state accuracy of the sensor — how well the sensor represents the true temperature of the surface it is in contact with.

The **transient response** is good for all sensors with all achieving steady state conditions within 90 seconds of a step change in pipe temperature. Use of a heat transfer compound improved the transient response marginally, but is unlikely to have any notable effect on practical performance in commercial conditions.

The **steady state** performance without heat transfer compound is notably better for the patch type sensors. The addition of heat transfer compound makes the PT100 chip sensor performance almost identical to the patch sensors. However, the thermistor bead sensor stands out as consistently poor.

Summary

With the cost of sensors being so low and plant temperatures within 1°C of the dew point temperature, errors of 0.5°C are significant, so accuracy is key. It would appear that the patch type thermistor or platinum resistance sensors have the best steady state and transient performance and should be chosen.

The practical choice for a grower will depend on which sensor type (thermistor or platinum resistance) is most easily integrated with their climate control computer. It is worth noting that although these sensors are not standard equipment available from climate computer suppliers, they can be integrated via readily available signal converters that produce a 0-5VDV signal.

The use of a heat transfer compound is not strictly necessary for the best sensors but again, for the very low cost its marginal benefit might as well be taken advantage of. However, note that sap flow sensors using a similar compound caused Fusarium stem rot.

Infrared sensors

The project which preceded this one (DEFRA Project HH3611SPC) used an older type of IR sensor. Shortly after the project was completed the specific make and model was updated.

Experience gained with the new model by Red Roofs Nursery and Hortitechnic suggested that their accuracy was not as good.

Figure 10 below compares one old type sensor and two new ones. Over the range 14 – 25°C the old sensor was superior up to 25°C. However, at 30°C the accuracy of the old sensor decreased. The new sensors tended to measure slightly higher than the true temperature. With an appropriate offset they would have been more accurate than the older sensor.

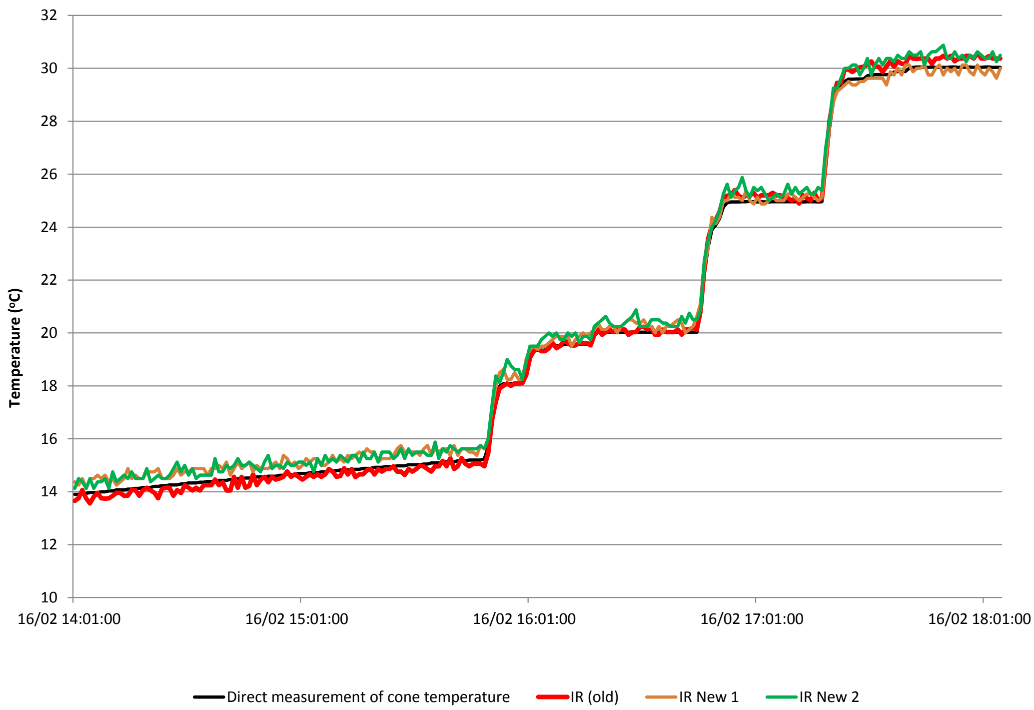

Figure 10. Comparison of IR sensors

One other important characteristic of the IR sensors was the temperature of the body caused by heating from the internal electronics. Clearly, if the sensor body is significantly higher in temperature than the plant, and it is located close to it, it has a potential to heat the plant and give an artificially high reading.

Figure 11 below shows that the body of the new IR sensors warms up significantly more than the old type. This did not affect the temperature measured in the lab tests because of the remoteness of the target area to the sensor body, but it demonstrates the potential for the new IR sensors to give falsely high temperature readings when used in a commercial situation. This supports the practical experience of Hortitechnic where the plant temperatures measured with the new sensors tended to be higher than expected.

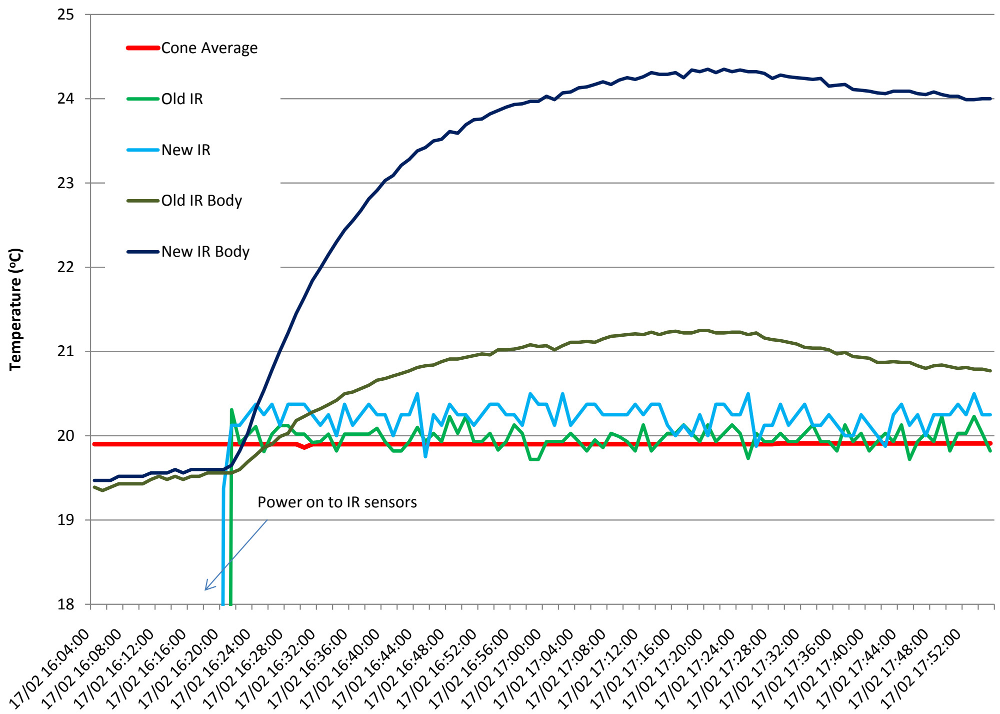

Figure 11. IR sensor body temperature

Work package 2

Commercial trials to validate work package 1

In laboratory tests the patch type sensor proved to be more accurate and responsive than the bead sensor. However, field tests (Figure 12) showed that, with sufficient care taken in their installation, both sensors performed equally as well.

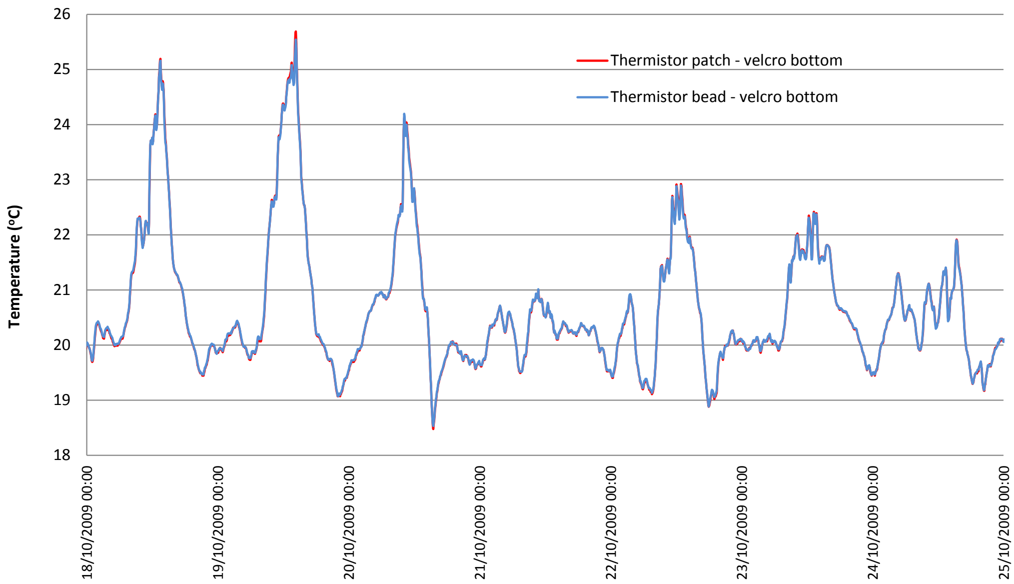

Figure 12. Comparison of patch and bead thermistors

Figure 13 compares the performance of the old and new IR sensors. First impressions suggest that they compared well with the thermistor patch until 20/10/2009 at which point something went wrong. In actual fact, a site visit was made on 20/10/2009 and the IR sensors were found to have moved and were measuring the background temperature, not the temperature of the stem. The sensors were repositioned and the effect is quite marked. Both IR sensors read consistently higher than the thermistor with the new IR reading the highest of all. Although not proven in laboratory conditions this supports the practical experience of Hortitechnic and the higher sensor body temperature measured in the laboratory.

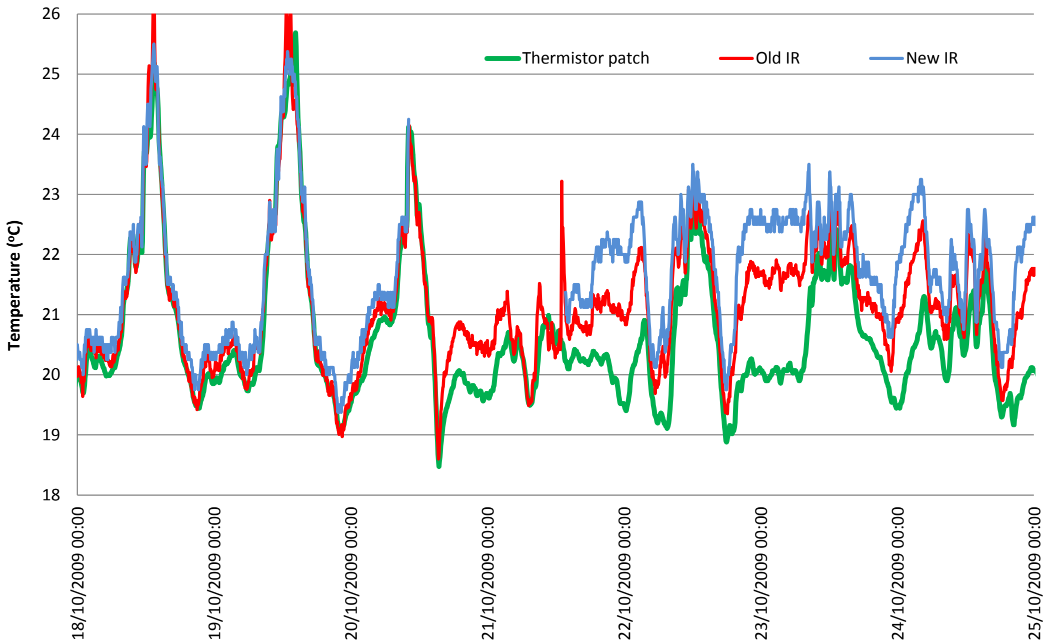

Figure 13. Comparison of IR sensors

Overall, using contact sensors to measure plant temperature at a single point is preferable to IR sensors because they are:

- Cheaper.
- More reliable.
- More accurate.
- Easier to use in practice.

Figure 14 contrasts the measurements from a ‘wetness sensor’ and the difference between the temperature of the bottom of the plant and the dew point temperature of the air around it. Any measurement greater than 0V on the wetness sensor indicates the onset of a condensation event. Clearly, it can be seen from the graph that these events correlate closely with temperature/dew point differentials of less than 2.1°C.

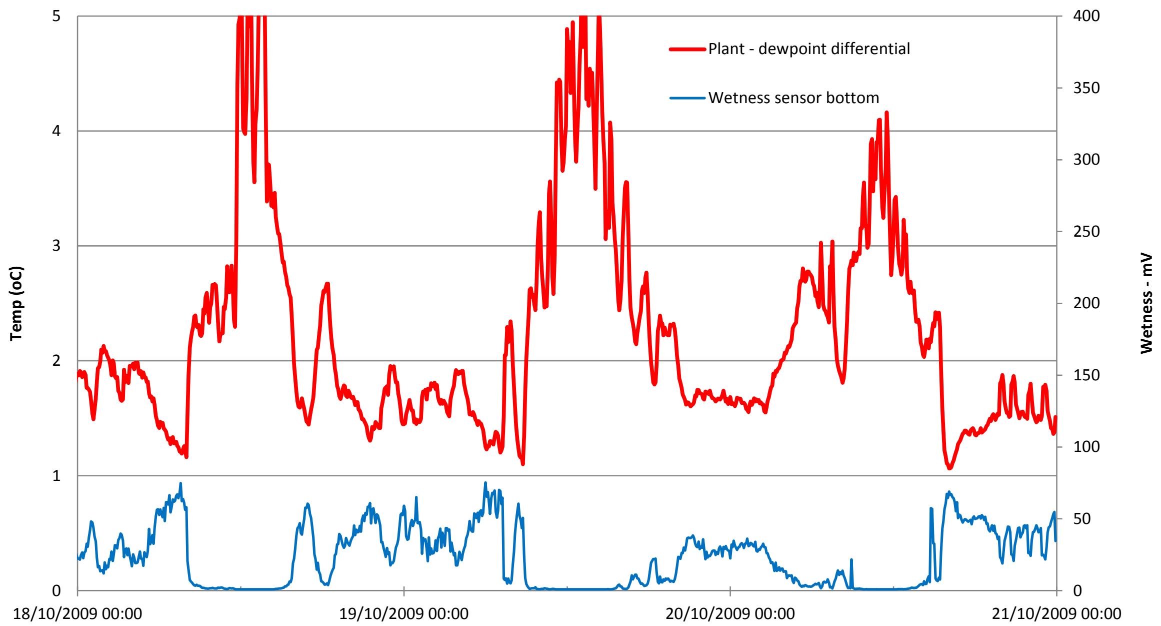

Figure 14. Comparison of wetness sensors with proximity to dew point

The disadvantage of using a wetness sensor for controlling humidity is that the wetness sensor is a free-standing unit unconnected to the plant. As such, it is not guaranteed to mimic the same results as that from the direct measurement of the dew point and temperature around the plant. More importantly, the wetness sensor gives little or no indication of an 'approaching' condensation event and only indicates when such an event has occurred. It is analogous therefore, to indicating that 'the stable door needs to be shut' — but only 'after the horse has already bolted'.

Summary

This brief period of monitoring in a commercial crop has confirmed many of the results of the laboratory testing. The patch type thermistor sensors were used as the benchmark measurement in the long term monitoring as they had better 'laboratory level' accuracy. However, the 'old' type thermistors were also used as, due to their low cost, they allowed more extensive monitoring of the variation in temperatures within a greenhouse.

Work package 3

Monitoring of commercial crops

The following observations focus on periods of time when the glasshouse humidities and condensation risks were high. Clearly, humidity measurement is not such a critical issue during long periods of the growing season when humidity is naturally lower. Specific observations are used to illustrate and demonstrate particular issues connected with the challenges of humidity and condensation control.

Micro-environment differences

Figures 15 – 18 compare plant temperature measurements at Northmoor Nursery on one day.

Measurements for each position on the plant are shown for two adjacent locations; a maximum of 4 m apart. As the locations are so close, and in the same horizontal plane, general air temperature and humidity related to the ‘macro environment’ could be expected to be similar. Therefore, any significant difference between the measurements taken at these locations is likely to be caused by some micro-environmental factor — that is localised differences in temperature, humidity or infrared radiation.

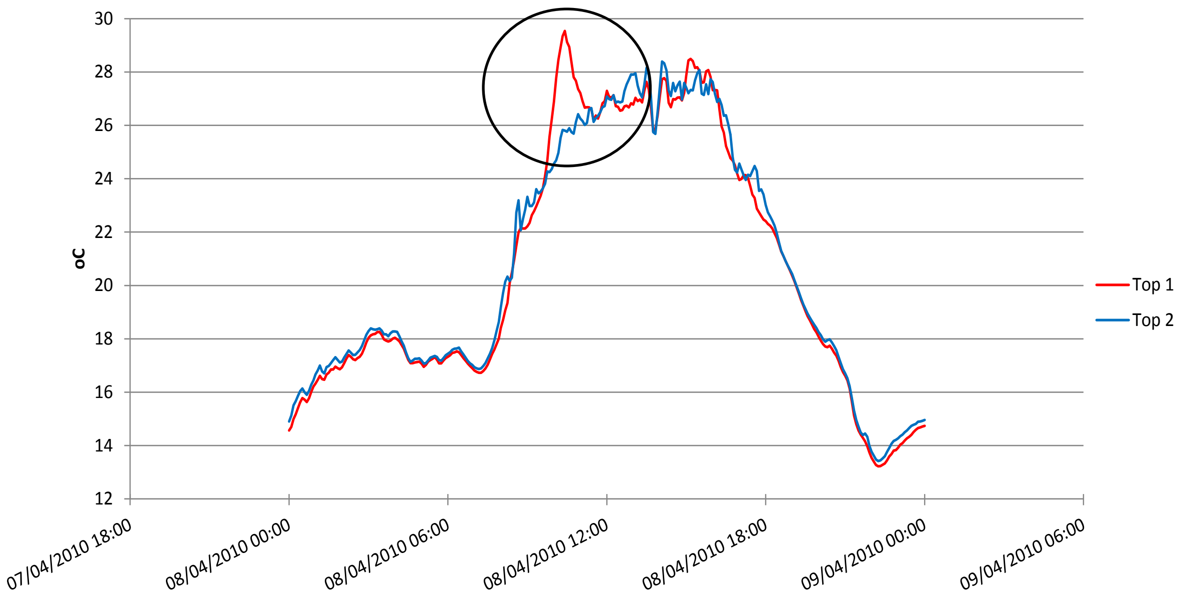

Figure 15. Top temperature

The effect of direct radiation from the sun or a cold sky can skew the result from a surface temperature sensor. Figure 15 shows close correlation between temperatures measured at two points throughout the day. However, the area circled shows the effect of the sensor/plant being in direct sunlight for a period of time. Therefore, in all cases, but mostly for the top of plant measurement, the effect of radiant heating from direct sunlight has to be considered. To help alleviate this effect the sensor should be mounted on the northeast side of the stem or the specific area effectively shaded.

Figure 16 shows a relatively constant difference between the two sensors of 0.3˚C. The difference remains during the night-time so, in this instance, radiant heating by the sun is not the cause. The difference is therefore likely to be due to a combination of measurement error and a true difference between the plants.

Closer analysis of the data has shown that the de-leaf temperatures were affected by radiant heating from the sun but to a lesser degree and less frequently than the top of plant measurements.

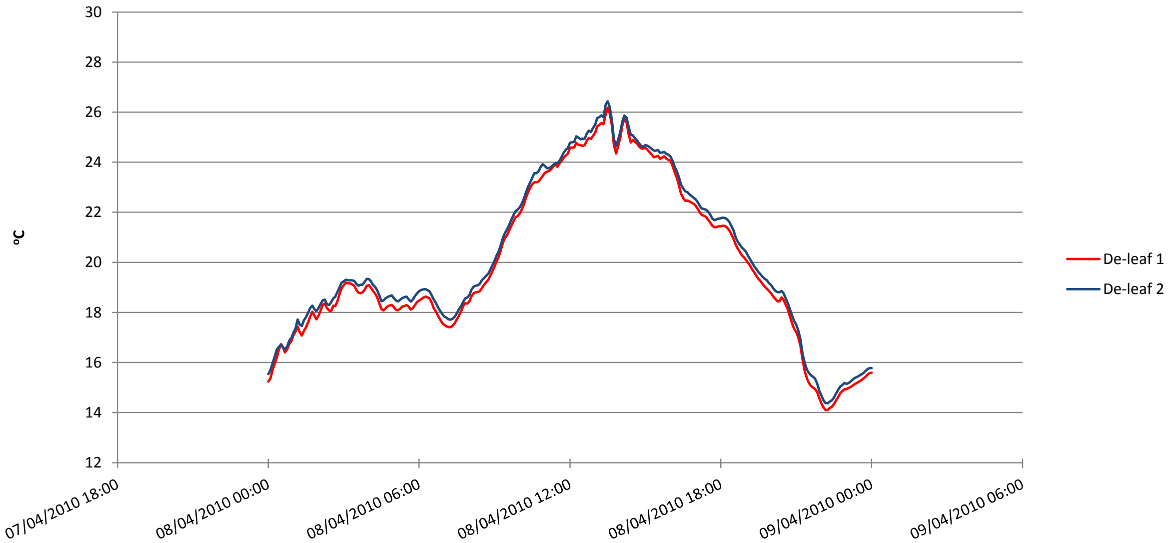

Figure 16. De-leaf temperature

Figure 17 shows that the two bottom temperatures were almost identical. There were occasions when they were different but it was typically no more than 0.2˚C for relatively short periods of time.

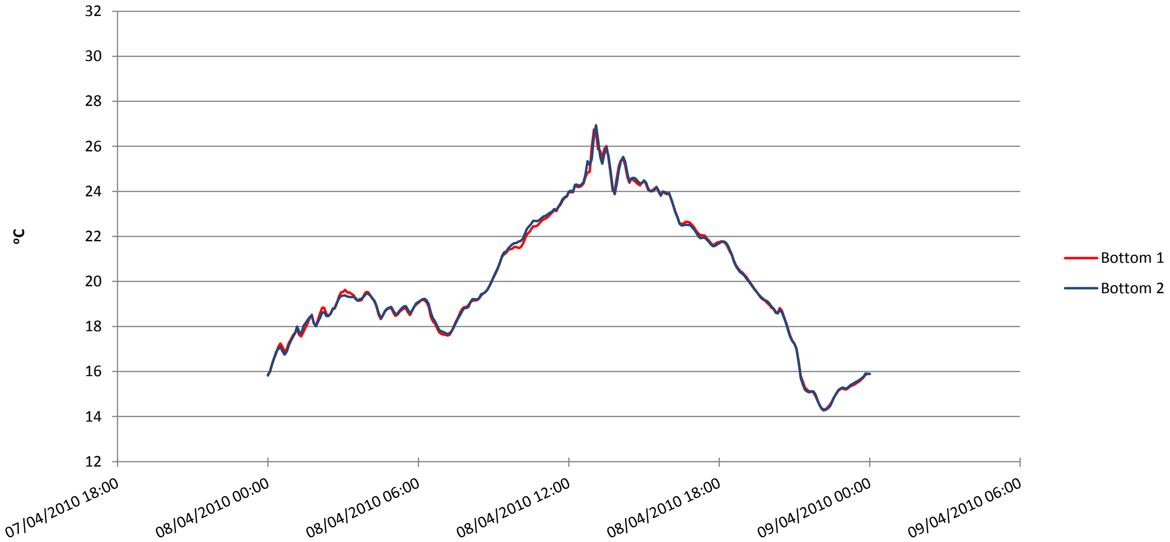

Figure 17. Bottom temperature

Figure 18 below compares the plant temperature at each location with the air temperature at the top, which is used by the majority of growers for climate control.

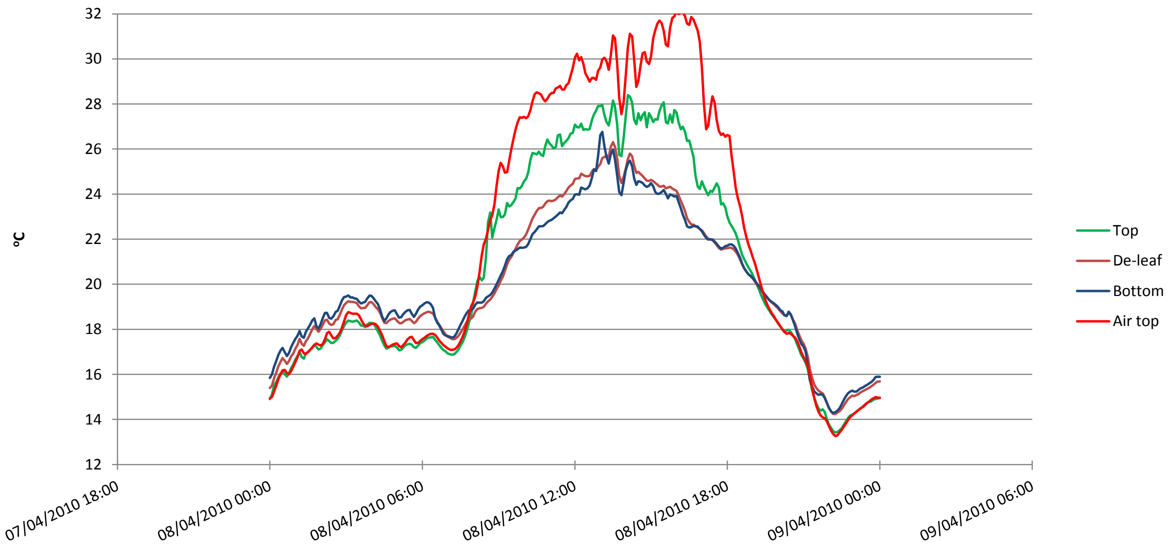

Figure 18. Top, de-leaf and bottom temperatures

From 00:00 to 06:00

All temperatures are reasonably close with the bottom temperature being highest — the effect of a bottom heating pipe temperature of 40 – 45°C. Note, this site had thermal screens; these 'shield' the crop from the radiant cooling effect of the sky and limit a fall in upper plant temperature during the night-time. Where thermal screens are not used, the top plant temperature can be as much as 1°C less than the general air temperature (Plackett *et al.* 2005).

From 06:00 to 10:00

This is when the balance of heat input to the greenhouse changes from pipe rail heating to predominantly energy from the sun. The first few hours after sunrise are considered by many to be the period of greatest condensation risk due to the combination of high humidity and rapidly changing temperatures.

Upper plant and air temperatures increase quickly, with the air temperature settling 2 – 3°C higher than the top of the plant. This differential is assumed to be due to cooling of the plant through transpiration.

The bottom and de-leaf temperatures lagged significantly behind the top air temperature and at times were 5 – 6°C colder; especially during the early warm up period. This provides significant potential for condensation on the colder parts of the plant if the humidity of the air is high.

From 10:00 to 12:00

Top and air temperature remained high through the influence of solar gain. The de-leaf temperature was consistently warmer than the bottom temperature. This was mostly due to radiant heat from the sun.

From 12:00 to 18:00

Radiant heat from the sun continues to dominate but temperature differentials narrow as the radiation wanes.

From 18:00 to 24:00

The glasshouse reverts to a night profile with the top plant temperature dropping and bottom heating pipe temperatures lifting the lower plant temperatures.

Some practical issues were revealed in the commercial use of the contact temperature measurements:

Top of plant sensor — this has to be repositioned every week to ensure that a representative measurement is obtained. This was often not carried out during this project. On occasions, crop work (training, layering etc.) also dislodged the sensors.

De-leafing sensor — similar issues to top of plant.

Bottom sensor — once layering had started there were few practical problems associated with this measurement position as the sensor did not require regular relocation. However, with little need for regular repositioning the sensor could suffer from neglect and remain dislodged if disturbed.

In all cases, if sensors of this type are used by growers they must be checked at least every week otherwise the results could be highly misleading. The installation of two sensors on the same part of the plant, but different plants, is recommended as this allows any obvious measurement errors to be more readily identified.

Summary

Top of plant temperature

This tracks the air temperature apart from when the crop is cooling itself by transpiration. As this period coincides with low humidity conditions and little risk of a condensation event, it is not a problem in practice. Radiant cooling of the top of the crop to clear skies, especially at night can be significant, especially where thermal screens are not used. As such, temperature measurement at this level could help in making crop management decisions.

De-leaf temperature

The leaf wound is known to be a common infection route for disease such as Botrytis. Therefore knowing the risk of condensation at this location may be useful. However, this measurement is prone to error through sensors being dislodged and/or not relocated regularly and may suffer from distortions by direct solar heating effect. In view of the fact that bottom measurements track de-leaf temperature for most of the time, there seems little point in measuring at the de-leaf level if bottom temperatures are being measured.

Bottom of plant temperature (stem bundle)

The lower part of the crop is where condensation risk and associated disease development is highest. This is also where there is likely to be the greatest difference between the general air temperature and the plant temperature. This location is also least prone to measurement error because the sensors do not need regular relocation. Therefore, it is concluded, the bottom of plant is the best place at which to concentrate stem temperature measurement for humidity/condensation control purposes.

Plant temperature vs. dew point temperature

A condensation event will occur when any part of the plant is below the dew point temperature of the air around it and that point does not necessarily have to be the coldest part of the plant. The key is the difference between the temperature of the plant and the dew point temperature of the air around it.

It is important not to use a measurement of dew point in the general environment to predict a condensation event at a particular position. More specifically, using the plant temperature at the bottom but the humidity of the air at the top of the crop (where it is most commonly measured) to predict condensation, is not reliable.

In the project, care was taken to measure both the temperature and humidity of the air at the bottom of the crop to determine dew point.

In Figure 19, the dew point temperature of the air at the top and bottom of the plant follow a similar pattern. The dew point temperature of the bottom air is lower than at the top for most of the time. On the rare occasion that it is higher at the bottom, it is only by a small amount 0.2 – 0.3°C. Although the dew point temperature of the top air is rarely significantly higher (>1.0°C) than the bottom air for any length of time, this tends to occur when the condensation risk is higher for the bottom of the crop. Therefore, there is a risk in relying on the top dew point measurement to predict the overall condensation risk for the plant.

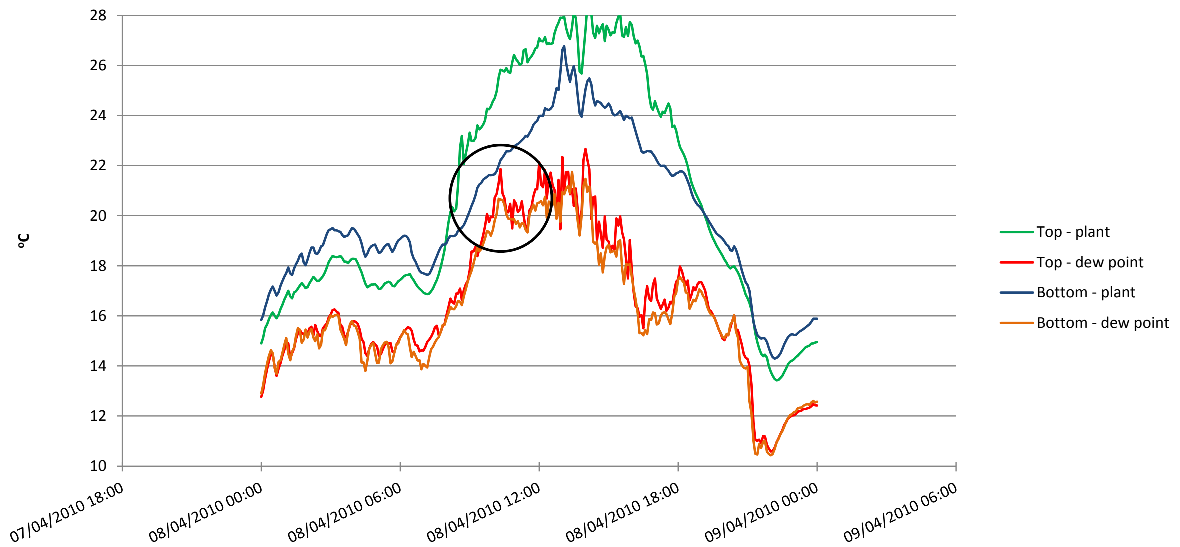

Figure 19. Plant temperature vs. dew point temperature

The area circled in Figure 19 above shows a point where, if only the dew point temperature of the top air was known, the risk of a condensation event would be seen as high. However, at this moment the bottom dew point is 1.5°C colder and the true risk of a condensation event is much lower.

Figure 20 shows one of only two condensation events recorded throughout this project. Earlier discussion suggested that the bottom of the crop tends to be at greatest risk to a condensation event, but in this case, the top plant area is affected. Unlike all the other greenhouses monitored, Buckland Gardens has a relatively low glasshouse with the top of the crop only 30 – 50 cm below the vents. The crop was therefore prone to chilling by cold air falling directly on it from the vents and does not benefit from the 'buffering' capacity of the greater volume of air above the crop found in taller glasshouses.

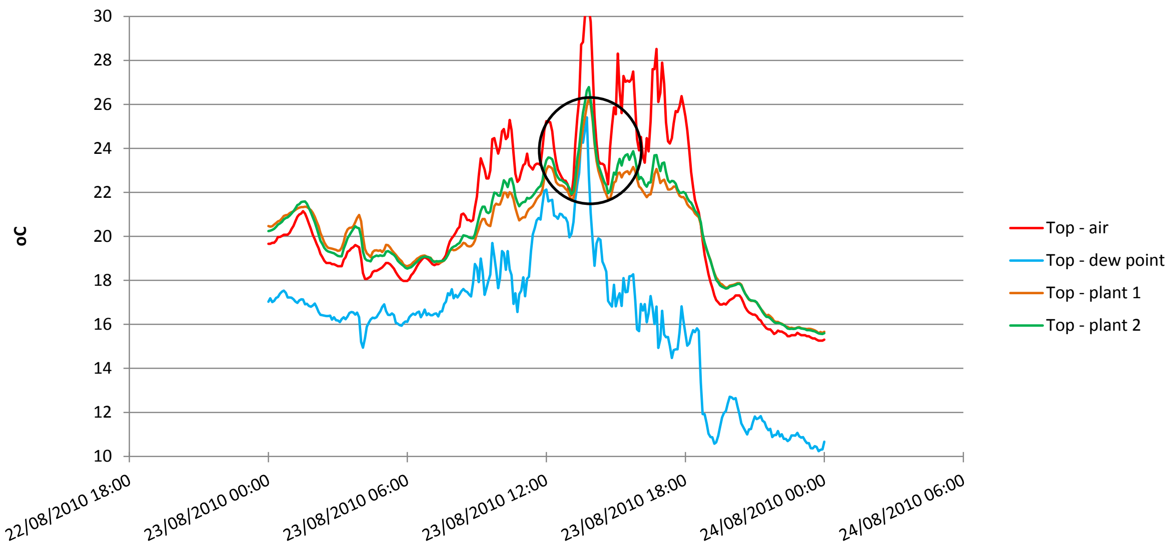

Figure 20. Top of crop condensation event

In the example above, the greenhouse temperature spiked briefly, driving the dew point high for a short period. One clear lesson from this is that rapid changes in greenhouse temperature are most likely to lead to higher condensation risk.

Comparison with software sensors

Several climate computers include what are often called 'software sensors'. These are software modules that, for example, calculate the temperature of the plant taking into account known parameters such as the light intensity, air temperature humidity and the specific heat capacity of the plant to predict likely condensation events.

These models tend to rely on the air temperature measurements at the top of the crop only and assume that this is representative for the whole of the greenhouse. Clearly, we know that temperature is not uniform. In addition, thermal inertia of plant material varies and solar events are very transient. Clearly direct plant temperature measurement has the potential to give greater sensitivity/accuracy of control.

In Figure 21, the calculated temperature is up to 2°C higher and at another time 1.5°C below the true plant temperature. Although the general trend is similar, the lack of any reasonable correlation renders the calculated temperature somewhat limited in comparison to direct measurement.

Accepting the limitations described above, calculated plant temperature and humidity is provided by some climate computer manufacturers within their standard system at no extra cost. As a facility, it can be a useful introduction to the concept of plant temperature based condensation management, as it does display the correct trends. However, its limited accuracy could lead to an overreaction to a perceived condensation event in the form of wasted energy or no reaction at all when action is required.

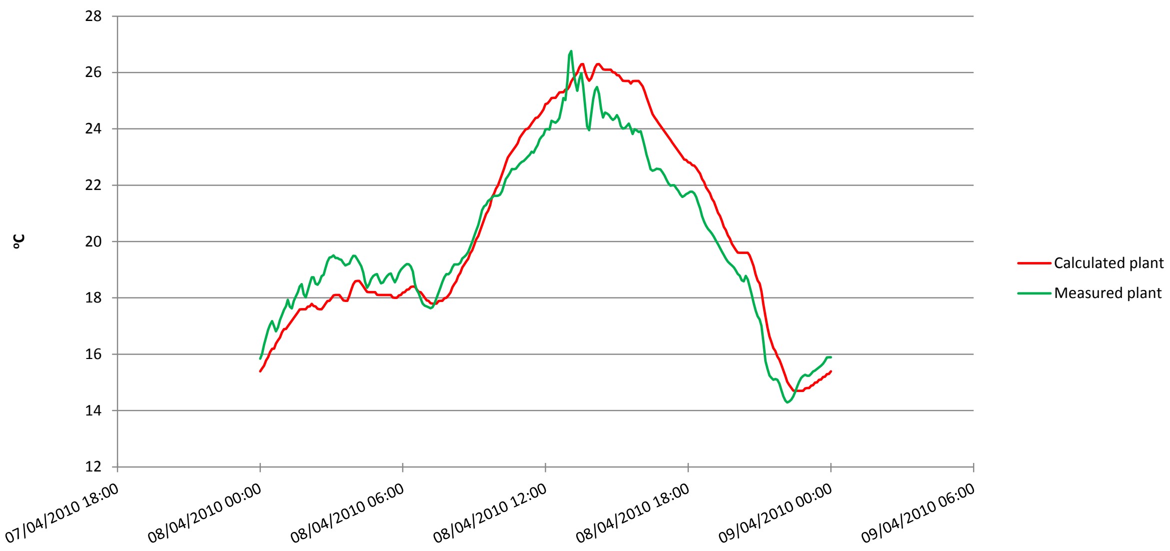

Figure 21. Measured vs. calculated plant temperature.

Uniformity of the greenhouse environment

Up to this point, analysis and discussion has assumed that the measurements taken in a relatively small area are representative of the whole greenhouse. Practical experience shows us that this is rarely, if ever, the case. Most growers are aware of warm and cold 'spots' in their greenhouses. Such variations tend to be worst during winter when the vents are closed, heating demand is high and there is a lower general risk of condensation events. When humidity control is difficult and a condensation event is likely, the vents will normally be open and the temperature uniformity is better. So, it could be argued that in these circumstances, localised measurements are still sufficiently representative to be reliable for humidity control purposes.

To illustrate the variation in temperatures throughout a glasshouse, Figure 22 shows data from a single day at Hornsfield Nursery. This site had a high number of plant temperature sensors and multiple air temperature and humidity sensors. Excluding the daytime solar temperature induced differences, the worst period with regard to spatial temperature uniformity is 00:00 – 05:00 with maximum differences of 1.5°C.

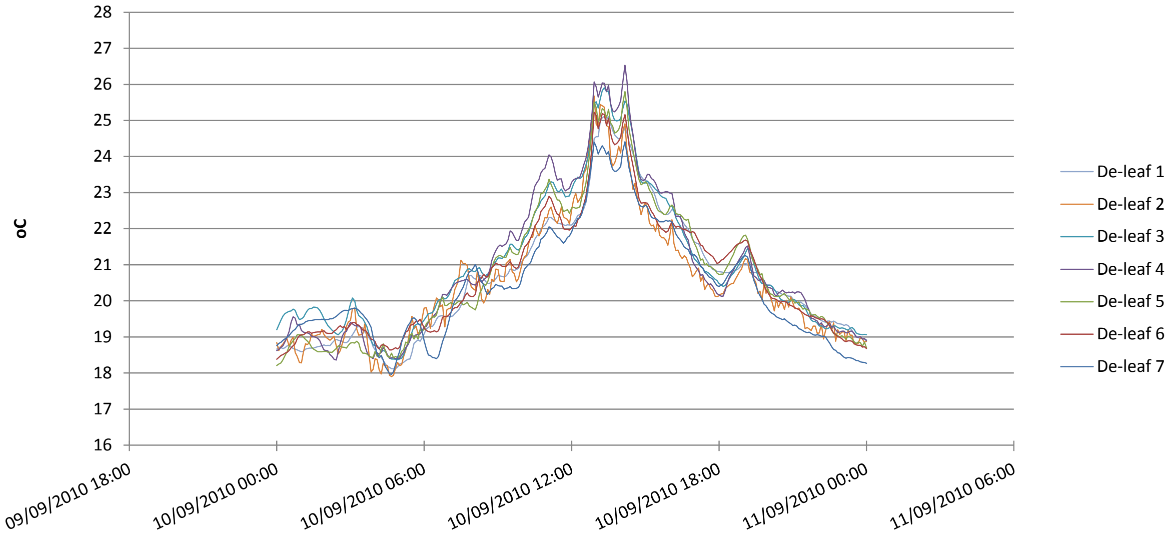

Figure 22. Bottom plant temperature at Hornsfield Nursery

Figure 23 below shows the air temperature measured over the same period and Figure 24 shows the dew point temperature. Again, the period 00:00 – 05:00 shows the worst spatial uniformity in both cases.

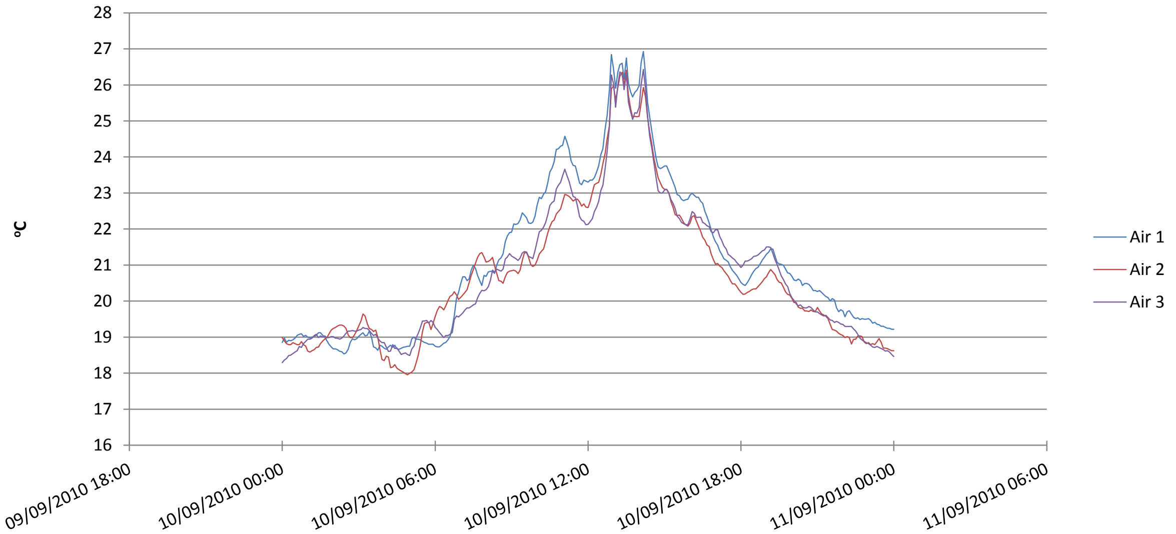

Figure 23. Air temperature

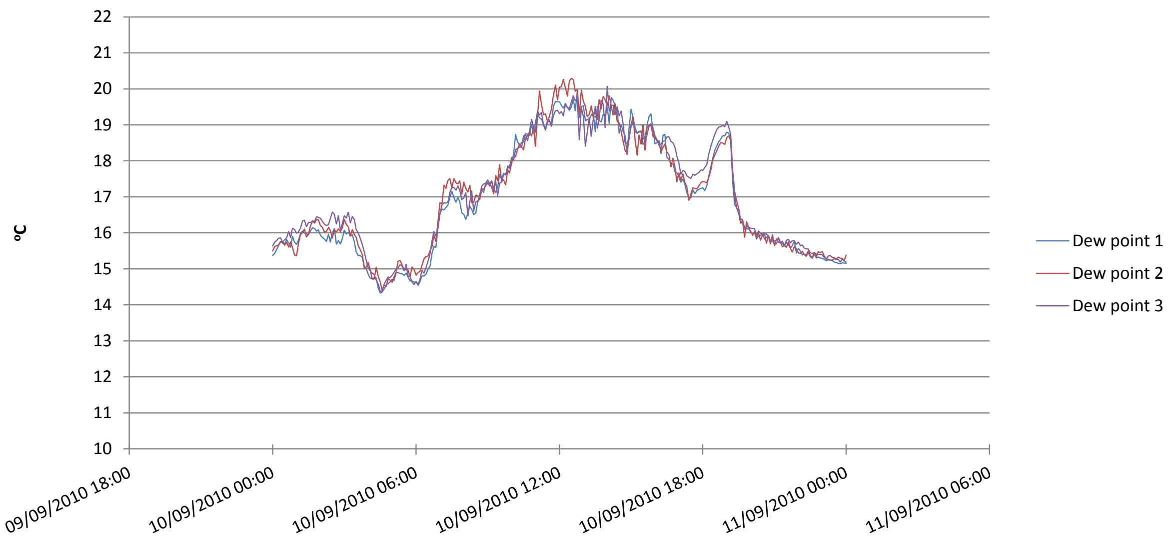

Figure 24. Dew point temperature

Results from (Pratt *et al*. 2011) show that a spatial air temperature variation of less than 1.0°C in the horizontal plane can be achieved in a modern greenhouse. Furthermore, the position of the hot and cold spots are likely to be relatively predictable, with the coldest areas being close to the walls. At a risk of providing a 'one size suits all' answer to the positioning of sensors, the following temperature sensing schedule is suggested. Sensors should be positioned on the same part of the plant at four positions down a row. Taking 0 % as next to the greenhouse wall and 100 % as next to the path, sensors should be located at:

20 % – expected to be a colder area but not so close to the wall as to be abnormally cold and representative of a relatively small part of the crop.
40 % – expected to be typical of the majority of the crop.
60 % – same as 40 % and serves as a cross-check for accuracy and sensor attachment.
80 % – expected to be a warmer area but not so close to the path as to be abnormally warm and representative of a relatively small part of the crop.

Disease assessment

The long-term monitored crops were assessed for disease incidence by Dr T O'Neill (ADAS UK Ltd). A full copy of his report is included in Appendix 1. The following is a summary of his findings.

Stem Botrytis was found at a moderately severe level in the Cheramy crop (Red Roofs Nursery), at a low level in the Encore crop (Mill Nusery), and not at all in the Jack Hawkins (Wight Salads Nursery) crop. This is in spite of the fact that no stem condensation events were recorded in any of these three crops between March and September in the locations monitored. This indicates therefore that stem condensation events are not a pre-requisite for stem Botrytis.

It is possible that increased occurrence of stem condensation may be associated with increased stem Botrytis intensity; for Botrytis infection and sporulation is known to be favoured by high humidity. However, as no stem condensation events occurred in this work, no conclusions can be drawn on this point.

The most likely explanation for occurrence of stem Botrytis in the absence of condensation events is that moisture and sugars exuding from fresh de-leafing wounds, especially those where a ragged or crushed stub is present, provide a suitable environment for Botrytis spores to infect damaged tissue. Although not investigated in detail, an area of crop that was de-leafed using knives, but not monitored for condensation events, showed significantly less disease.

Discussion

Compare methods/sensors for measuring stem temperature and decide upon the most suitable approach to use

A comparison of thermistor and PT100 temperature sensor technology showed that there was little difference between the two types. The more expensive patch sensor (£15) delivered faster response and accuracy compared to bead (thermistor) or chip (PT100) type sensors. However, the difference was small.

Short-term tests on a commercial nursery in October 2009 largely confirmed the results of the laboratory testing. The main difference was that, although the patch type sensors were superior in the laboratory, no consistent difference was noted between them and the bead or chip package types.

The integration of sensors with existing climate control computers is not ‘plug and play’ especially where manufacturers chose special sensor types as their ‘standard’. However, all climate computers have the ability to accept a 0-5V DC signal that, with the application of a simple electronic interface and a calibration curve, can be readily converted into a temperature readout. There are many ‘off the shelf’ signal converters that convert the output from standard sensor types (as used) into a 0-5V DC signal which, with a little knowledge, can be adapted.

Monitor stem temperatures and condensation events occurring in commercial crops and investigate the spatial variation

Only two condensation events were recorded throughout the commercial trial stage of the project and these occurred on one site that was monitored for two weeks. This is not to say of course, that such events do not occur widely in commercial practice. Clearly, the growers involved in these trials became involved because they were especially interested in humidity control and it could have been expected that their humidity control performance would be better than the normal.

Sites were avoiding condensation events successfully with the tools available to them, using conventional sensor positioning and control strategies. They may have been doing this at higher energy costs than strictly necessary, because their existing sensor installations and processing capabilities would not have allowed them to refine their operation any further without introducing too much risk — but nevertheless they were successful.

Spatial variation of crop temperature in the horizontal plane, naturally mirrors variation in air temperature, with some areas of the glasshouse suffering from hot/cold spots. All growers are aware hot or cold spots within their greenhouses but manage the greenhouse according to what they consider to be the most representative location (often the middle). The severity of the hot/cold spots dictates how much they influence the strategy adopted for the greenhouse as a whole.

Clearly, where horizontal plane special variation is particularly high, it is necessary to consider the worst areas when considering control. For the purposes of the project, these larger special temperature variations were ignored, with work focusing on the rows closest to the location of the climate computer measuring box. In the participating greenhouses, the maximum to minimum difference was typically 1.0 – 1.5°C. The end of the row close to the central path was typically 0.5°C warmer than the average, and the end closest to the wall was 0.5°C colder.

The spatial variation in the dew point temperature of the air is equally important when considering the risk of condensation. The pattern of variation was the same as the air temperature but the difference (maximum to minimum) was slightly less.

With regard to spatial variation in the vertical plane, the dew point temperature of the air around the bottom of the crop was invariably different to that at the top. This was especially the case when the risk of condensation was greatest. Therefore, if sensors of the type tested are used, the temperature and humidity in the bottom of the crop should be measured.

Develop optimal control strategies for the control of humidity to maximise energy savings while minimising the incidence of Botrytis and carry out a commercial trial

This was part of the original project plan. However, a project review meeting held following completion of work package 3 concluded that the results already proved the benefit of these sensors. The cost-benefit of a year-long ‘with and without’ commercial trial was not deemed to be worthwhile. Instead, effective communication of the results via the HDC’s GrowSave energy communications project was decided as the most cost effective route.

Disease incidence

Disease monitoring on the long-term sites showed some levels of Botrytis in spite of no condensation events being measured. Although not a new finding, this reinforces the fact that a condensation event is not a pre-requisite for Botrytis to develop. Nevertheless, it is still true to state that where condensation events occur, an increase in disease incidence is likely to be found; but the two events are not mutually dependent. One of the participating growers was encouraged by the lack of condensation events, especially as he used relatively little energy for humidity control. This provided him with the confidence to continue with the strategy taken and concentrate his efforts on the other factors that affect disease incidence.

Practical considerations

Particular attention needs to be paid to the effect of radiant heating from sunlight on the sensor/plant. From the point of view of condensation, the coldest part of the plant is the critical area; therefore, any radiant heating will give a high false reading leading to an underestimate of condensation risk. This occurs mostly at the top of the plant although the effect was also noted on the de-leafing location. The bottom of crop sensor is least affected. Mounting the sensors on the northeast side of the plant helps to reduce this effect.

The top of crop and de-leafing sensors require regular relocation and are prone to being dislodged whilst plant work is carried out. The bottom of crop sensor still has to be checked, but is less prone to problems of this type. The bottom of crop sensor gave almost identical results to the de-leafing sensor, therefore the latter is deemed unnecessary.

Condensation events allied to disease incidence are most prevalent in the lower part of the crop; therefore, if budgets are limited, bottom sensor installation should be the priority.

Variation in the greenhouse environment should be considered. As a minimum, sensors should be placed close to the climate computer measuring box and at the colder end of the rows (typically the wall end). In all cases, a second measuring box located around the bottom of the crop is required as the humidity conditions can be different to those at the top of the crop, especially when the risk of condensation is high.

Other benefits

The main temperature measurement used by growers in manipulating environment to manage crop development is the air temperature at the top of the crop. The top of crop sensor was shown to reveal significant differences between the temperature of the crop and the air around it. Although these differences were expected and generally understood by growers, the ability to see the direct relationship and difference, offers the potential for improved crop management.

Financial

Financial benefits and returns from using stem temperature monitoring as a method of controlling glasshouse humidity is not simple to evaluate, as these will be very dependent on the ability of the grower to interpret and act on the results available.

Clearly, the project did not allow a direct with/without comparison to be made to evaluate benefits; however, it is worth considering some typical numbers to relate possible expenditure to benefits.

Cost — the total installed cost of a single sensor integrated with an existing climate computer is highly dependent on site specific circumstances. A single sensor may only cost £15. However, the total installed cost can easily be £250 per sensor. In most cases, a second measuring box is also required. Some money also needs to be put aside for training to enable information from the system to be interpreted correctly and acted upon. A budget of £3,000 per greenhouse compartment seems sensible.

Energy — estimates of the amount of energy used for humidity control range from 25 – 40 % of total annual use. This represents £15,000 – £45,000 per hectare per annum.

Investment return — based on the above costs and a one hectare greenhouse, a pay back on investment within three years would require an energy saving of 3 % of annual consumption.

The value of a reduction in the level of Botrytis infection is more difficult to assess, as this will be very site specific.

Conclusions

- Contact type temperature sensors can be used to assess the risk of condensation on commercial tomato crops and provide growers with feedback regarding the success of humidity control strategies, leading to energy savings and/or reduced crop loss.

- A second measuring box is required to allow the risk of condensation in the bottom of the crop to be determined.

- Patch type contact temperature sensors are superior to more readily available and cheaper bead type sensors. The small increase in cost is justified due to their inherently better design for this application.

- It is possible to significantly reduce energy use for humidity control whilst avoiding condensation events. This requires a good understanding of climate control and the causes of condensation.

- Avoiding condensation events is an important part of any disease control strategy. However, disease can still develop in the absence of condensation.

- The direct measurement of plant temperature offers the potential to improve crop management through improved understanding and manipulation of the greenhouse climate.

Knowledge and Technology Transfer

September 2009 – HDC News

February 2011 – HDC Energy News

March 2011 – HDC News

March 2011 – Humidity and disease control workshops (Chichester & Hull). Presentation are available from the Knowledge Base page of the GrowSave website here: http://www.growsave.co.uk.noisegate2.webhoster.co.uk/knowledgebase?tab=1

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Plackett, C.W. and Pratt, C.T. and O'Neill, T. (2005). PC 198 Annual report - The use of thermal screens for energy saving and greenhouse climate management in protected edible crop production.

Pratt, C.T. and Swain, J.G. and Adams, S.R. (2008). PC 265 Final report - Sweet peppers: the use of thermal screens for summer shading and their effect on plant growth and fruit quality.

Pratt, C.T. and Swain, J.G. and O'Neill, T. (2011). PC 278 Annual report - The development and commercial demonstration of ducted air systems for glasshouse environmental control.

Appendices

Appendix 1

Disease assessment carried out by Dr T O'Neil ADAS UK Ltd.

Introduction

Moisture is one of several factors that influence Botrytis risk. Monitoring of a commercial tomato crop by Warwick HRI in summer 2007 indicated, somewhat surprisingly, that condensation on stems had occurred on many nights. The main objective of this project in 2010 was to determine if condensation occurs commonly in commercial tomato crops, and to determine its occurrence at different crop heights and different locations in a glasshouse; this work is detailed in another section of this report. A secondary objective in 2010 was to determine whether or not stem Botrytis was present in the three crops used by Warwick HRI and FEC for stem condensation monitoring, and, where found, to identify infection points on plants. This work is detailed below.

Methods

Full details of the crops examined are given elsewhere in this report. Each crop was examined for stem Botrytis by slowly walking six paths and checking plants on both sides of the pathway; both the horizontal bundle of layered stems and the individual vertical stems were examined for Botrytis lesions. Botrytis was identified by its typical grey sporulation and/or brown lesions. Dates of crop examination are given in Table 1. In addition to crop examination, 20 de-leafing stubs were collected from the Isle of Wight crop on 14 July and tested for Botrytis by incubation in a humid chamber.

Table 1. Details of tomato crops that were monitored for stem condensation (March–September 2010) and examined for stem Botrytis

County	Variety	Date(s) examined for Botrytis	Fungicides used for Botrytis
Isle of Wight	Jack Hawkins	25 May, 14 July,	Programme
Yorkshire	Cheramy (on Efialto rootstock)	27 August, 4 November	Switch (x1)
Yorkshire	Encore	9 July, 27 August, 12 October	Nil

Results and discussion

Stem Botrytis was found at a moderately severe level in the Cheramy crop, at a low level in the Encore crop, and not in the Jack Hawkins crop.

On 27 August, in the crop of cv. Cheramy, there were obvious spreading and girdling Botrytis stem lesions and some plants were dead from Botrytis stem rot; a total of around 2% of stems were affected. The main infection point leading to stem Botrytis was de-leafing stubs. There was also evidence of contact spread between adjacent stems in the layered bundle. This crop was badly affected by powdery mildew on leaves and stems at this time, but there was no evidence of Botrytis development on leaf tissues that were yellowing because of mildew. Spent fruit trusses had been pulled off and there was no sign of Botrytis infection on stem epidermal tears that sometimes occurred with this treatment. The number of Botrytis stem lesions was not counted at a visit near the end of cropping (4 November), although a visual inspection indicated higher levels than were found in August.

In a crop of Santasian in the same glasshouse (on the opposite side of the central pathway), leaves had been cut off with a knife rather than being snapped off because of difficulty in de-leafing this large leaf variety without leaving a ragged petiole stub. The resultant stem wounds appeared smooth and flush to the stem and no Botrytis was found on 27 August. Also in this variety, spent fruit trusses had been left on the plants and the vast majority were still fully green; no stem lesions arising from fruit truss dieback were found

On 27 August in the Yorkshire crop of cv. Encore (a variety known to be susceptible to stem Botrytis), a total of four stem botrytis lesions on 720 plants was found (0.5% stems affected). At a final examination in October, a total of 78 Botrytis stem lesions were found on 720 stems (10.8% stems affected).

No stem Botrytis was observed in the Isle of Wight crop in July, and none developed from the de-leafing stubs collected at this time when tested by humid incubation. Possibly some Botrytis stem rot would have been found if the crop had been examined later in the season. However, the grower reported very little Botrytis was found in this crop at any stage in 2010, and considered this was largely because of the programme of fungicide and biofungicides applied to protect this known susceptible variety.

Elsewhere in this report, results are given that no stem condensation events were recorded in any of these three crops between March and September. The occurrence of stem Botrytis in crops where no stem condensation has occurred indicates that stem condensation events are not a prerequisite for stem Botrytis. It is possible that increased occurrence of stem condensation may be associated with increased stem Botrytis intensity, for Botrytis infection and sporulation is known to be favoured by high humidity; however, as no stem condensation events occurred in this work, no conclusions can be drawn on this point. The most likely explanation for occurrence of stem Botrytis in the absence of condensation events is that moisture and sugars exuding from fresh de-leafing wounds, especially those where a ragged or crushed stub is present, provide a suitable environment for Botrytis spores to infect damaged tissue and from this food base develop to cause spreading or girdling stem Botrytis lesions.